A-level Physics Tutor Guides

A-level Physics COURSE NOTES

NUCLEAR PHYSICS

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CONTENTS

The Nucleus

Revision

From intermediate physics you should know these rudimentary facts:

- Three types of particles make up the general structure of an atom: **electrons**, **protons** & **neutrons**.
- Neutrons and protons exist in the **nucleus** at the centre of the atom.
- Electrons orbit around the nucleus in **orbits**.
- The number of protons in a nucleus is called the **atomic number Z**.
- The total number of protons & neutrons in a nucleus is called the **mass number A**.
- In an electrically neutral atom, the numbers of protons equals the numbers of electrons.
- **Ions** are electrically charged atoms, when an atom has more or less than the normal numbers of electrons.
- **Isotope** are forms of atoms of an element with differing numbers of neutrons in the nucleus.

The particles(nucleons) in a nucleus may be represented as:

$$^{A}_{Z}(\text{element symbol})$$

$$\text{eg} \quad ^{12}_{6}C \quad ^{4}_{2}He \quad ^{235}_{92}U$$

The Relative Atomic Mass A_r

This must not be confused with the mass unit **A**, which is the the number of nucleons(protons + neutrons) in the nucleus.

The relative atomic mass of an atom($\mathbf{A_r}$) is defined as:

$$A_r = \frac{\text{mass of atom}}{\frac{1}{12}\text{ the mass of a carbon atom } ^{12}_{6}C}$$

So for a carbon atom this exactly equals 12 (A_r=12).

One of these **relative atomic mass units**(sometimes called the *unified* atomic mass unit) is called **1*u***.

So carbon has a relative atomic mass of 12u .

The actually value of 1u can be measured experimentally by dividing the mass of a carbon atom(1.992×10^{-26}kg) by 12.

$$1u = 1.660 \times 10^{-27}$$

Nuclear radii

The nucleus is much smaller than the atom. The radius of a nucleus is approximately 10^{-4} that of the atom it occupies.

The radius of a nucleus is proportional to cube root of the mass number(nucleon number) A.

$$r \propto A^{1/3}$$
$$\underline{r = r_0 A^{1/3}}$$

$$\text{where } r_0 = 1.2\times10^{-15}\,\text{m}$$

Nuclear density

The volume of a nucleus is approximately 10^{-12} that of the atom. Since most of the mass resides in the nucleus, it follows that its density is extremely high. The nuclear density is approximately the same for all nuclei(10^{17} kg m^{-3}).

calculation: the density of a carbon nucleus(nuclear density)

$$\text{density} = \frac{\text{mass}}{\text{volume}} = \frac{m}{\frac{4}{3}\pi r^3}$$

$$\text{but} \quad r = r_0 A^{1/3}$$

$$\therefore \text{density} = \frac{3m}{4\pi (r_0 A^{1/3})^3}$$

$$m = 1.992\times10^{-26} \quad r_0 = 1.2\times10^{-15} \quad A = 12$$

$$\therefore \text{density} = \frac{3\times1.992\times10^{-26}}{4\times3.142\times(1.2\times10^{-15})^3\times12}$$
$$= \frac{6\times10^{-26}}{4\times3.142\times1.7\times10^{-45}\times1.2\times10^{1}}$$
$$= \frac{6\times10^{-26}}{2.6\times10^{-43}} = 2.3\times10^{17}$$

$$\underline{\text{nuclear density} = 2.3\times10^{17} \text{ kg m}^{-3}}$$

The range of nuclear forces

In all there are four forces that act on matter. This is the order of their relative strength:

the **Strong Force**, the **Electromagnetic**, the **Weak** and the**Gravity** force.

notes:
The range of the Strong Force is approximately the diameter of an average nucleus.

The range of the Weak Force is approximately 0.001 the diameter of a proton.

The Weak Force particles are the intermediate vector bosons: $\mathbf{W^+}$ $\mathbf{W^-}$ $\mathbf{Z_o}$

	strong	**electromagnetic**	**weak**	**gravity**
strength	**1**	**7.3×10^{-3}**	**10^{-6}**	**6×10^{-39}**
range(m)	**10^{-15}**	**∞**	**10^{-18}**	**∞**
particle	**mesons, gluons**	**photons**	**bosons**	**gravitons**

Radioactivity

Discovery

Radioactivity was discovered by Henri Becquerel in 1896, when he noticed 'fogging' of photographic plates that were placed in a drawer in close contact with uranium salts.

Emissions

Radioactivity is simply the spontaneous disintegration of nuclei to move from an unstable state to a stable one.

There are three types of radiation emitted in radioactive decay: **alpha particles**, **beta particles** and **gamma rays**.

Alpha Particles(α)

These are helium nuclei, and therefore consist of two protons and two neutrons.

Beta Particles ($\beta^- \beta^+$)

There are two types of beta particle: beta-plus and beta-minus. The beta-plus is sometimes called an anti-electron. Each can travel up to 98% the speed of light. A beta-minus particle is released as a result of a neutron changing into a proton, while a beta-plus particle is released as a result of a proton changing into a neutron.

Gamma Rays (γ)

Gamma rays are high energy, short wavelength photons of electromagnetic radiation. Gamma rays are emitted because the atom is usually in a high energy state after emission of alpha or beta particles. This unstable state is made stable by emission of gamma ray photons.

Balancing equations

The effect of radioactive emissions can be summarised as follows:

alpha decay:

atomic mass decreases by 4
atomic number decreases by 2

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

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

beta-minus decay:

mass number unchanged
atomic number increases by 1

$${}^{14}_{6}C \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$$

beta-plus decay:

mass number unchanged
atomic number decreases by 1

$${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\mathrm{e}$$

(neutrinos omitted)

The Radioactive Decay Equation

The rate of decay(activity, ***A***) is proportional to the number of parent nuclei(***N***) present.

$$A \propto N$$
$$A = \frac{dN}{dt}$$
$$\frac{dN}{dt} \propto N$$
$$\underline{\frac{dN}{dt} = -\lambda N}$$

λ(lambda) is a positive constant called **the decay constant**. It has the unit s^{-1} .

The minus sign is included because ***N*** decreases as the time **t**in seconds (s) increases .

Half Life

The **half life** of a radioactive substance is the time taken for half the nuclei present to disintegrate.

$$T_{\frac{1}{2}} = \frac{0.6931}{\lambda}$$

λ(lambda) is the decay constant

The half-life curve illustrates that that the number of nuclei halves whenever the time '*t*' increases by $T_{1/2}$. The half-life is a constant for a particular radio-nuclide.

Here is a list of half-lives of radio-nuclides from the Uraniun series.

nuclide	half-life
uranium 238	4.51×10^9 years
thorium 234	24.1 days
protactinium	6.75 hours
uranium 234	2.47×10^5 years
thorium 230	8.0×10^4 years
radium226	1620 years

Radioactive Equilibrium is when the rate of decay of a nuclide is approximately the same as its rate of production.

This happens to products of the Uranium Series. We start off with the production of thorium exceeding its rate of decay. Then as the amount of thorium increases, the activity increases. Eventually the rate of production of thorium equals its rate of decay. So the amount of thorium in the sample is constant.

This continues down the series with constant amounts of each product being formed in a sample. This being the case, all the rates of decay are equal.

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

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt} = \ldots$$

and

$$\lambda_1 N_1 = \lambda_2 N_2 = \lambda_3 N_3 = \ldots \qquad \text{(i}$$

$$\text{since } \lambda = \frac{0.6931}{T}$$

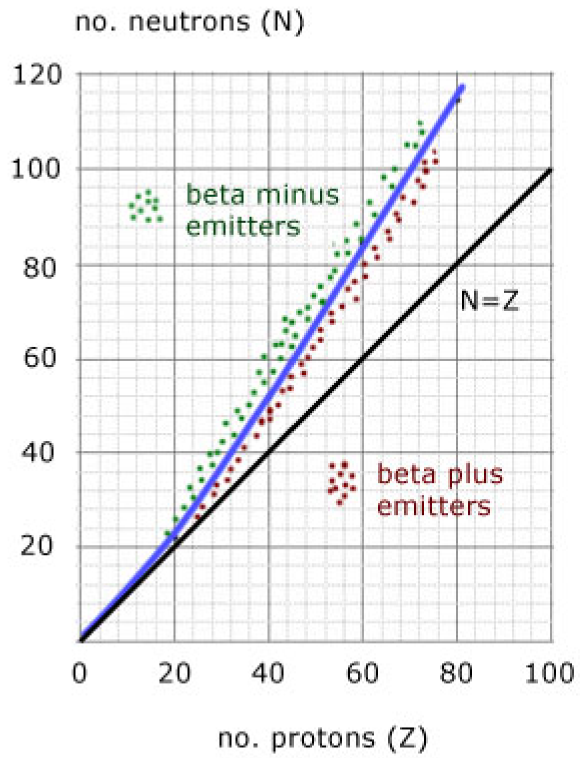
$$\lambda_1 = \frac{0.6931}{T_1}, \quad \lambda_2 = \frac{0.6931}{T_2}, \quad \lambda_3 = \frac{0.6931}{T_3} \quad \ldots$$

substituting for λ_1 λ_2 $\lambda_3 \ldots$ into (i

$$\therefore \quad \underline{\frac{N_1}{T_1} = \frac{N_2}{T_2} = \frac{N_3}{T_3} = \ldots}$$

Stability: the N-Z curve

The N-Z curve



The N-Z curve is a plot of the number of neutrons(N) against the number of protons(Z).

lines:

i) the 'stability' line - a gentle curve starting from the origin and of increasing gradient

ii) the line of N = Z - a straight line of gradient '1' through the origin

regions

i) beta minus(electron) particle emitters

ii)beta plus(positron) particle emitters

iii) alpha particle emitters top of curve(not shown)

description:

- for proton numbers(Z) up to 20, N=Z a straight line
- for all nuclei with Z>20 , stable nuclei have more neutrons than protons, the line curves upwards
- unstable nuclei <u>above</u> the stability curve are called **neutron-rich**
- unstable nuclei <u>below</u> the stability curve are called **neutron-poor**

the decay process:

Unstable neutron-rich nuclei can become more stable by<u>losing</u> neutrons. They do this by '**beta decay**'. The effect of this for a single nucleus is to raise its the proton number (Z) by 1 and decrease its neutron number(N) by 1, bringing the N-Z plot of the nucleus closer to the stability curve. The movement of the point is right one unit and down one unit.

beta decay: Z + 1 N - 1

$${}^{14}_{6}C \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$$

Unstable neutron-poor nuclei can become more stable bygaining neutrons. They do this by '**positron decay**'. The effect of this for a single nucleus is to lower its proton number (Z) by 1 and increase its neutron number(N) by 1 , bringing N-Z plot of the nucleus closer to the stability curve. The movement of the point is left one unit and up one unit.

positron decay: Z - 1 N + 1

$${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\mathrm{e}$$

Alpha decay has very little effect on the position of a nucleus relative to the stability curve. This is is because the loss of an alpha particle(2 protons + 2 neutrons)does not upset the N-Z ratio too much. The point representing a nucleus has Z - 2 and N - 2 . Only large nuclei participate in alpha decay. So the effect is only confined to the very top section of the curve.

alpha decay: Z - 2 N - 2

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

Decay Chains

A **decay chain** (or **radioactive series**) charts the different types of radioactive decay a nucleus undergoes until a stable isotope is reached.

There are only 3 naturally occuring decay chains called the:

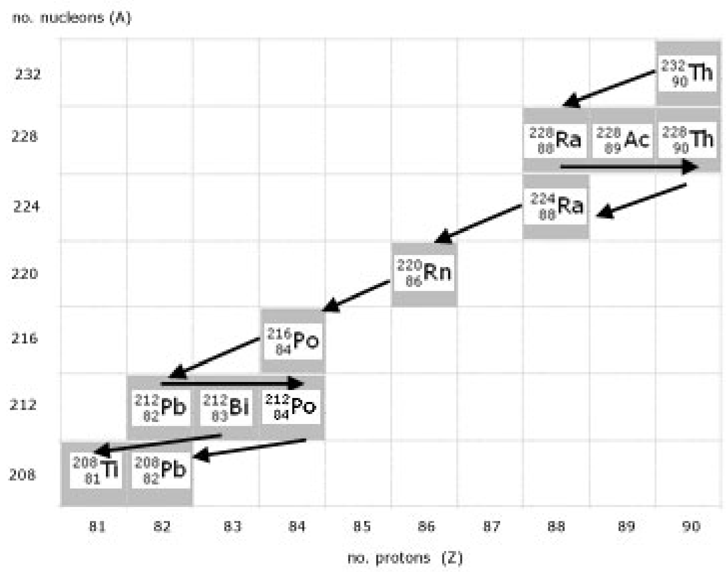
- actinium series
- thorium series
- uranium series

plus one other involving a trans-uranium element

- neptunium series

A decay chain is accurately described using a graph of nucleon number(A) against proton number(Z).

The graph illustrates the complete Thorium-232 decay chain.



click on image to magnify (in pop-out page)

Important observations are:

alpha decay ....2 units to the left, 4 units down
beta$^-$ decay ....1 unit to the right
Bismuth ....2 possible decay outcomes

Equations describing the Thorium Series:

$$^{232}_{90}\mathrm{Th} \rightarrow {}^{228}_{88}\mathrm{Ra} + {}^{4}_{2}\mathrm{He}$$

$$^{228}_{88}\mathrm{Ra} \rightarrow {}^{228}_{89}\mathrm{Ac} + {}^{0}_{-1}\mathrm{e}$$

$$^{228}_{89}\mathrm{Ac} \rightarrow {}^{228}_{90}\mathrm{Th} + {}^{0}_{-1}\mathrm{e}$$

$$^{228}_{90}\mathrm{Th} \rightarrow {}^{224}_{88}\mathrm{Ra} + {}^{4}_{2}\mathrm{He}$$

. . . etc.

As an exercise, it is left to the reader to complete the series using the decay chain graph(above).

Stability: binding energy

Units

To thoroughly understand this work we must have a firm grasp of the units involved:

Joules(J), electron volts(eV) and atomic mass units (*u)*

There is a discrepancy between the mass of a nucleus and the sum total of the individual masses of its constituents.

This difference is called the **mass defect**.

We know that energy is equivalent to mass in Einstein's equation,

$$E = mc^2$$

where E is energy(J), m is mass(kg) and c is the velocity of light (ms^{-1}).

So the mass can be given in terms of energy. That is in**Joules**(J).

There is however another energy unit much used in nuclear physics called the '**electron volt**' (eV).

One electron volt is the kinetic energy an electron gains when accelerated through a potential difference of 1 volt.
Since,

energy = charge x potential difference

$$E = eV$$

e is the charge on the electron 1.602 x 10^{-19} Coulomb
V is the p.d., 1 volt in this case

So the energy of 1eV is 1.602 x 10^{-19} Joules.

However, there is still another mass unit to consider. This is called the **atomic mass unit** (*u*).

By definition 1 *u* is equal to 1/12 the mass of a carbon-12 atom.

$$\begin{aligned} 1 \text{ atomic mass unit} &= 1u \\ &= 1.66 \times 10^{-27}\,\text{kg} \\ &\equiv 931\ \text{MeV} \\ &\equiv 1.49 \times 10^{-10}\,\text{J} \end{aligned}$$

To summarize, mass defects can be given in:

kilograms(kg)
atomic mass units(u)
Joules(J)
electron volts(eV).

The key to solving problems on binding energy is to know these units and how they inter-relate to one another.

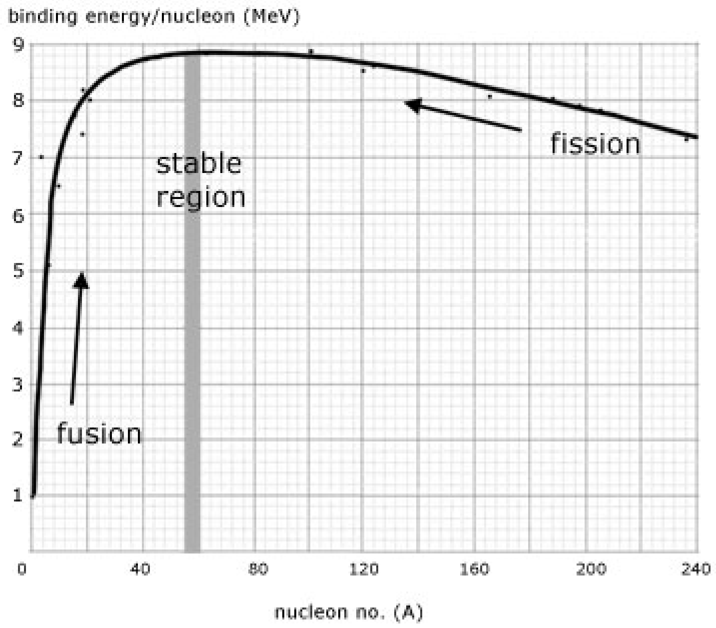
Stability

A measure of the stability of an atom is its **binding energy per nucleon**, usually expressed in MeV(millions of electron-volts).

binding energy/nucleon = total binding energy for the nucleus/mass number

This is an average of the energy needed to remove a nucleon from the nucleus.

In nuclear reactions energy is released or absorbed as a result of differences in the nuclear binding energy of the original materials and the resulting products.



In the graph of binding energy per nucleon against mass number, the following observations can be made as the nucleon number increases:

1. the binding energy/nucleon increases quickly at first then less so, up to a maximum at iron(Fe-56)

2. after iron the binding energy/nucleon slowly decreases

3. less massive nucleons, up to iron, participate in **fusion** reactions.

4. nucleons more massive than iron participate in **fission** reactions.

Reactions

A **radioactive** reaction proceeds because the original nucleus has a greater mass than the mass of its products. Hence there is a mass loss, which manifests itself as energy.

This energy takes the form of the kinetic energy of the products of the reaction or if gamma rays are emitted, their photon energy($E = h\nu$).

Similarly when a nucleus splits into two almost equal parts in a **fission** reaction. The mass of the original nucleus is greater than the sum of its products.

Fusion reactions obey the same rule. The masses of the original nuclei are greater than the mass of the nucleus they create.

Fundamental Particles

Particles & anti-particles

Simply put, an **anti-particle** has the opposite charge to the original particle, but the same mass.

proton p^+ anti-proton p^-

electron e^- anti-electron(positron) e^+

More generally, an antiparticle is signified by a short line drawn above it.

$$\nu \ \bar{\nu} \quad \pi \ \bar{\pi} \quad K \ \bar{K}$$

Anti-matter has the same structure as ordinary matter, but all the signs of the particles are reversed. So anti-matter hydrogen would be an anti-proton nucleus (p^-) with a positron (e^+) in orbit around it.

However, it must be borne in mind that 'sign change' is often the result of changes at a more basic level. This will become more apparent when 'quarks' are discussed.

Particles and anti-particles are created and destroyed in pairs. The two processes are **pair production** and **pair annihilation**.

Pair Production is the creation of a particle and its anti-particle when a gamma ray photon passes close to a nucleus.

Pair Annihilation is when a particle and its anti-particle collide. The result is energy in the form of gamma ray photons and/or other particles being produced.

Quarks

By definition, a fundamental particle cannot be split up into anything simpler. So an electron is a fundamental particle, but a proton is not.

When high energy electrons are fired at protons and neutrons, the electrons are deflected(scattered) through a wide range of angles.

The explanation is that an electron penetrates the nucleon (proton/neutron) and makes an inelastic collision with other particles within it. The electron can do this because it is unaffected by the **Strong Force**. The phenomenon is called**deep inelastic scattering**.

These 'other particles' are what we now call **quarks**. They are fundamental particles that have fractional charges on them, positive or negative, with masses much greater than electrons.

There appear to be 6 basic types of quark(sometimes called their **flavour**).

up (u) ....**down** (d)

charm (c) ....**strange** (s)

top (t) ....**bottom** (b)

So with their anti-particles, there are 12 quarks in total.

Quarks & anti-quarks are described as having the following properties:

<u>charge</u>
Each has either + or - values of 2e/3 or e/3 (e: electronic charge). Charge is always conserved in interactions.

<u>baryon number B</u>

Each has a baryon number of 1/3. Like charge, this is also conserved in interactions.

<u>strangeness S</u>

This property is conserved in 'strong' and 'electromagnetic' interactions. The values can however be altered in 'weak' interactions.

quark	symbol	charge/e	baryon no./B	strangeness/S
up	u	+2/3	1/3	0
up*	$\bar{u}$	-2/3	-1/3	0
down	d	-1/3	1/3	0
down*	$\bar{d}$	+1/3	-1/3	0
charm	c	+2/3	1/3	0
charm*	$\bar{c}$	-2/3	-1/3	0
strange	s	-1/3	1/3	-1
strange*	$\bar{s}$	+1/3	-1/3	+1
top	t	+2/3	1/3	0
top*	$\bar{t}$	-2/3	-1/3	0
bottom	b	-1/3	1/3	0
bottom*	$\bar{b}$	+1/3	-1/3	0

* signifies anti-particle

The structure of protons, neutrons, anti-protons and anti-neutrons can now be described:

u ... up quark　　　　　　　d ... down quark

proton ....u u d ...... charge totals (+2/3 +2/3 -1/3 = +1)

neutron .... u d d ....charge totals (+2/3 -1/3 -1/3 = 0)

anti-proton... $\bar{u}$ $\bar{u}$ $\bar{d}$...... charge totals (-2/3 -2/3 +1/3 = -1)

anti-neutron.. $\bar{u}$ $\bar{d}$ $\bar{d}$...... charge totals (-2/3 +1/3 +1/3 = 0)

<u>Leptons</u>

Leptons, like quarks, are also fundamental particles. They cannot be split up into anything simpler. Leptons are only affected by the 'weak' nuclear force.

There are 3 families of lepton:

<u>The Electron Family</u>

electron	e^-
positron	e^+
electron neutrino	ν_e
electron anti-neutrino	$\bar{\nu}_e$

<u>The Muon Family</u>

muon$^+$	μ^+
muon$^-$	μ^-
muon neutrino	ν_μ
muon anti-neutrino	$\bar{\nu}_\mu$

<u>The Tauon Family</u>

tauon$^+$	τ^+
tauon$^-$	τ^-
tauon neutrino	ν_τ
tauon anti-neutrino	$\bar{\nu}_\tau$

Hadrons

Hadrons are **not** fundamental particles. Hadrons are exclusively composed of quarks. Further, hadrons are affected by both the 'strong' and the 'weak' nuclear forces.

Hadrons fall into 2 groups called **baryons** and **mesons**.

Baryons

Baryons are composed of 3 quarks. There are only two baryons with quarks in stable configurations. These are the proton(uud) and the neutron(udd).

Mesons

Mesons are composed of 2 quarks (a quark and an anti-quark). Note, the quarks and anti-quarks can be of different flavours.

Mesons fall into two families called **pions*** and **kaons**. each family(including anti-particles) has 6 members

*sometimes called **pi-mesons**

Pions

pion	structure	charge/e	baryon no. B	strangeness S
π^o	$u\bar{u}/d\bar{d}$	0	0	0
π^+	$u\bar{d}$	+1	0	0
π^-	$\bar{u}d$	-1	0	0

Kaons

kaon	structure	charge/e	baryon no. B	strangeness S
k^o	$d\bar{s}$	0	0	+1
k^+	$u\bar{s}$	+1	0	+1
k^-	$\bar{u}s$	-1	0	-1

Exchange(Virtual) Particles

Explaining fields

An electrostatic field is a region around a charged object, where force is applied to another charged object. Similarly a gravitational field is a region around a mass, where force is applied to another mass.
The sizes of the forces involved are dictated by the magnitude of charges, masses and distances.
Now these forces can be calculated quite accurately using the relevant equations, but these equations do not explain what causes the forces.

To answer this question we need to introduce the concept of**exchange particles**.
Exchange or **virtual particles** interact with particles to produce the effects of attraction or repulsion. They do this by shuttling back and forth between the particles, carrying small packets of energy.
For repulsion, the effect is much the same as two ice-skaters passing a heavy ball between them. They might start off close together, but as the ball is passed between them, the skaters will diverge from eachother.

Feynman diagrams

rules(generally accepted):
1. particles - strt. lines with arrows pointing upwards
2. anti-particles - strt. lines with arrows pointing downwards
3. electrons(Electromagnetic Force)- wavy lines
4. gluons(Strong Force) - looped lines
5. bosons(Weak Force) - dashed lines
6. time is measured vertically(sometimes horizontally)
7. space is measured horizontally(sometimes vertically)
8. charge is conserved at each junction
9. baryon number is conserved at each junction

The Strong Force(Interaction)

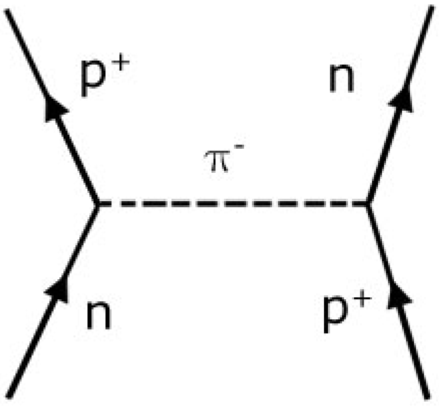
Sometimes called the **Colour Force**, the **Strong Force** is what holds the nucleus together and also withinin each nucleon, the force that holds the quarks together.

The Strong force can therefore be thought of as two forces. So the exchange particles for the nucleus and nucleons are different.

Pions are the exchange particles that hold protons(and neutrons) together in the nucleus.

$$(\pi^o, \pi^+, \pi^-)$$

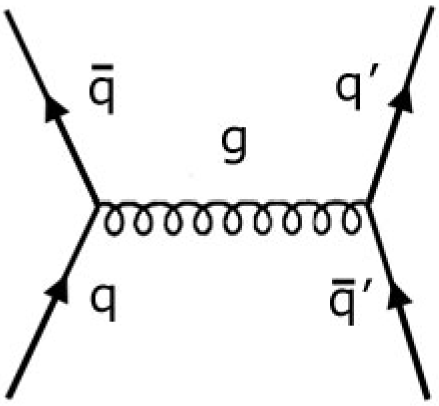
example: proton-neutron interaction



In this case, the Strong Force is called the 'residual' or 'nuclear' force. It is in effect a consequence of the main Strong Force, which holds quarks together in a nucleon.

Gluons (**g**)are the exchange particles responsible for holding quarks within the confines of individual nucleons. They are termed 'Gauge Bosons' with 8 different types or 'colours'.

The Feyman diagram represents a quark-antiquark annihilation and creation, with gluon exchange.



Physics at this level does not require any more on this topic. However, if the Reader wants to explore further, there is an in depth article on gluons in Wikipedia.

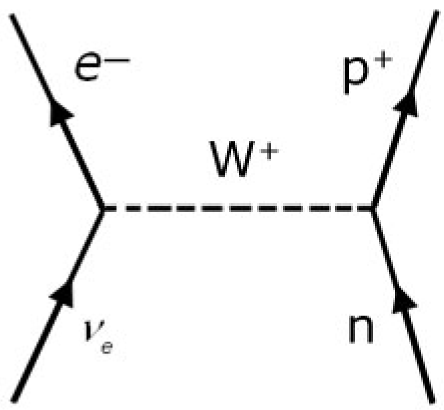
Quantum Chromo Dynamics (**QCD**) is the name given to the branch of physics describing the Strong Force. This in turn is part of what is termed the **Standard Model** of particle physics.

<u>The Weak Force(Interaction)</u>

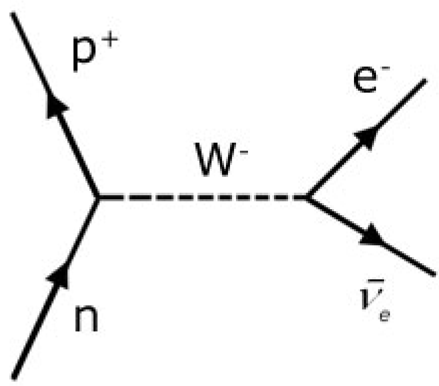
A small group of particles called **intermediate vector bosons**are responsible for metering out the Weak Force.

W^+ W^- Z^o

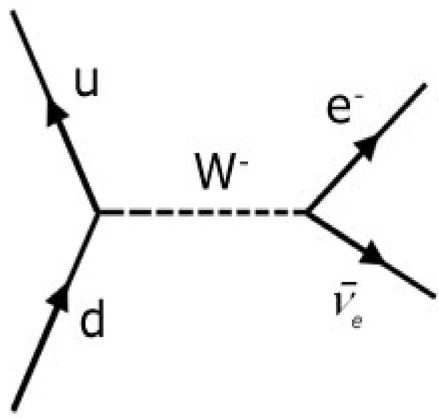
The **W^+** boson is involved in the interaction between a neutrino and a neutron creating a proton and an electron.



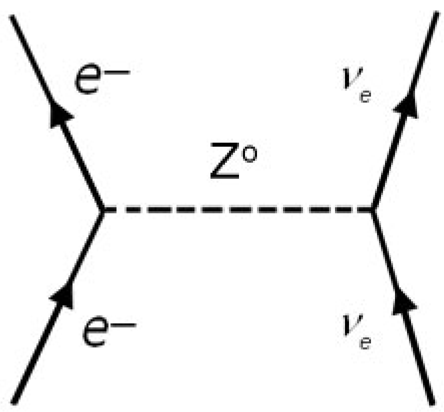
The **W^-** boson is involved in the decay of a neutron into a proton, an electron and a neutrino.



What really happens within a nucleon is that the Weak Force changes a 'd' quark into a 'u' quark. The structure thus changes from 'udd'(a neutron) to 'uud'(a proton). At the point of change a W^- particle is emitted, which promptly decays into an electron and an electron anti-neutrino.



The **Z°** boson is involved in collisions between particles, where there is no transfer of charge.

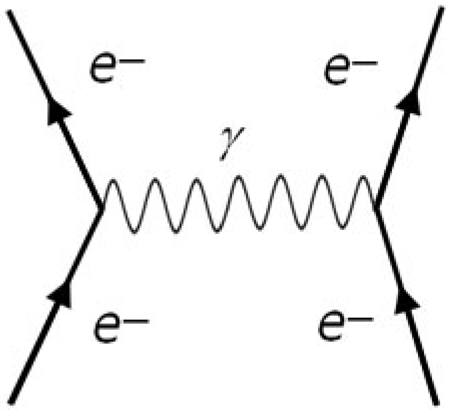


The Electromagnetic Force(Interaction)

Electromagnetic Force is the the interaction between electrically charged particles. The sphere of influence of the force is manifest in what we call the electromagnetic field (both electrostatic & magnetic).

The exchange particle for the electromagnetic force is the **virtual photon** (**γ** gamma).

Here a virtual photon is exchanged between two electrons causing them to repel.



The closer the electrons approach each other, the shorter the virtual photon wavelength becomes.

Gravitational Force(Interaction)

The **graviton** (**G**) is the exchange particle for the Gravitational Force. The graviton is at present a theoretical particle. It is being looked for, but as yet has not been observed. However, some of the properties of the exchange particle have been inferred.

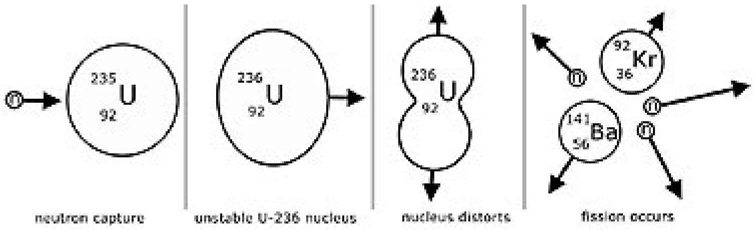
predicted graviton properties:

1. gauge boson (like W^+ W^- Z^o)
2. rest mass - zero
3. electronic charge - zero
4. spin = 2

Nuclear Fission

Energy from Fission

Nuclear fission is the disintegration of a large nucleus(the parent)into two smaller(daughter) nuclei by the capture of a 'slow' (thermal) neutron.



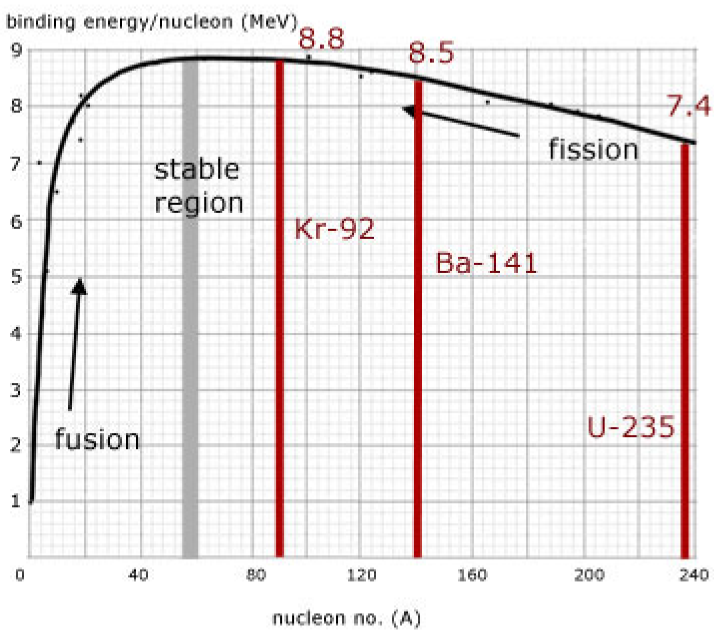
The equation describes the fission of uranium-235 by a slow neutron into barium and krypton nuclei, with the emission of three fast neutrons.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

Energy(200MeV/fission), mostly in the form of kinetic energy of the fragments and gamma ray radiation, is released as a result of a loss of mass in the reaction. This 'lost mass'(about 0.1%) is converted to energy as described by Einstein's mass-energy equation: $E=mc^2$.

In more detail, the average binding energy per nucleon of the products is greater than that of the parent nucleus.

From the graph, the binding energy per nucleon increases from about 7.4 to 8.8 MeV.



total binding energy of parent nucleus uranium-235

= no. nucleons x binding energy per nucleon
= 235 x (7.4) = 1739.0

total binding energy of fragments, barium-141 + krypton-92

= no. nucleons x binding energy per nucleon
= 141 x (8.5) + 92 x (8.8) = 2008.1

difference in total binding energy(and hence energy released)

= 2008.1 - 1739.0 = <u>269.1 MeV</u> (approx)

A more accurate value for the fission yield/reaction is 215Mev.

We can get an idea now of the energy released when a small mass of U-235, say 10 kg, undergoes fission.

235 g of U-235 contains 6.02 x 10^{23} atoms.

(The mass number of an element expressed in grams contains the Avagadro Number of atoms.)

therefore 10 kg of U-235 contains:

(atoms per kg) x (10 kg)
(6.02 x 10^{23}/0.235 kg) x (10kg)
(6.02 x 10^{24}) / (2.35 x 10^{-1})
= 2.56 x 10^{25} atoms

total energy release = (no. U-235 atoms)x(energy per fission)

= 2.56 x 10^{25} x 215 = <u>5.5 x 10^{27}</u> Mev

As 1 MeV = 10^6 x 1.6 x 10^{-19} = 1.6 x 10^{-13} Joules

The energy released is 1.6 x 10^{-13} x 5.5 x 10^{27} = 8.8 x 10^{14}J
or 880,000,000,000,000 J

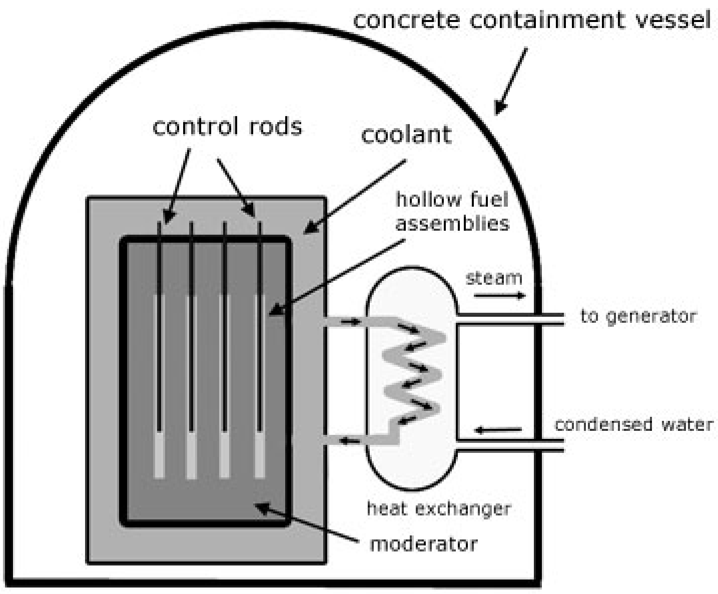
Compare the burning of coal: energy/kg = 3.5 x 10^7 J/kg
10 kg of coal therefore produces 3.5 x 10^8 J

1 kg U-235 produces 2,514,000 times the energy of 1 kg coal.

1 kg U-235 produces approximately the same energy as burning 2,514 tonnes of coal.

Nuclear Reactor Design

The neutrons created by fission are fast. In fact they are too fast to be captured by other U-235 nuclei to maintain fission. For capture to occur, the neutrons must be slowed down. The material used to do this is called a **moderator**. Common examples are carbon(graphite) and heavy water(deuterium dioxide D_2O .

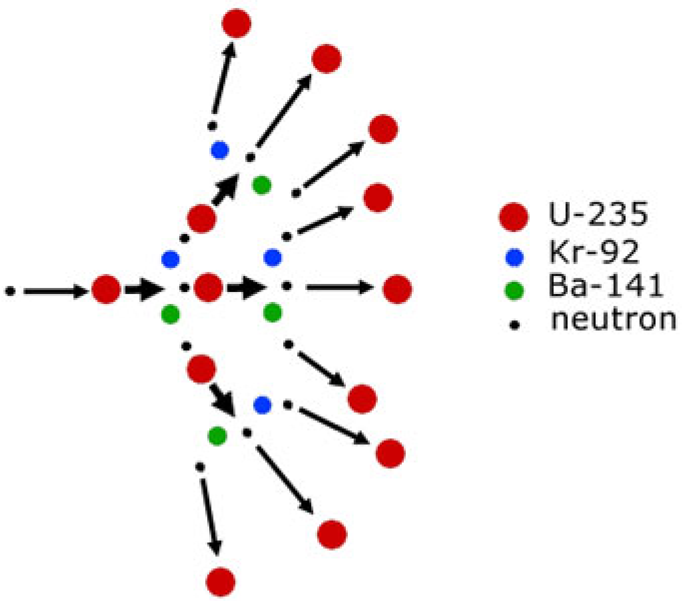


Ideally fission should proceed at the rate of one fission for one neutron produced. The trouble is that in the process two and sometimes three neutrons are produced. To limit the numbers of neutrons in the reactor **control rods** are used. These are rods of boron-coated steel which absorb neutrons. When the rods are raised from the reactor, neutron numbers increase. When they are lowered, neutron numbers decrease. In this way the rate of fission is controlled.

The heat energy produced by the reactor must eventually be used to produce steam to drive turbines. The water used for this purpose cannot be used to cool the reactor, otherwise the turbines would themselves become radioactive and the escaped steam would pollute the atmosphere. So what is needed is an intermediary fluid called the **coolant**. This can be a liquid or a gas. Examples are: carbon dioxide, pressurized water, liquid sodium. The coolant circulates around pipes carrying water in an arrangement called a **heat exchanger**.

The whole reactor is encased in a large **containment vessel** made of thick concrete. This is for security to protect the core against aircraft crashes and terrorism. The concrete shield is also to prevent the escape of harmful radiation to protect workers and the environment.

The Chain Reaction



A chain reaction in broad terms means one that is self-sustaining. In other words it carries on by itself without any further external intervention.

Chain reactions occur both in nuclear reactors and atomic (fission) bombs. For a fission reaction to continue a uranium-235 nucleus(or other fissionable material) must at the very least emit one neutron to initiate fission in another nucleus.

This level of reaction of one neutron/nucleus is the approximate level used in nuclear reactors. However, in atomic bombs all the available neutrons per nucleus (max. 3) are used to trigger more fissions. A run-away fission reaction ensues.

In a reactor, this set of circumstances is called a **melt-down**. So much heat is generated that the actual core melts. This gives rise to what is called the **China Syndrome**(also a film, Michael Douglas). The melted reactor is so hot it melts its way out of the containment vessel, down into the rocks below. If you live in the USA it would melt itself through the crust in the direction of China, on the other side of the globe. Of course in reality, before going much further the melt would meet ground water. This would create a titanic explosion and contaminate a vast area of the surrounding countryside (note: **Chernobl disaster 26th April 1986**).

There is a minimum amount of mass for fission to be maintained called the **critical mass**. Less than this amount, the fission reaction will die out for lack of neutrons. For uranium-235 the critical mass is approximately 15 kg.

The size of the critical mass is governed to some extent by the loss of neutrons from the surface. When the mass is encased in a '**neutron reflector**' material (eg lead, graphite, steel) to contain the neutrons, the critical mass can be made smaller.

Artificial Nuclides

These are man-made nuclei that have a short half-life and give out a required type of radioactivity. Artificial nuclides are made in reactors, where there is a plentiful supply of neutrons. Exposure to neutrons makes nuclei larger(neutron rich) and unstable. So radioactivity occurs to redress the balance and make nuclei more stable again.

Another way of altering the nucleus is by firing particles at it in a **particle accelerator**. In this way artificial elements(those with Z >92) were first created e.g. Curium, Einsteinium, Californium, Fermium etc.

The whole process of changing one nucleus into a different nucleus is called **artificial transmutation**.

The radioactivity and radiation from radionuclides can be measured and imaged in a variety of situations.

uses:

nuclear medicine - diagnosis/treatment of cancer, genetics, biochemistry, - use of radioactive 'tags' called **tracers** to follow chemical processes and flow and to highlight targeted areas for imaging.

technetium-99m, **cobalt-60**,

strontium-90, **caesium-137**

industry - monitoring of flow, corrosion, cracks, rate of wear

potassium-40, **thorium** series, **uranium** series

arms industry - tank armour, armour piercing shells

depleted uranium

ionisation detectors - smoke alarms

americium-241

Nuclear Fusion

Energy from Fusion

Nuclear fusion: two (or more) atomic nuclei form a single heavier nucleus. The reaction only takes place at very high densities and temperatures.
There are many examples of fusion reactions. This is one of the more common ones - the fusion of deuterium with tritium to make helium(plus a neutron). Termed the D-T reaction.

$$^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

The fusion reaction of two (or more) nuclei with masses lower than iron is **exothermic** (heat given out).
Conversely, the fusion reaction of two (or more) nuclei with masses greater than iron is **endothermic** (heat absorbed).

The source of the energy emitted is from the '**lost mass**' when individual nucleons fuse together to make a nucleus. Matter is hence converted to energy according to Einstein's mass-energy equation $E=mc^2$.

Of all the elements, iron has nuclei with the highest binding energy per nucleon. So progressively, nuclei heavier than hydrogen are fused together. This increases the mass of resultant nuclei and the binding energy per nucleon up to the maximum at iron.

calculation of energy released in the D-T reaction(above). The method is to sum the mass of the products and subtract this from the mass of the reactants. This mass defect is then converted to energy units(MeV).

u = unified atomic mass unit (1/12 mass of a C-12 nucleus)
= 1.660539×10^{-27} kg = 931.494 MeV

mass of D = 2.014102 u mass of T = 3.016049 u
mass of He-4 = 4.002602 u mass of neutron = 1.008665 u

mass defect = mass of reactants - mass of products

= (2.014102)u + (3.016049)u - (4.002602)u - (1.008665)u

= 0.018884 u

since 1 u = 931.494 MeV,

mass defect = (0.018884) x (931.494) = 17.5903 MeV

Stellar Reactions

Hans Bethe(1939) was the first to suggest that fusion reactions involving hydrogen and helium were responsible for fusion in stars(the **proton-proton cycle**). This is the reaction that is common in 'low temperature' stars, like our sun, which is one of the '**Main Sequence**' group.

$$
\begin{aligned}
&{}^{1}_{2}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}D + {}^{0}_{+1}e \ (\beta^{+}) \\
&{}^{2}_{1}D + {}^{1}_{1}H \rightarrow {}^{3}_{2}He \\
&{}^{3}_{2}He + {}^{1}_{1}H \rightarrow {}^{4}_{2}He + {}^{0}_{+1}e \ (\beta^{+}) \\
\hline
&4\ {}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}e \ (\beta^{+})
\end{aligned}
$$

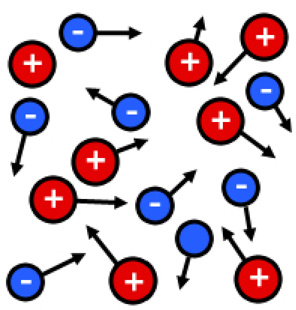
The energy release is approximately 27 MeV per cycle.

Another cycle, called the **carbon-nitrogen cycle** is thought to be prevalent in larger 'Main Sequence' stars. The cycle produces exactly the same result as the proton-proton reaction, but involves nitrogen and carbon in the reaction.

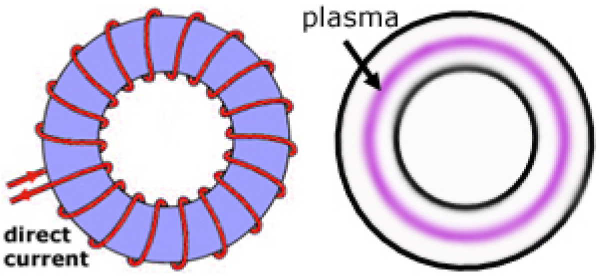
$$
\begin{aligned}
&{}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{13}_{7}N \\
&{}^{13}_{7}N \rightarrow {}^{13}_{6}C + {}^{0}_{+1}e \ (\beta^{+}) \\
&{}^{13}_{6}C + {}^{1}_{1}H \rightarrow {}^{14}_{7}N \\
&{}^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{15}_{8}O \\
&{}^{15}_{8}O \rightarrow {}^{15}_{7}N + {}^{0}_{+1}e \ (\beta^{+}) \\
&{}^{15}_{7}N + {}^{1}_{1}H \rightarrow {}^{12}_{6}C + {}^{4}_{2}He \\
\hline
&4\ {}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}e \ (\beta^{+})
\end{aligned}
$$

Plasma

First observed in a discharge tube(Crooke's Tube) around 1879, plasma is accepted as being a neutral 'gas' composed of electrons and ions. The plasma state for fusion to occur is at around 10^8 K.



So the problem of studying plasma is one of containment, since all materials would vaporize on exposure to the high temperatures. The answer is to use a 'magnetic bottle'. Essentially, the plasma is contained within a magnetic field.



Because the particles are charged they corkscrew around the magnetic field lines. The most effective shape is a doughnut or toroid. This produces a powerful magnetic field within it, much like a linear electromagnet, but closed into a loop.

Controlled Fusion

A **tokamak** (Russian acronym) is a toroidal reactor.

To be fair, fusion is not at present a viable source of energy. However, there is much international collaboration to make fusion-power a reality. The **International Thermonuclear Experimental Reactor** project is central to this aspiration.

When it is complete, the **ITER Tokamak** will be the largest fusion reactor ever built. It will be approximately 30 m tall, weigh 23 000 tonnes and have a plasma volume of 840 m^3. This scale is almost a factor of ten over previous reactors.

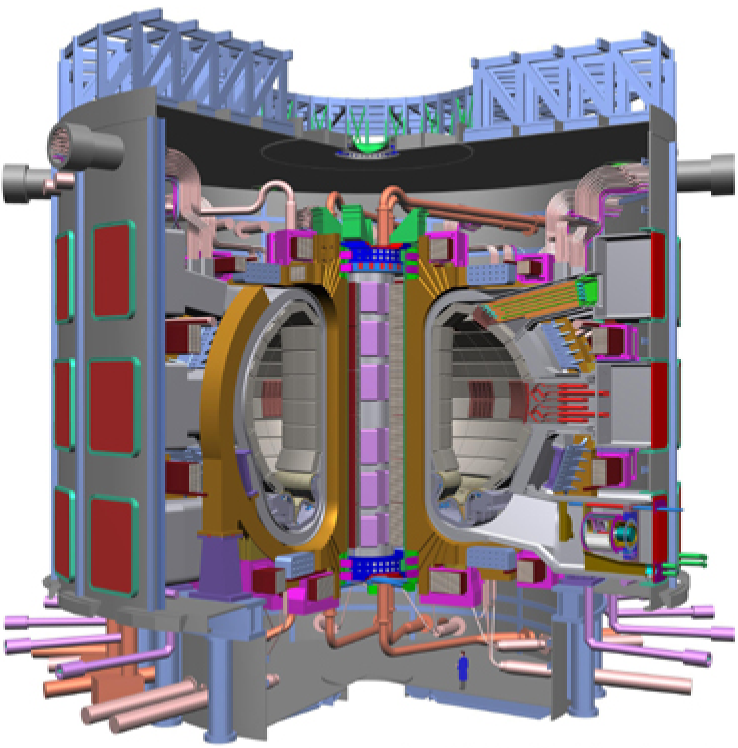


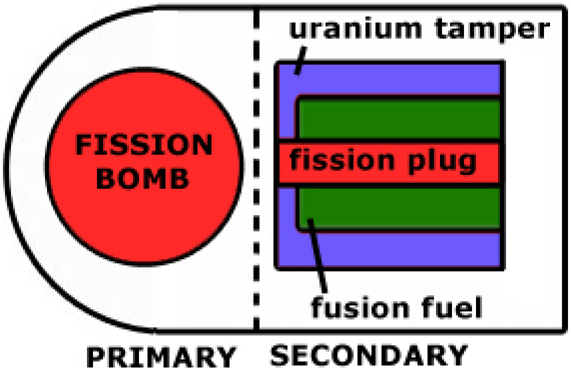
image courtesy of ITER http://www.iter.org/

When ITER comes on-stream in 2018, it hopes to achieve 500 MW of output power for 50 MW input. This amounts to a power output/input ratio of 10.

The H-bomb

Believe it or not, the **H-bomb** does NOT get most of its energy from nuclear fusion. Most of the energy released in a thermonuclear explosion comes from the fission reaction. True, a fusion reaction does take place, but this is just to make the fission reaction more efficient. This happens by the fusion reactions providing a greater neutron density. So a greater number of fission reactions can take place.

The H-bomb owes its design to **Edward Teller** and **Stanislaw Ulam**. Essentially, one fission bomb sets off another with fusion material(lithium deuteride) sandwiched within it. Compression and a supply of neutrons from the first bomb initiates fusion. The massive numbers of neutrons produced trigger the second fission reaction.



Neutrons are created by fission from the primary explosion:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

Under intense heat lithium deuteride(LiD) dissociates into lithium and deuterium ions:

$$Li\,D \rightarrow Li^{-} + D^{+}$$

More neutrons go on to react with the lithium to provide tritium.

$$^{0}_{1}n + ^{3}_{6}Li \rightarrow ^{2}_{4}He + ^{1}_{3}H$$

The deuterium and the tritium react, producing helium and a supply of neutrons.

$$^{1}_{3}H + ^{1}_{2}H \rightarrow ^{2}_{4}He + ^{0}_{1}n$$

Remember it is these neutrons that go on to initiate the second(and more powerful) fission reaction.