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Tecniche Diagnostiche per Reattori a Fusione Termonucleare

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Nuclear Structure

Nuclear Structure

Symbol for a nucleid

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

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

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Nuclear Structure

Symbol for a nucleid

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

Proton number - Z

The number of protons in the nucleus.

Isotopes

Nuclei (atoms) with the same number of protons but different numbers of neutrons.

Neutron number - N (N = A – Z): The number of neutrons in the nucleus.

Nuclear Structure

- **proton**

$m_p = 1.6726231 \times 10^{-24}$ g = 1.00727647 AMU = 938.27231 MeV/c^2
carica elettrica positiva $|e| = 1.60217733 \times 10^{-19}$ C

- **neutron**

$m_n = 1.6749286 \times 10^{-24}$ = g = 1.008664904 AMU = 939.56563 MeV/c^2
carica elettrica nulla

- *Note that:*

  $m_n - m_p \approx 1.3$MeV/c2 , m_n - 1 AMU ≈ 8MeV/c2
  (electron: $m_e = 9.1093897 \times 10^{-28}$ g = 0.51099906 MeV/c^2
  Negative electric charge $|e| = 1.60217733 \times 10^{-19}$ C)

Ref.: TABLE OF ISOTOPES, 8th edition 1996, edited by Richard B. Firestone and Virginia S. Shirley, *Lawrence Berkeley Laboratory*, Published by John Wiley & Sons, Inc.

Isotopes

Isotopes – Nuclei (atoms) of the same element differing in masses due to different numbers of neutrons (the same proton number, different nucleon number).

- The existence of isotopes is evidence for the existence of neutrons, **because there is no other way to explain the mass difference of two isotopes of the same element.**
- The same number of electrons – the same bonding - the same chemical properties
- Different masses – different physical properties

Isotopes

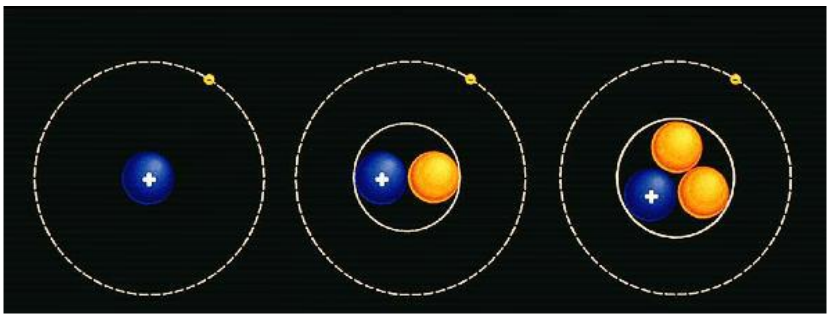
Many isotopes do not occur naturally, and the most massive isotope found in nature is uranium isotope $^{238}_{92}U$

About 339 nuclides occur naturally on Earth, of which 269 (about 79%) are stable

The current largest atomic number element, with atomic number 118, survived for less than a thousandth of a second

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)

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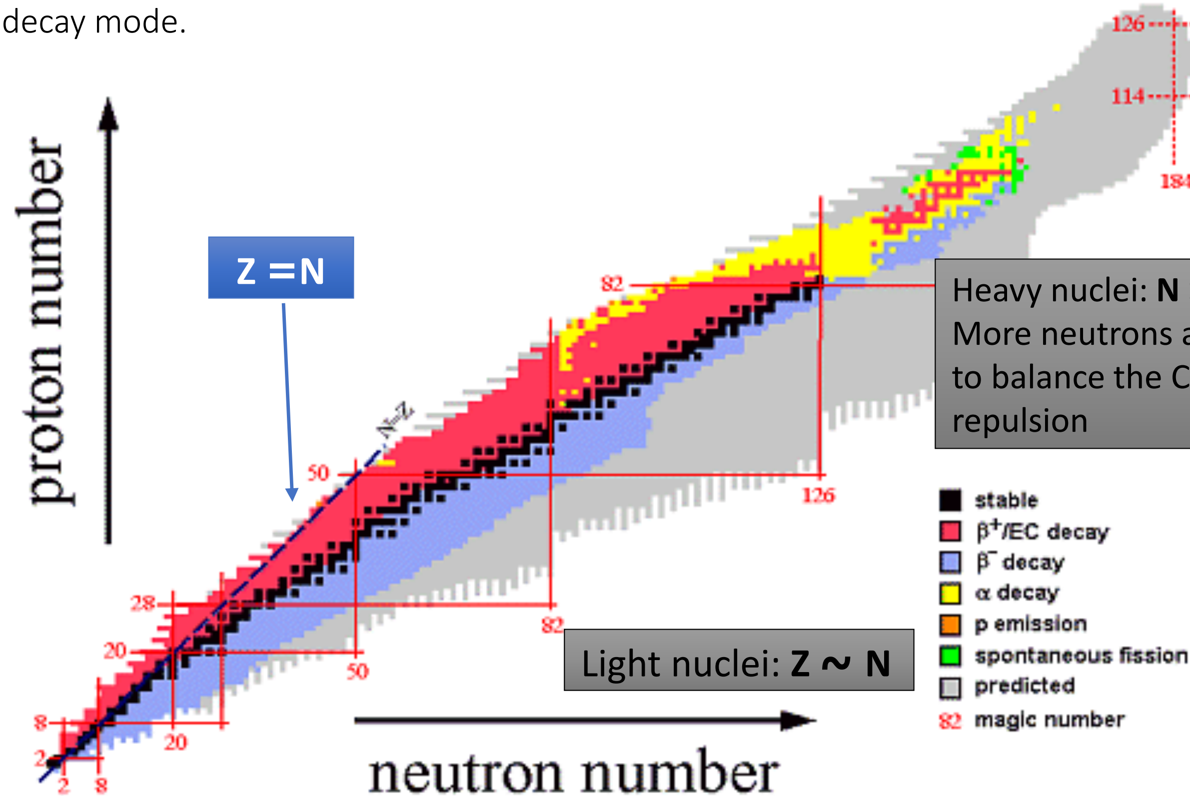
Chart of nuclides

The Chart of the Nuclides shows the known nuclei in terms of their atomic number, Z, and neutron number, N. Each box represents a particular nuclide and is color-coded according to its predominant decay mode.



Z =N

Heavy nuclei: **N > Z**
More neutrons are needed to balance the Coulombian repulsion

Light nuclei: **Z ~ N**

The strong nuclear force

What holds the nucleus together?

Protons are positive, neutrons are neutral (they would drift apart if put them together), so if the electric force was the only force involved, you couldn't create a nucleus.

There has to be some other force that holds protons and neutrons together and it must be stronger than the electric force. Well, in a brilliant stroke of imagination, physicists have named this force "the strong force."

The strong nuclear force

What holds the nucleus together?

Although the nuclear force is strong, nuclei do not attract each other, so that force must be very short range, unlike the electric force that extends forever.

The strong nuclear force was first described by the Japanese physicist Hideki Yukawa in 1935. It is the strongest force in the universe, 1038 times stronger than gravitational force and 100 times stronger than the electromagnetic force.

The strong nuclear force

It is the force which attracts protons to protons, neutrons to neutrons, and protons and neutrons to each other. That force has a very short range, about 1.5 radii of a proton or neutron (1.5×10^{-14}m) and is independent of charge and this is the reason the nucleus of an atom turns out to be so small.

If the protons can't get that close, the strong force is too weak to make them stick together, and competing electromagnetic force can influence the particles to move apart.

The strong nuclear force

As long as the attractive nuclear forces between all nucleons win over the repulsive Coulomb forces between the protons the nucleus is stable. It happens as long as the number of protons is not too high. Atomic nuclei are stable subject to the condition that they contain an adequate number of neutrons, in order to "dilute" the concentration of positive charges brought about by the protons.

The most massive isotope found in nature is uranium isotope $^{238}_{92}U$

For more massive nuclei strong nuclear force can't overcome electric repulsion.

Binding energy

Binding energy

- Energy (work) must be applied to a nucleus to break it up into separate, free particles. So, if work is done, then the energy must have been transferred to nucleons.
- On the other hand the sum of the masses of the constituent free protons and neutrons is found to be more than the mass of original nucleus.

The only possible conclusion: energy is converted into mass ?????

Einstein's Mass-Energy Equivalence Relationship:

In 1905, while developing his special theory of relativity, Einstein made the startling suggestion that *energy and mass are equivalent*.

Binding energy

He predicted that if the energy of a body changes by an amount E, its mass changes by an amount m given by the equation

$E = mc^2$ where c is the speed of light.

When nucleons bind together to form nucleus the mass of a nucleus is found to be less than the sum of the masses of the constituent protons and neutrons.

Mass defect (deficit) - difference between the mass of a nucleus and the sum of the masses of its isolated nucleons

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**.

Calculations of binding energy

Unified Atomic Mass Unit (amu abbreviated as u) –

1/12 of the mass of one atom of carbon-12 (6p+6n+6e).

- 1 u = $1.66053886 \times 10^{-27}$ kg

Mass Defect $\delta = Zm_p + Nm_n - M_{nucleus}$ in unified atomic mass units (u)

E = $(1.66053886 \times 10^{-27}\ \text{kg})\ (2.99792458 \times 10^{8}\ \text{ms}^{-1})^2 = 1.4924178992 \times 10^{-10}\ \text{J} = 931.5\ \text{MeV}$

1 electron volt = $1.60217646 \times 10^{-19}$ joules

$$1.4924178992\times10^{-10}\text{J} = \frac{1.4924178992\times10^{-10}}{1.60217646\times10^{-19}}\ \text{MeV} = 931.5\ \text{MeV}$$

usual way:

Calculations of binding energy

$$1.4924178992\times10^{-10}\text{J} = \frac{1.4924178992\times10^{-10}}{1.60217646\times10^{-19}}\ \text{MeV} = 931.5\ \text{MeV}$$

1 electron volt = 1.60217646 × 10^{-19} joules

$$E = mc^2$$

1u is converted into 1.492 x 10^{-10} J energy = 931.5 MeV:

Binding Energy: mass deficit converted into energy $BE = \delta\ c^2$

Calculations of binding energy

Remember that periodic tables give atomic masses not nuclear masses. To get nuclear masses you have to subtract the masses of electrons in the atom from atomic mass

Example: Calculate the binding energy of iron Fe

From the periodic table: Z = 26 A = 54 mass = 53.940u (pure $^{54}_{26}Fe$)

from data booklet: m_{proton} = 1.007276u $m_{neutron}$ = 1.008665u $m_{electron}$ = 0.000549u

$\delta = Zm_p + Nm_n - M_{nucleus}$

δ = 26x 1.007276u + (54-26)x 1.008665u – (53.940u – 26x 0.000549u)

δ = 54.431796u – 53.925726u = 0.50607u

Calculations of binding energy

$BE = \delta(u)\ x\ 931.5$ (MeV) → $BE = 0.50607\ x\ 931.5$ (MeV)

$BE = 471.4$ MeV

very often instead of atomic mass,
nuclear mass will be given
(nuclear mass of Fe is 53.925726u)

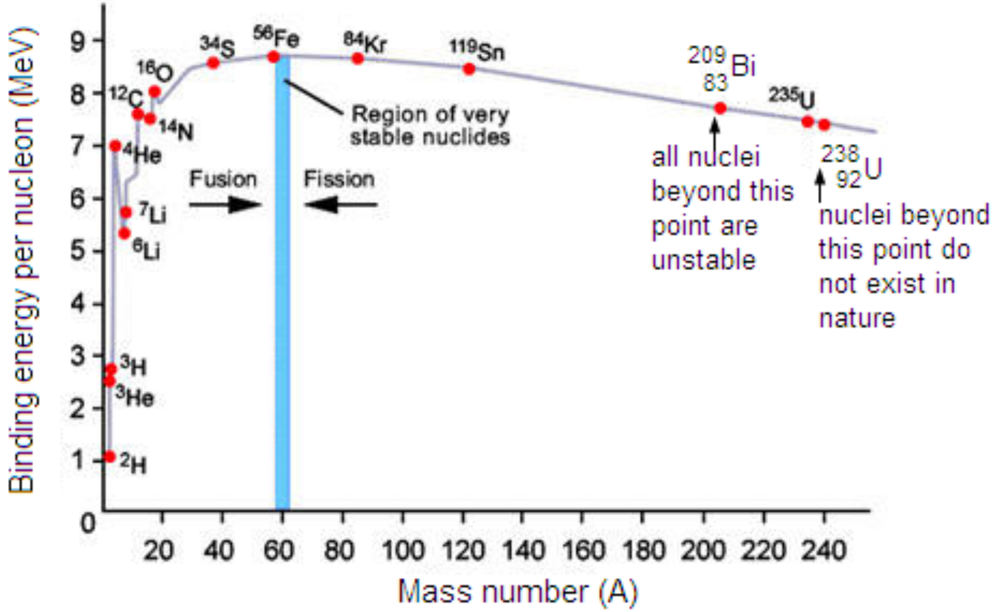
binding energy per nucleon - the binding energy of a nucleus is divided by its mass number

$$\frac{BE}{A}$$

For pure Fe it is 8.7 MeV/nucleon

Binding energy curve

Graph of binding energy per nucleon



BE varies with mass number;

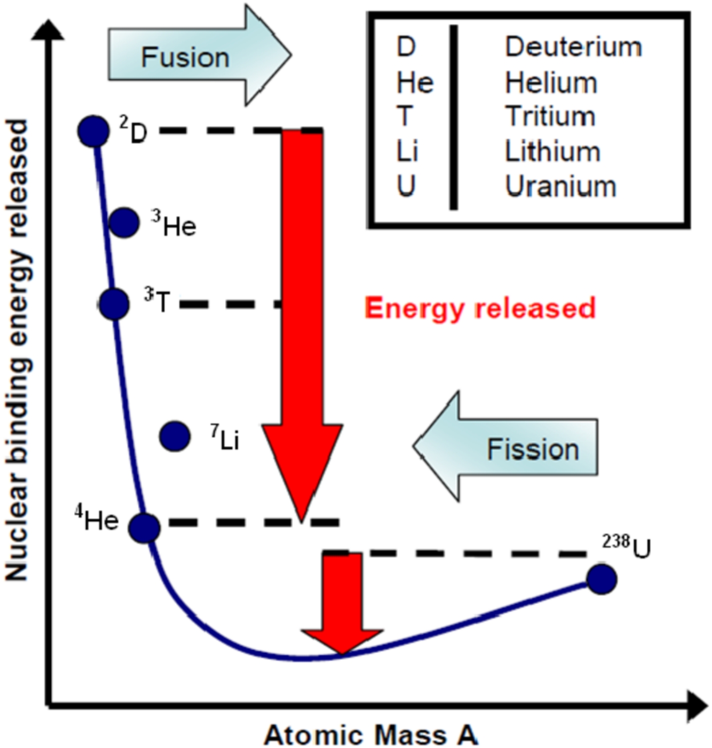
BE increase as the mass (nucleon) number increases up to Fe.

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.

Binding energy curve



Graph of binding energy per nucleon

BE varies with mass number;

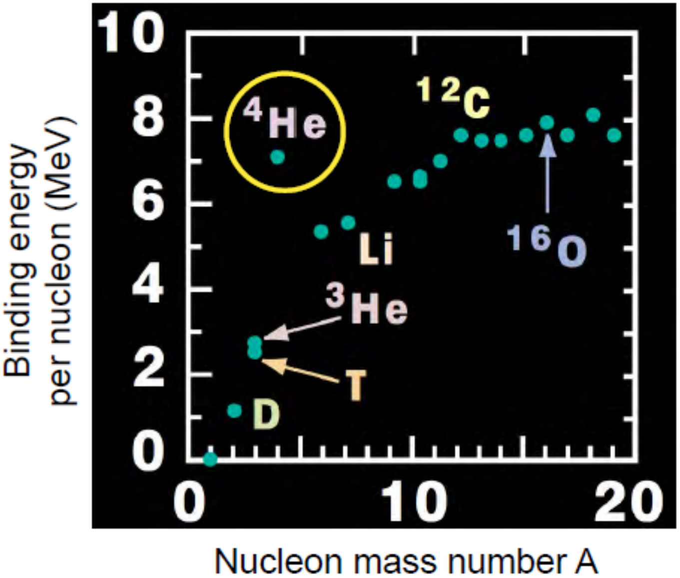
BE increase as the mass (nucleon) number increases up to Fe.

Fe is most stable.
After that it slightly decreases.

In most cases it is about 8 MeV

Binding energy curve

^{4}He has a particularly large binding energy

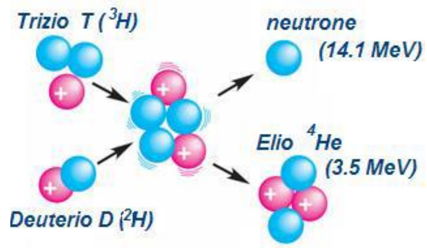


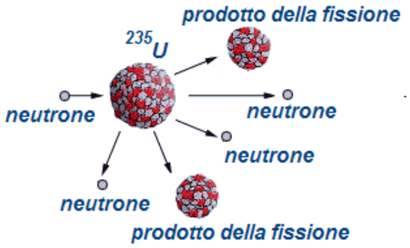
Nucleus	Total Binding Energy (MeV)
D = ^{2}H	2.22457
T = ^{3}H	8.48182
^{3}He	7.71806
^{4}He	28.29567

Large gain in energy when ^{4}He is one of the reaction products

Nuclear fusion reactions

- Nuclear fusion is a nuclear reaction in which two or more atomic nuclei collide at very high speed and join to form the nucleus of a new element.
- During this process, matter is not conserved: some of the mass of the fusing nuclei is converted into energy.
- Fusion is the process that powers active stars.
- Release of energy occurs in fusion of nuclei with masses lower than Fe, Ni (having the largest binding energy per nucleon).
- Fusion process is opposite of nuclear fission.





Fusion reactions in stars

- In the the Sun about 680 million tons of H are “burnt” every second, and converted in He with a generation of 3.8 x 10^{23} kW
- The dominating mechanism is the proton–proton chain reaction
- <u>The chain reaction is so slow that a complete conversion of the star's hydrogen would take more than 10^{10} (ten billion) years</u>

p – p cycle (Sun, small –medium stars)

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu \qquad (Q = 0.42\ MeV)$$
$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma \qquad (Q = 5.49\ MeV)$$
$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2({}^{1}H) \qquad (Q = 12.86\ MeV)$$

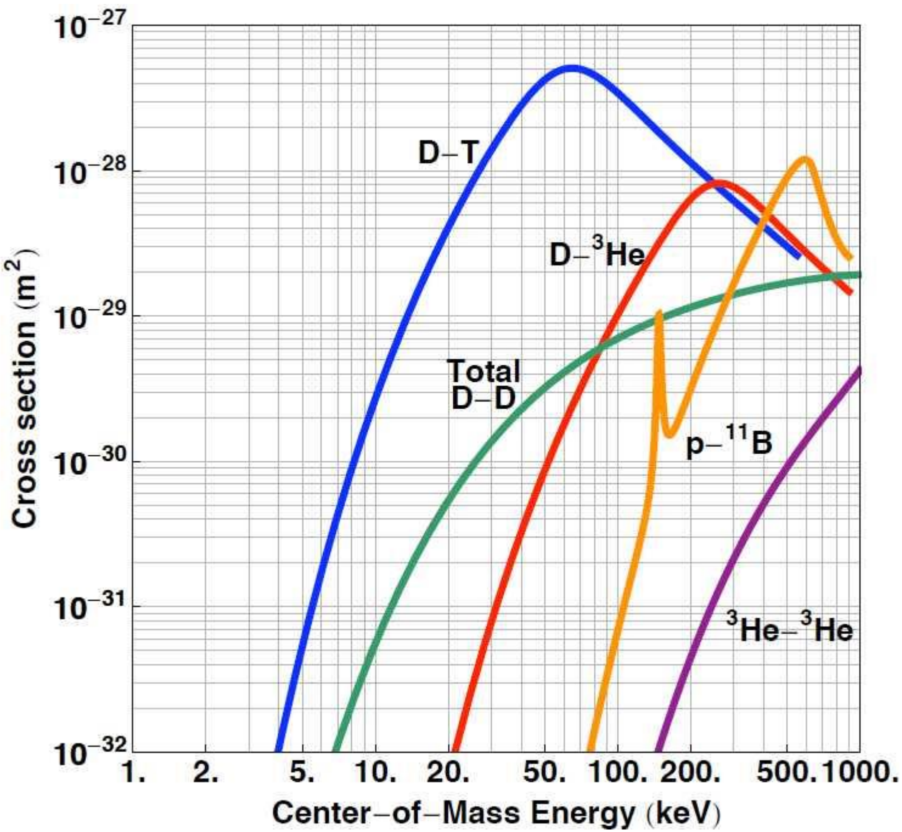
C-N-O Cycle (Large stars)

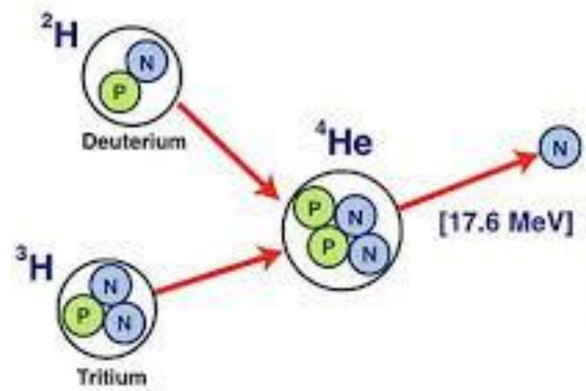
$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma \qquad (Q = 1.95\ MeV)$$
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu \qquad (Q = 1.20\ MeV)$$
$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma \qquad (Q = 7.55\ MeV)$$
$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma \qquad (Q = 7.34\ MeV)$$
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu \qquad (Q = 1.68\ MeV)$$
$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He \qquad (Q = 4.96\ MeV)$$

Fusion reactions

$D + T$	$\rightarrow {}^4He + n + 17.6\ MeV$
$D + D$	$\rightarrow T + p + 4.03\ MeV$
	$\rightarrow {}^3He + n + 3.27\ MeV$
$T + T$	$\rightarrow {}^4He + 2n + 11.3\ MeV$
$D + {}^3He$	$\rightarrow {}^4He + p + 18.3\ MeV$
$D + {}^6Li$	$\rightarrow 2\ {}^4He + 22.4\ MeV$
$p + {}^6Li$	$\rightarrow {}^4He + {}^3He + 4.0\ MeV$
$p + {}^7Li$	$\rightarrow 2\ {}^4He + 17.3\ MeV$
	$\rightarrow {}^7Be + n - 1.6\ MeV$
$p + {}^{11}B$	$\rightarrow 3\ {}^4He + 8.7\ MeV$
${}^3He + {}^6Li$	$\rightarrow 2\ {}^4He + p + 16.9\ MeV$
${}^3He + {}^3He$	$\rightarrow {}^4He + 2\ p + 12.86\ MeV$

Fusion reaction cross-sections





Cross section: is a measure of the probability that a specific process will take place when some kind of radiant excitation intersects a localized phenomenon (e.g. a particle)

Energy release

$D + T \rightarrow {}^{4}He + n$

$m_D + m_T = 2.01410AMU + 3.01605AMU = 5.03015AMU$
$m_{4He} + m_n = 4.00260AMU + 1.00867AMU = 5.01127AMU$

$AMU = 931\ MeV/c^2$.

Energy:
$Q = (m_D + m_T)c^2 - (m_{4He} + m_n)c^2 = 0.01888AMU \times 931\ MeV/AMU = 17.6MeV$.

Energy is released in the form of kinetic energy of the reaction products:

$En = m\,{}^{4}He / (m\,{}^{4}He + mn) \times Q = 14.1\ MeV$
$E4He = mn / (m^{4}He + mn) \times Q = 3.5\ MeV$

E_n = 14 MeV is higher than the mean binding energy per nucleon

Fusion as energy source

Deuterium’s natural abundance in Earth's oceans is about one atom in 6,420 atoms of hydrogen. Thus deuterium accounts for approximately 0.0156% of atoms (or 0.0312% of weight) of all the naturally occurring hydrogen.

31 mg D (1 l water) + 46 mg T (109 mg Lithium) → 7.2×10^3 kWh

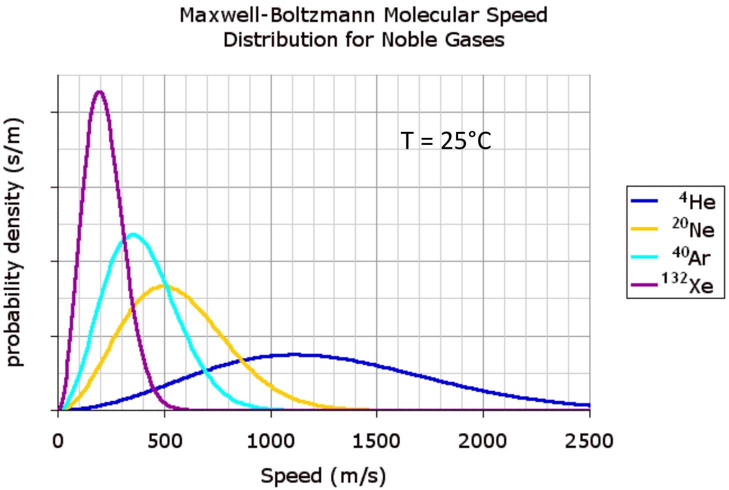
Equivalent to about 1 ton carbon (2.5 ton CO_2)

Maxwellian reactivity

In laboratory (and also in astrophysical) conditions, we usually have gaseous mixtures of nuclei of different species in thermal equilibrium, characterized by Maxwellian velocity distributions

$$f\left(v\right) = 4\pi\left(\frac{m}{2\pi kT}\right)^{3/2} v^2 \exp\left(-mv^2 / 2kT\right)$$

where, T is the temperature and k is the Boltzmann constant.



Maxwellian reactivity

The reaction cross section depends on the relative velocity of the reacting nuclei. Moreover, the number of reactions increases with increasing velocity of the reacting nuclei.

The **probability of reaction** per unit time and per unit nuclei density is given by the *reactivity*

$$\langle \sigma v \rangle = \frac{4\pi}{(2\pi m_{\mathrm{r}})^{1/2}} \frac{1}{(k_{\mathrm{B}} T)^{3/2}} \int_0^{\infty} \sigma(\epsilon)\, \epsilon \, \exp(-\epsilon / k_{\mathrm{B}} T) d\epsilon .$$

where $\epsilon = \frac{1}{2} m_{\mathrm{r}} v^2, \quad m_{\mathrm{r}} = \frac{m_1 m_2}{m_1 + m_2}$

and v is the relative velocity of reacting ion pairs.

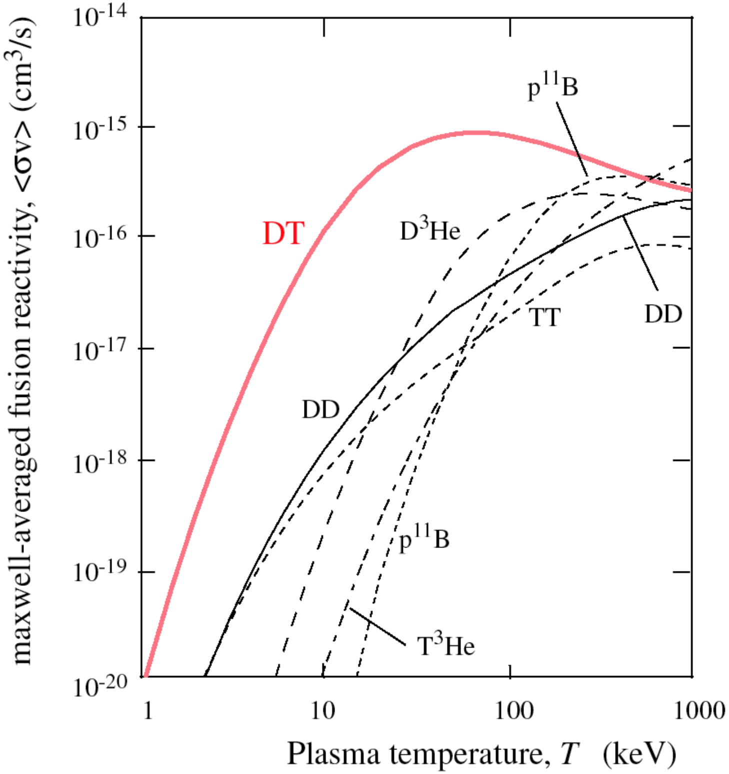
Maxwellian reactivity

The DT reaction has the largest reactivity in the whole temperature interval below 400 keV (100 times larger than that of any other reaction at 10–20 keV). It has a broad maximum at about 64 keV;

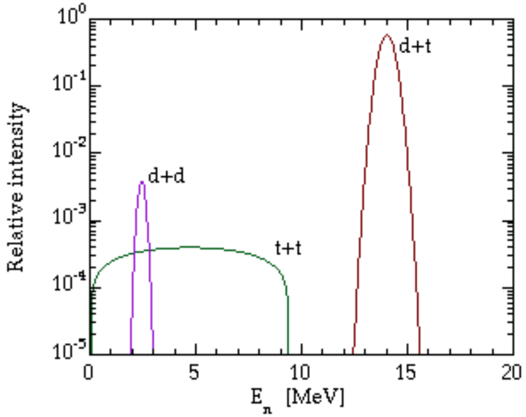
In the temperature range 8–25 keV the DT reactivity is approximated to within 15% by

$$\langle \sigma v \rangle_{DT} = 1.1 \cdot 10^{-18} T^2 \, {cm^3}/{s}$$

The second most probable reaction is DD at *T* < 25 keV, and D3He for 25 < *T* < 250 keV.



Neutron energy spectra

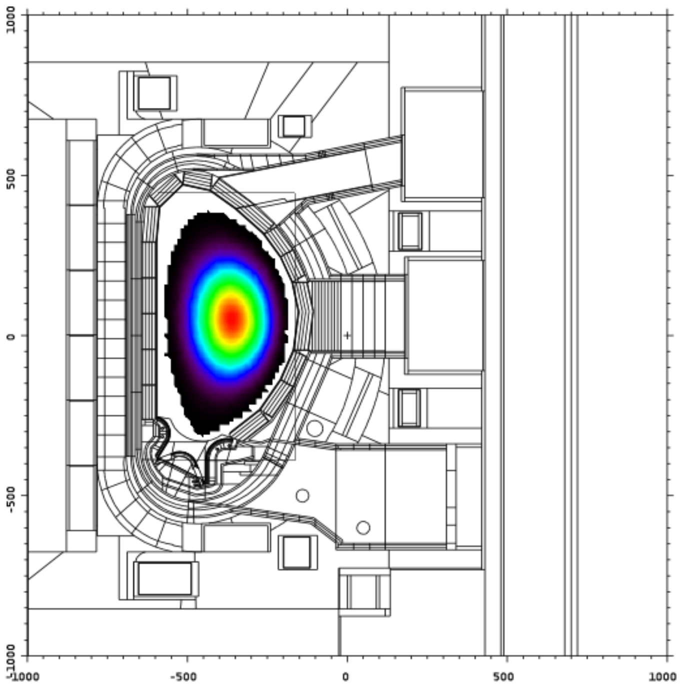


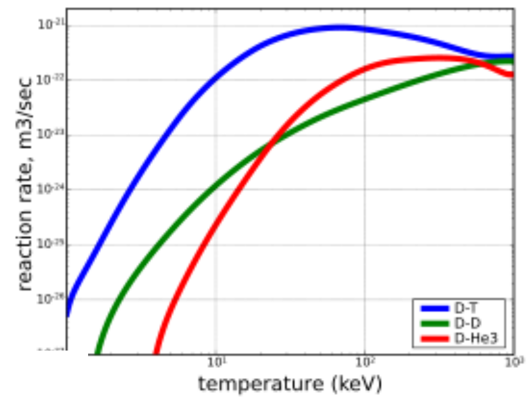
The T+T =^4He + 2n is a three-body reaction

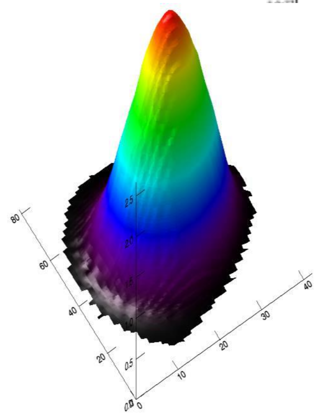
The width of the DD and the DT neutron energy lines is due to the velocity distribution of reacting ions (K=relative kinetic energy, $v_{c.m.}$=velocity of center of mass, θ = angle between the neutron velocity and $v_{c.m}$

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

Neutron source spatial distribution







Fusion power & Neutron Wall Loading (DT)

$P_{fus} = N_{fus} \cdot E_{fus}$ Fusion Power

N_{fus} = Fusion reactions per unit time

$E_{fus} = 17.6$ MeV

$E_n = 14.1$ MeV

1 eV = $1.6 \cdot 10^{-19}$ Ws

$$N_{fus}(1000MW) = \frac{1000MW}{17.6MeV} = \frac{1000MW}{17.6MeV \times 1.6 \times 10^{-19} Ws} = 3.55 \times 10^{20} s^{-1}$$

Neutrons produced in time unit at P_{fus} = 1000 MW

Neutron Wall Loading (NWL) - Energy flux carried by fusion neutrons into the first wall that surrounds the plasma .

$$NWL(\frac{1MW}{m^2}) = \frac{10^6 eV}{10^4 cm^2 \times 1.6 \times 10^{-19} s} = 6.241 \times 10^{14} \frac{MeV}{cm^2 s}$$

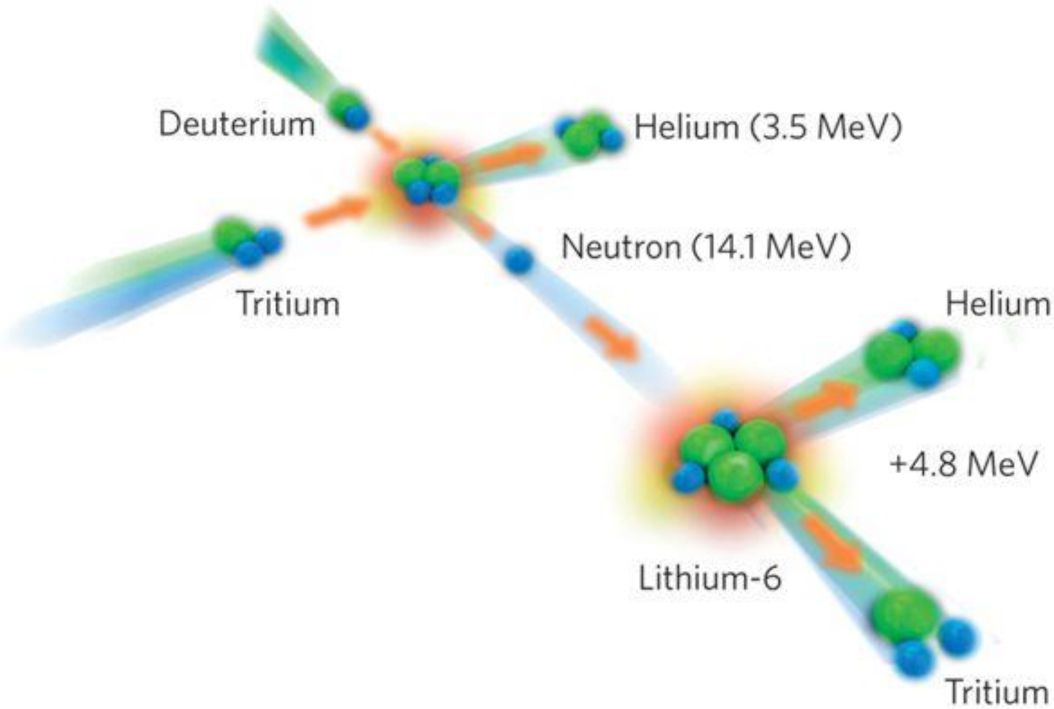
Number of incollided neutrons crossing the the first wall surface per unit time and surface - J_{n-14}.

Normalized to 1 MW/m²

$$J_{n-14}(\frac{1MW}{m^2}) = \frac{6.241 \times 10^{14}}{14.06MeV} \frac{MeV}{cm^2 s} = 4.439 \times 10^{13} cm^{-2} s^{-1}$$

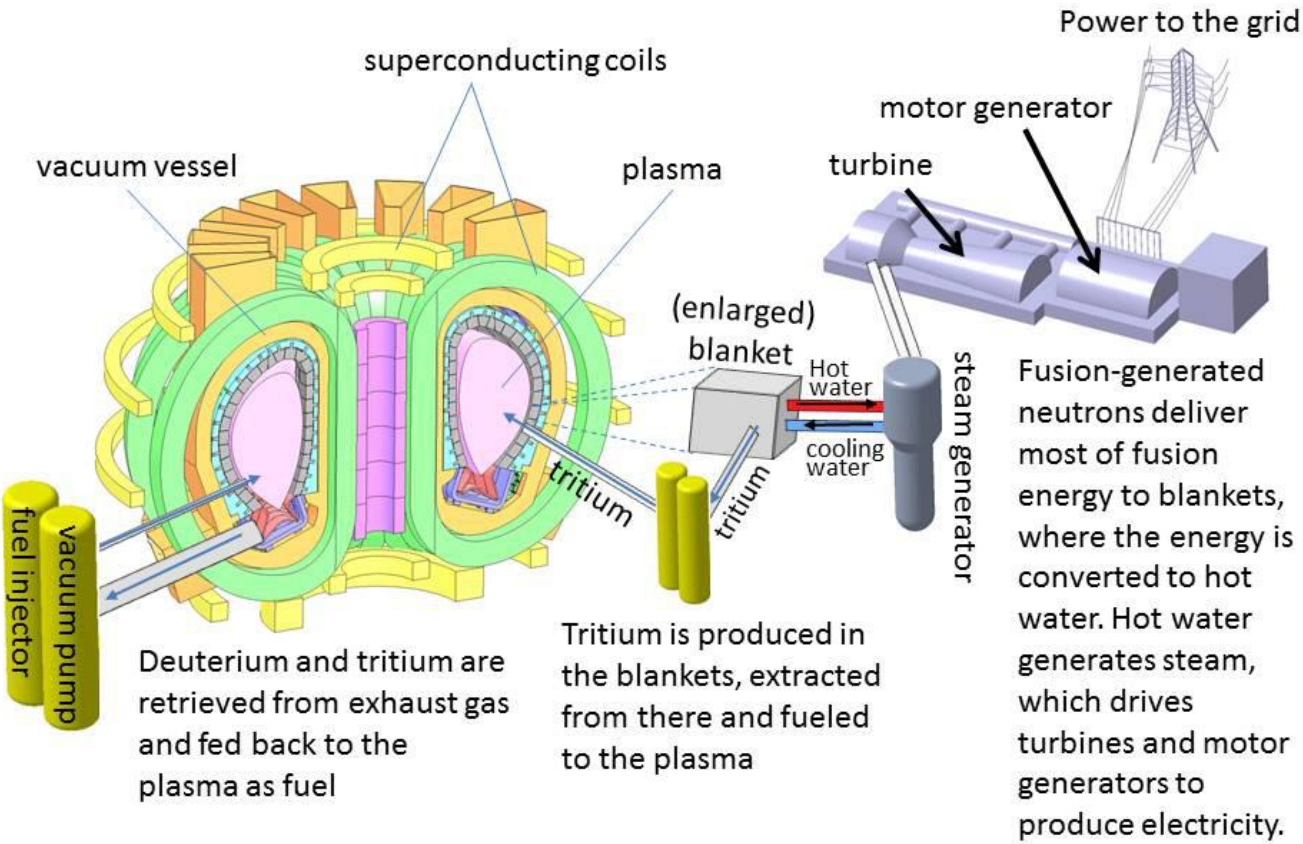
Tritium production in the DT fusion cycle

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

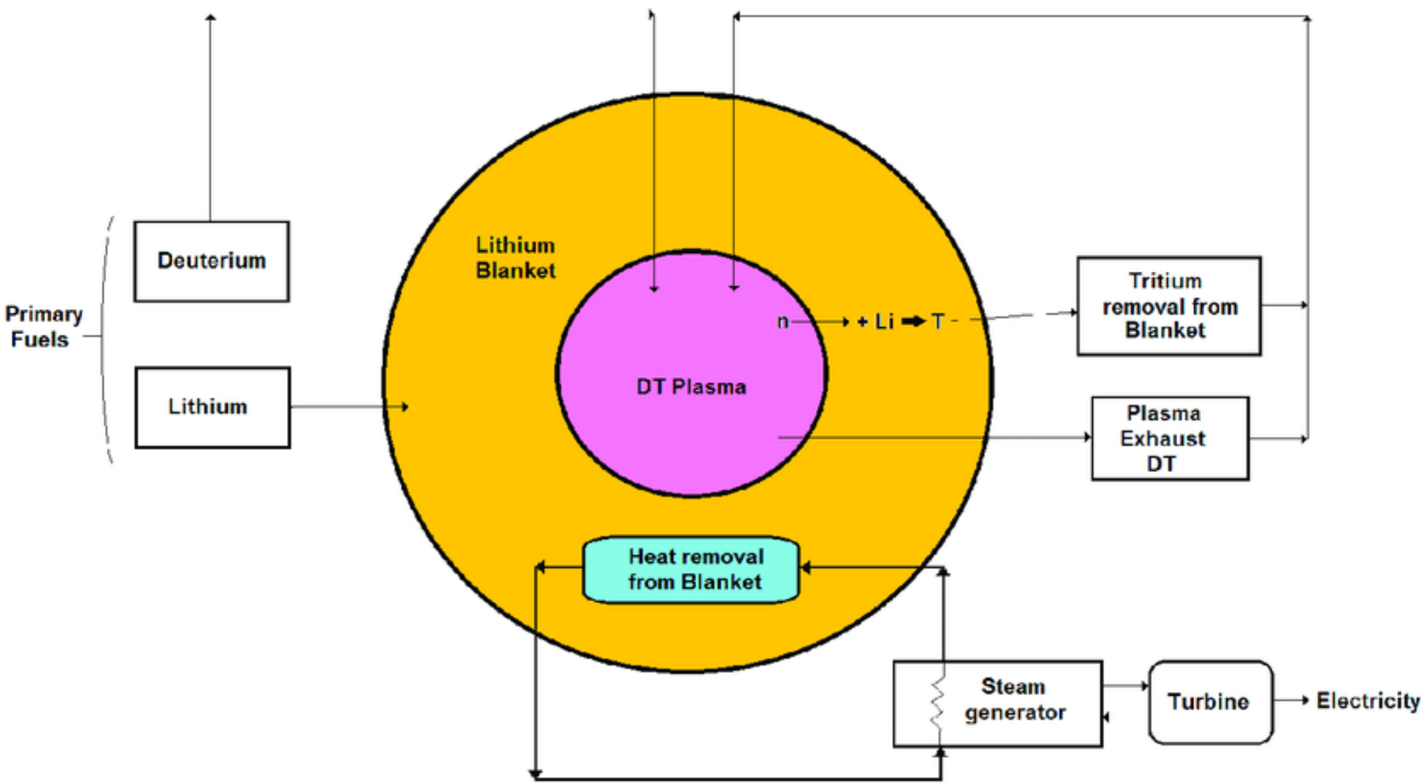


N. Holloway, CCFE.

Fusion Power



Fusion Power



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

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

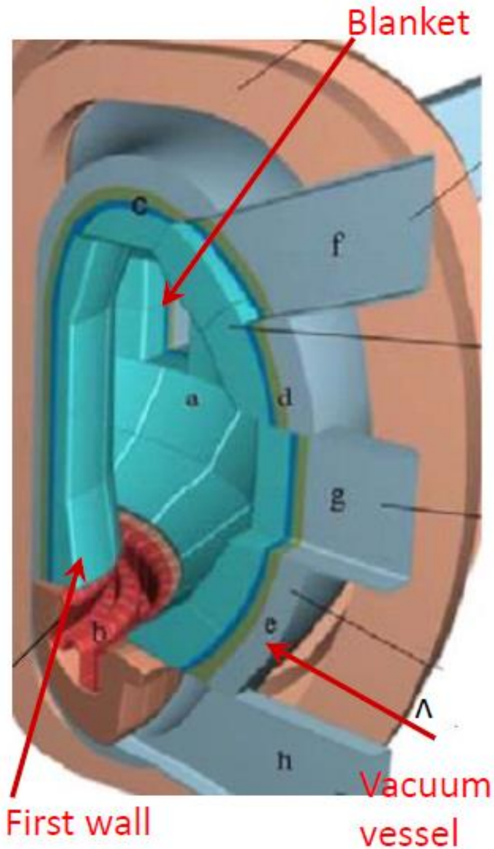
Blanket functions

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*



Fusion neutronics

- **Tritium Breeding** – self-sufficiency
- **Nuclear heating** – Power deposition distribution, nuclear heating, heat removal, plant efficiency
- **Shielding** – Protection of permanent components from radiation damage
- **Neutron induced radioactivity** – Safety, occupational dose, maintenance, waste prduction and management
- **Transmutations and radiation damage in materials** – Degradation of thermo-mechanical and physical propertiels
- **Decay heat** – Deat removal in shutdown