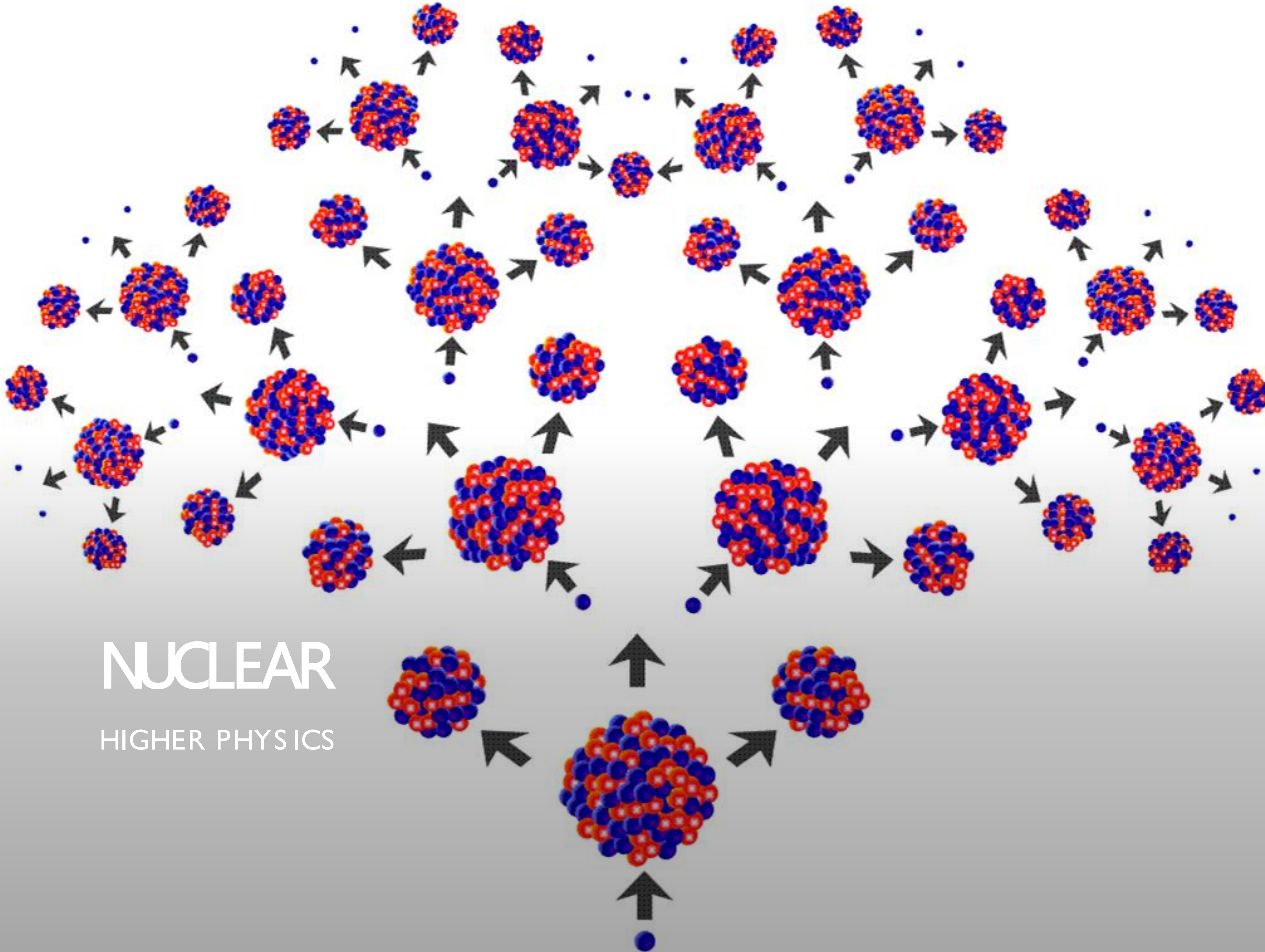
NUCLEAR

HIGHER PHYSICS



11.	Nuclear reactions
eq	$E = mc^2$
a	I can use nuclear equations to describe radioactive decay, fission (spontaneous and induced), with reference to mass and energy equivalence.
b	I can use nuclear equations to describe fusion reactions, with reference to mass and energy equivalence.
c	Use of an appropriate relationship to solve problems involving the mass loss and the energy released by a nuclear reaction. $E = mc^2$
d	I know that nuclear fusion reactors require charged particles at a very high temperature (plasma) which have to be contained by magnetic fields.

LEARNING OUTCOMES

BACKGROUND

Nucleon A nucleon is a particle in a nucleus, i.e. either a proton or a neutron.

Atomic Number The atomic number, Z, equals the number of protons in the nucleus. In a chemical symbol for an element it is written as a subscript before the element symbol.

Decay The process of emitting radiation

Isotope Isotopes are nuclides of the same atomic number but different mass numbers, i.e. nuclei containing the same number of protons but different numbers of neutrons.

Mass Number The mass number, A, is the number of nucleons in a nucleus. In a chemical symbol for an element it is written as a superscript before the element symbol.

Radioactive decay The breakdown of a nucleus to release energy and matter from the nucleus. This is the basis of the word 'nuclear'. The release of energy and/or matter allows unstable nuclei to achieve stability.

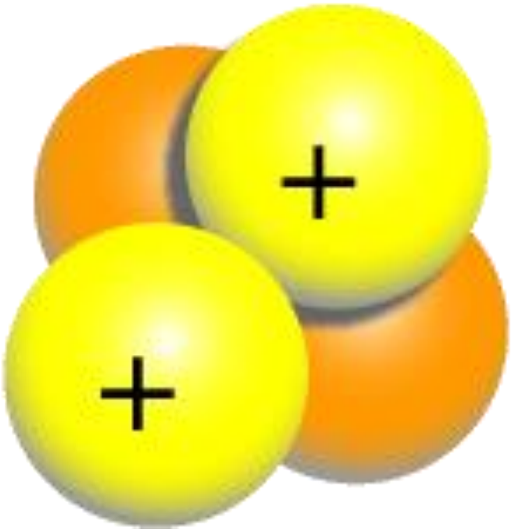
Radioisotopes or radionuclides. Unstable nuclei

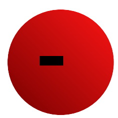
NUCLEAR DECAY

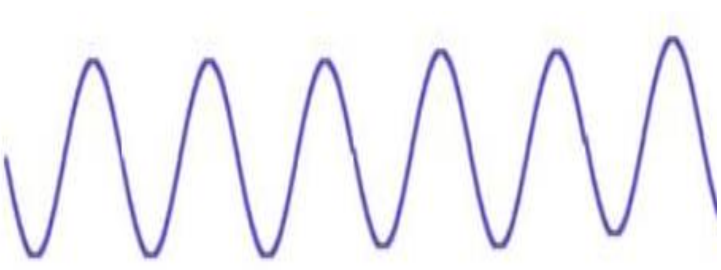
Many nuclei are unstable. In order to achieve stability, they can emit nuclear radiation: alpha, beta or gamma, neutrons etc.

Radiation	Nature	Symbol
Alpha particle	Helium nucleus $^{4}_{2}\mathrm{He}$	α
Beta particle	Fast electron $^{0}_{-1}\mathrm{e}$	β / β-
Positron	The antiparticle of an electron $^{0}_{+1}\mathrm{e}$	β+
Gamma ray	High frequency electromagnetic wave	γ

TYPES OF RADIATION



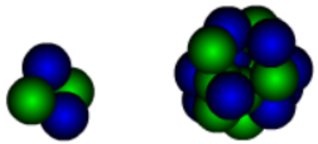




- Alpha Particle (α)
- Beta Particle (β)
- Gamma Ray (γ)

Alpha, beta and gamma emission

2p + 2n



Nucleus emitting an alpha particle.

β- A fast moving electron
Formed when a neutron decays to a proton
With the emission of a beta particle and antineutrino

Nucleus emitting a beta particle.

β+ A fast moving positron
Formed when a proton decays to a neutron
With the emission of a beta+ particle and neutrino

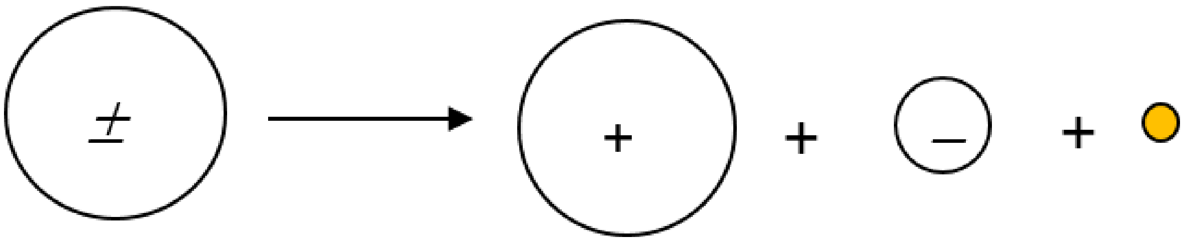
Nucleus emitting a gamma ray.

A photon of em radiation

BETA PARTICLE-

Evidence of the neutrino
Associated with
ELECTROWEAK FORCE

NEUTRON → PROTON + ELECTRON (OR β particle) ANTINEUTRINO



$$\boldsymbol{{}^1_0n \rightarrow {}^1_1p + {}^{0}_{-1}e + {}^0_0\bar{v}} \qquad \boldsymbol{OR} \qquad \boldsymbol{{}^1_0n \rightarrow {}^1_1p + {}^{0}_{-1}e + \bar{\nu}}$$

Try to work out the process for positron emission

$$\boldsymbol{{}^1_1p \rightarrow {}^1_0n + {}^{0}_{+1}e + {}^0_0v} \qquad \boldsymbol{OR} \qquad \boldsymbol{{}^1_1p \rightarrow {}^1_0n + {}^{0}_{+1}e + \nu}$$

PARTICLE DETAILS

Particle	Mass number	Mass (kg)	Charge	Symbol
Proton	1	$1.67262158 \times 10^{-27}$	+ 1	${}^{1}_{1}p$
Neutron	1	1.674929×10^{-27} kg	0	${}^{1}_{0}n$
Electron	0*	9.11×10^{-31} kg	-1	${}^{0}_{-1}\mathrm{e}$
Positron	0*	9.11×10^{-31} kg	+ 1	${}^{0}_{+1}\mathrm{e}$

- mass of electron/positron = 1/1840 mass of proton.
- The mass number is given in terms of the mass of a proton where one proton is given the number 1.

CHEMISTRY CODE!

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

In small nuclei, no. of protons is often = no. of neutrons
In larger nuclei no. of protons < no. of neutrons

where

A = mass number (no. of protons +neutrons)
Z = atomic number (no.of protons)
X = symbol to represent the element, 1 capital letter or 1 capital followed by 1 lower case letter.
You can work out the number of neutrons by subtracting the atomic number from the mass number

eg no. of neutrons = A-Z

CHEMSTRY CODE!

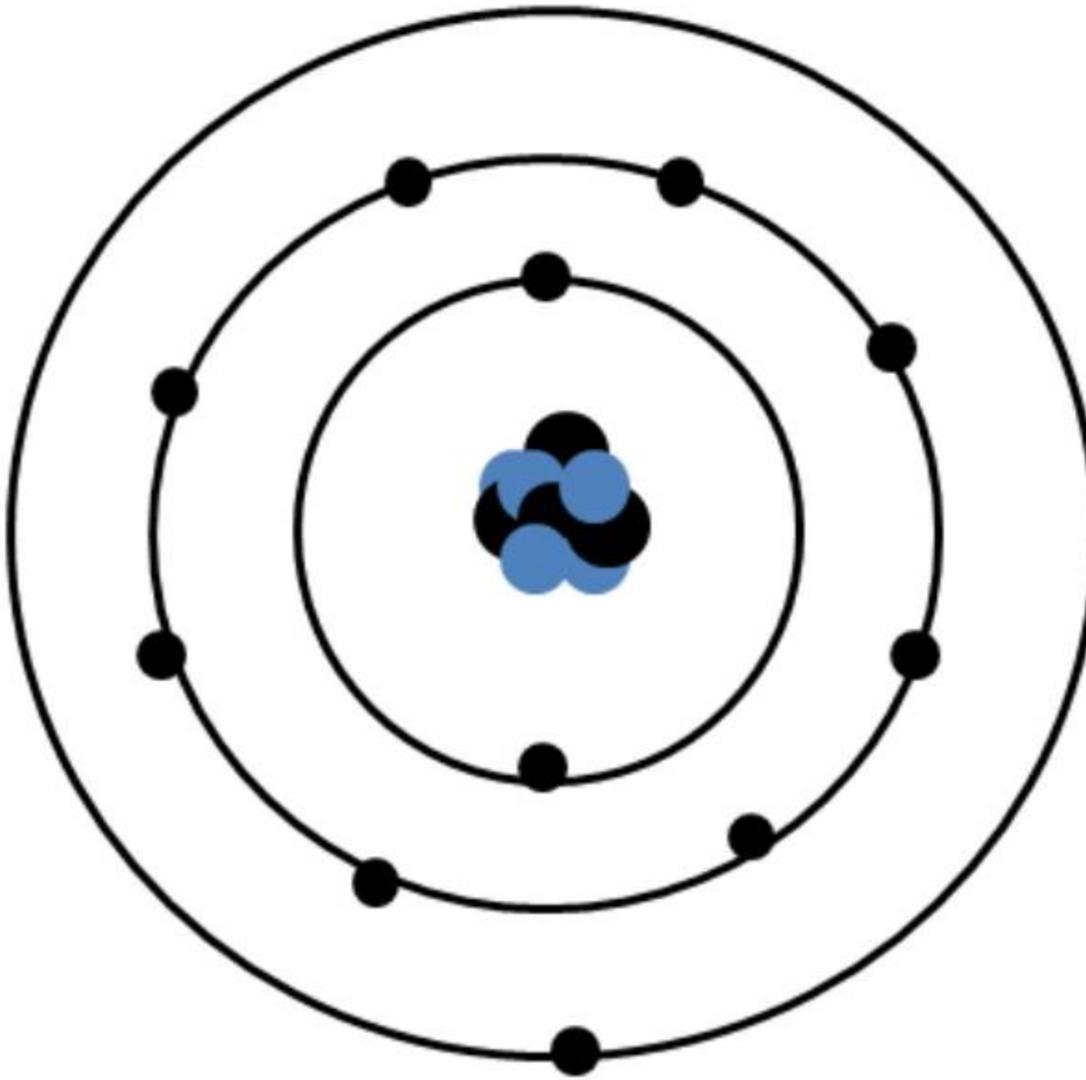
Each element defined by no. protons,

eg Hydrogen always 1 proton, Carbon always 6.

In an atom number of protons = number of electrons, (if no.$p \neq$ no.e then it is an ion!)

The number of neutrons in the nucleus of any element varies giving isotopes

eg carbon usually has 6 neutrons but can have 8.



What element is this?

EQUATIONS FOR NUCLEAR REACTIONS

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

$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e + \gamma$$

Summarise

$$^{238}_{92}U \xrightarrow{\quad\alpha\quad} {}^{234}_{90}Th \xrightarrow{\quad\beta\quad} {}^{234}_{91}Pa$$

- When a nucleus decays, it often undergoes several disintegrations until it becomes stable, e.g. Uranium 238 decays to Thorium 234 emitting α and γ radiation. The thorium then decays to protactinium-234 emitting β & γ.

SUMMARY- RESULT OF DIFFERENT RADIATIONS BEING RELEASED

Particle	Symbol	Changes to Mass No, A.	Changes to Atomic No. Z
α	${}^{4}_{2}He$	-4	-2
β / β-	${}^{0}_{-1}e$	0	+ 1
β+	${}^{0}_{+1}e$	0	-1
γ	γ	0	0
${}^{1}_{0}n$	${}^{1}_{0}n$	-1	0

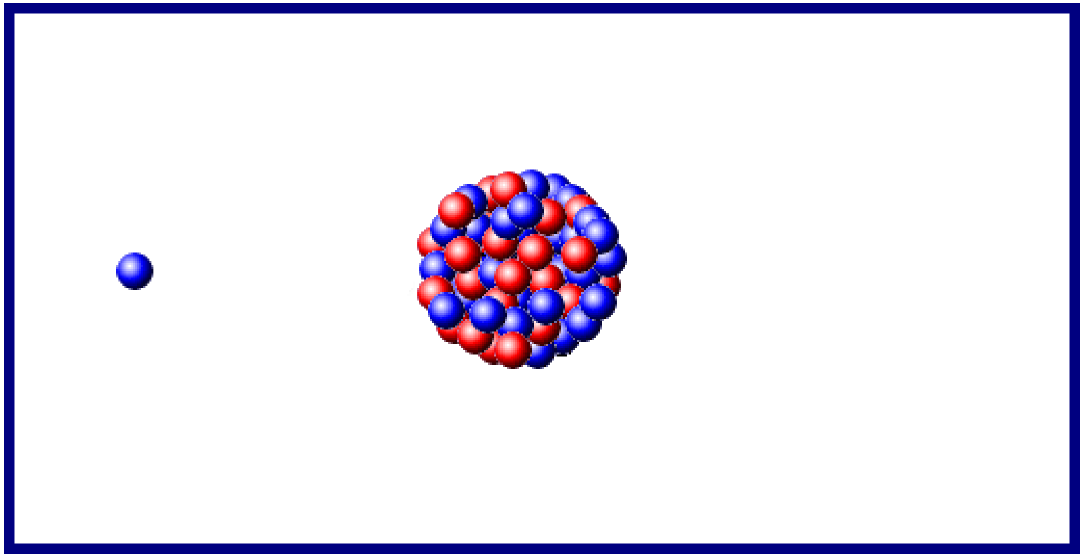
e.g when an alpha particle is released the A decreases by 4, Z by 2!

NUCLEAR FISSION

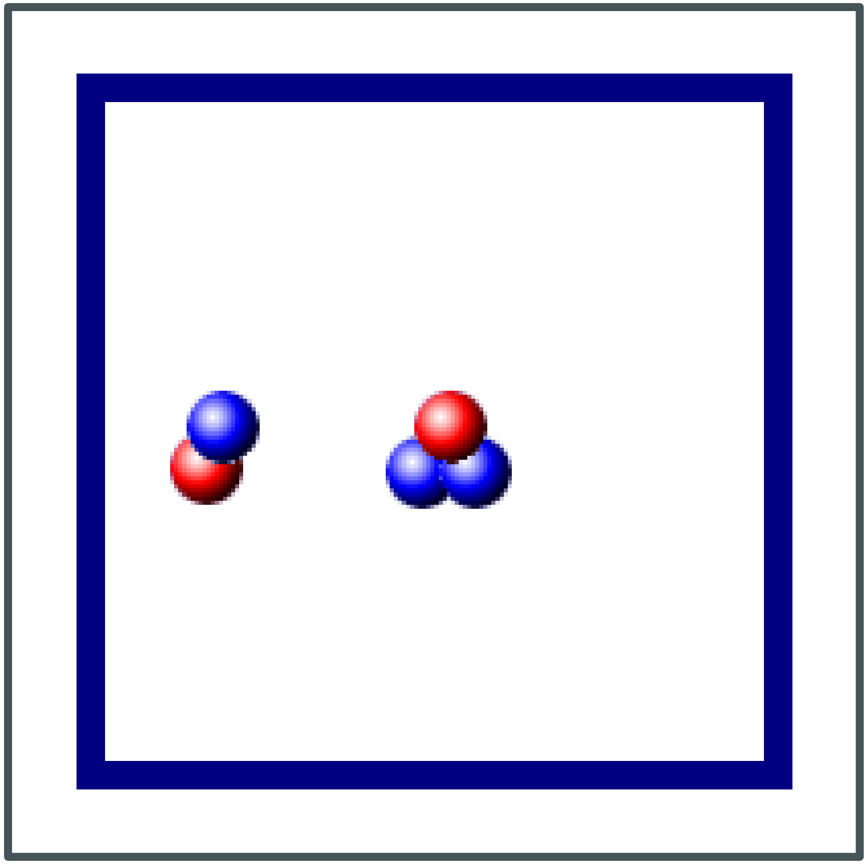
Fission is the process of splitting a large **nucleus** into two (or more) smaller **nuclei**

This process can happen for no apparent reason, in which case it is called **spontaneous fission**

If the nucleus is hit by a neutron this process is called **induced fission**



NUCLEAR FUSION



Fusion is the process of joining two smaller **nuclei** to make a larger **nucleus**

This is the process that powers the Sun and all the stars. It Is also used in hydrogen bombs (which are about 100 times more powerful than fission bombs)

Fission in Nuclear Reactors (in Power stations)

Control rods are boron steel and are used to regulate the number of neutrons going from one stage of the the chain reaction to the next. When a sustainable chain reaction is operating only one neutron will progress from one stage to another.

Moderator is graphite to slow down the fast neutrons emitted and allow the slower ‘thermal’ neutrons to be absorbed by the next uranium nucleus.

Binding Energy

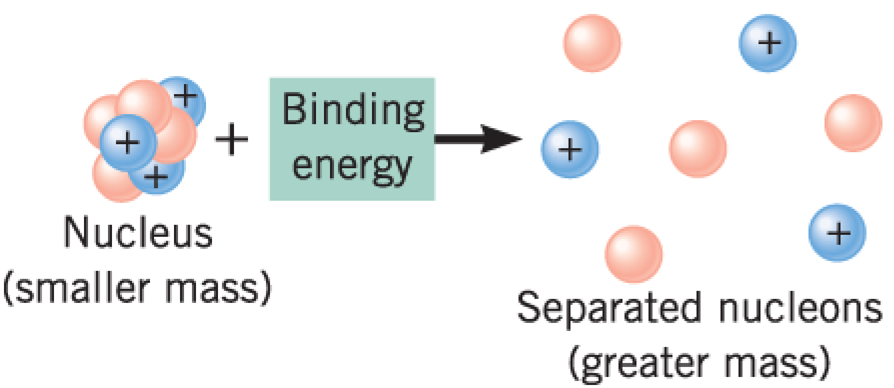
A force exists between the protons and neutrons in a nucleus, this is due to the strong force.

Scientists have proven that the individual nucleons (protons and neutrons) are heavier than the bound nucleus.
This difference in mass is called the mass defect.

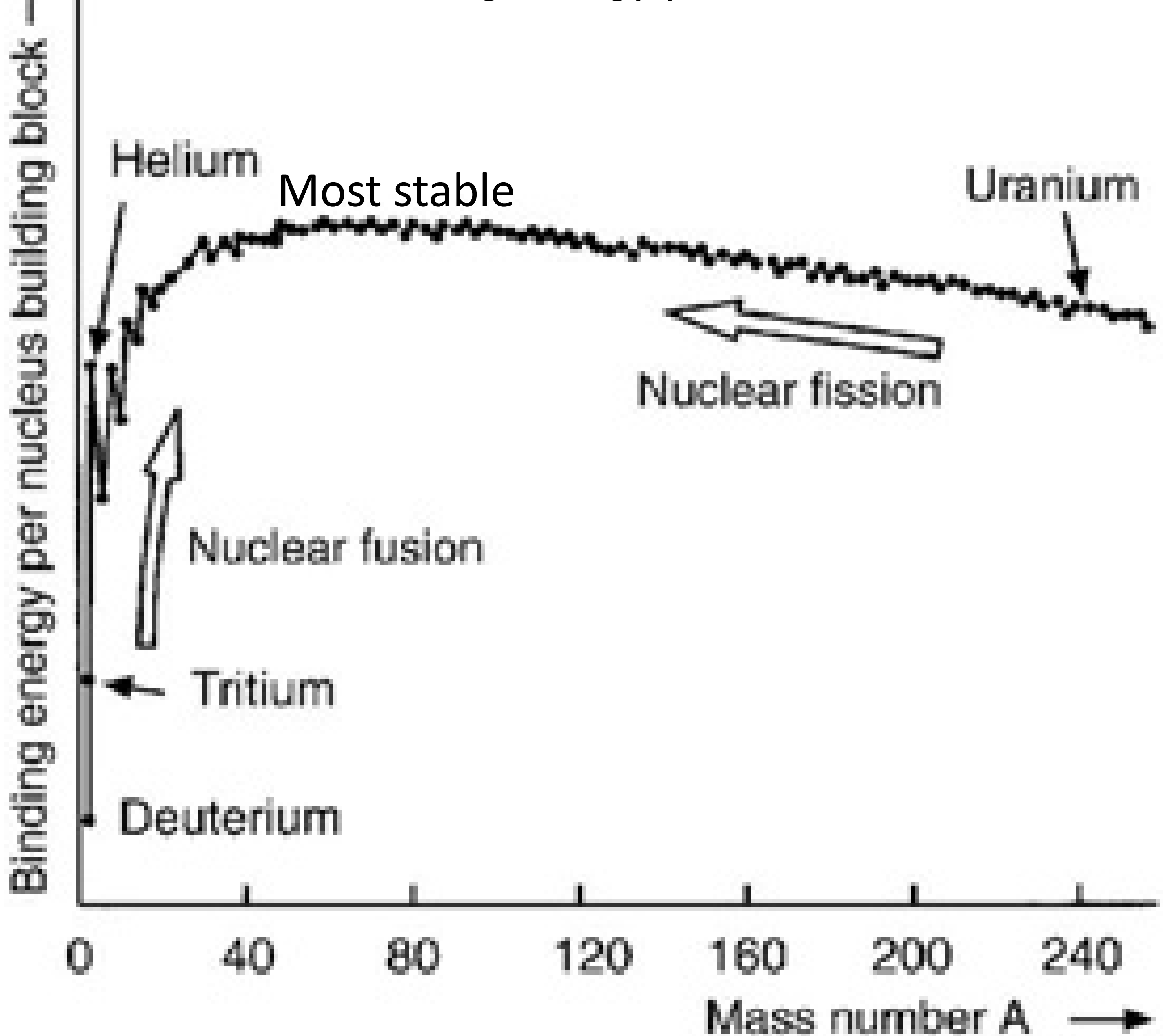
Einstein showed that the relationship between the mass and energy is:

$$E = mc^2$$

E – Energy
m – mass defect
c – speed of light (3×10^8 ms^{-1})



Binding energy per nucleon



Mass Difference

There is a small change in mass following a fission or fusion. This is called the mass difference.

The energy released from the reaction can be calculated using

Joules

$$E = mc^2$$

kg (3x10⁸ ms⁻¹)²

Example:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{136}_{54}Xe + ^{98}_{42}Mo + 2^{1}_{0}n + 4^{\ 0}_{-1}\beta$$

Particle	U	Xe	Mo	n
Mass ($\times 10^{-27}$ kg)	390.173	225.606	162.522	1.675

1. What type of reaction is this
2. Calculate the energy released in this reaction

Step 1: Find the actual mass before the reaction
Step 2: Find the actual total mass after the reaction
Step 3: Find the 'lost' mass (convert to kilograms if necessary)
Step 4: Use E = m c² to calculate the energy released

Solution

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{136}_{54}Xe + ^{98}_{42}Mo + 2^{1}_{0}n + 4^{\ 0}_{-1}\beta$$

Total Mass before reaction		Total Mass after reaction
390.173 + 1.675	Lost mass	225.606 + 162.522 + 2(1.675)
391.848×10^{-27} kg	391.848 – 391.478	391.478×10^{-27} kg
	0.370×10^{-27} kg	

$$E = mc^2$$
$$E = 0.370 \times 10^{-27} \times (3 \times 10^8)^2$$
$$\underline{E = 3.3 \times 10^{-11} J}$$

$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{42}^{98}Mo + {}_{54}^{136}Xe + 2\,{}_{0}^{1}n + 4\,{}_{-1}^{0}e $$

<u>Mass Before</u>		<u>*Mass after*</u>	
${}_{92}^{235}U$	3.90088×10^{-25} kg	${}_{42}^{98}Mo$	1.6249×10^{-25} kg
${}_{0}^{1}n$	1.6749×10^{-27} kg	${}_{54}^{136}Xe$	2.2556×10^{-25} kg
Total 3.917629×10^{-25} kg		$2\,{}_{0}^{1}n$	3.3498×10^{-27} kg
		$4\,{}_{-1}^{0}e$	3.32×10^{-30} kg
		Total 3.914031×10^{-25} kg	

<u>**Mass is not conserved**</u> mass is lost and since mass has been lost and kinetic energy has been gained we conclude that the mass has been converted into ***energy***. The kinetic energy of the products is found to be much greater than the initial kinetic energy of the reactants. The loss of mass has been accompanied by a huge increase in energy.

$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{42}^{98}Mo + {}_{54}^{136}Xe + 2\,{}_{0}^{1}n + 4\,{}_{-1}^{0}e $$

In our example

mass change = mass before – mass after

mass change = 3.917629×10^{-25} kg - 3.914031×10^{-25} kg

mass change = 3.598×10^{-28} kg

Keep all the sig fig until the end!

energy equivalence:

$E = mc^2$

$$E = 3.598 \times 10^{-28} \times (3 \times 10^{8})^{2}$$

$$E = 3.598 \times 10^{-28} \times 9 \times 10^{16}$$

$$E = 3.24 \times 10^{-11} J$$

Identifying Reactions

Identify if the following equations are induced/spontaneous **fission** or **fusion**.

(1) $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{93}_{36}Kr + ^{140}_{56}Ba + 3^{1}_{0}n$

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

(3) $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$

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

Summary

In a fission reaction, the mass of the products is less than the mass of the reactants. This mass difference has been converted to energy according to the relationship

$$E = mc^2.$$

11. The following statement represents a nuclear reaction which may form the basis of a nuclear power station of the future.

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

(*a*) State the name given to the above type of nuclear reaction.

(*b*) Explain, using $E = mc^2$, how this nuclear reaction results in the production of energy.

(*c*) Using the information given below, and any other data required from the Data Sheet, calculate the energy released in the above nuclear reaction.

$$\text{mass of } ^{3}_{1}H = 5\cdot00890 \times 10^{-27}\,\text{kg}$$
$$\text{mass of } ^{2}_{1}H = 3\cdot34441 \times 10^{-27}\,\text{kg}$$
$$\text{mass of } ^{4}_{2}He = 6\cdot64632 \times 10^{-27}\,\text{kg}$$
$$\text{mass of } ^{1}_{0}n = 1\cdot67490 \times 10^{-27}\,\text{kg}$$

(*d*) Calculate how many of the reactions of the type represented above would occur each second to produce a power of 25 MW.

11.a. The reaction is an example of **nuclear fusion.**

b. The total mass of the products from the fusion reaction is less than the mass of the initial reactants. The difference in mass is converted into energy. The amount of energy produced can be calculated using the equation: $E = mc^2$, where m is the difference in mass and c is the speed of light.

c. $M_{reactants} = (5.00890x10^{-27}+3.34441x10^{-27})kg$

$M_{reactants} = 8.35331x10^{-27}kg$

$M_{products} = (6.64632x10^{-27}+1.67490x10^{-27})kg$

$M_{products} = 8.32122x10^{-27}kg$

Mass defect = $M_{reactants} - M_{products}$

Mass defect = $8.35331x10^{-27} - 8.32122x10^{-27}$

Mass defect = $0.03209x10^{-27}kg$

$E = M_{defect}c^2$

$E = 0.03209x10^{-27} \times (3x10^8)^2$

$\mathbf{E = 2.8881x10^{-12}J}$

d. Number of reactions = Total energy per second/energy per reaction

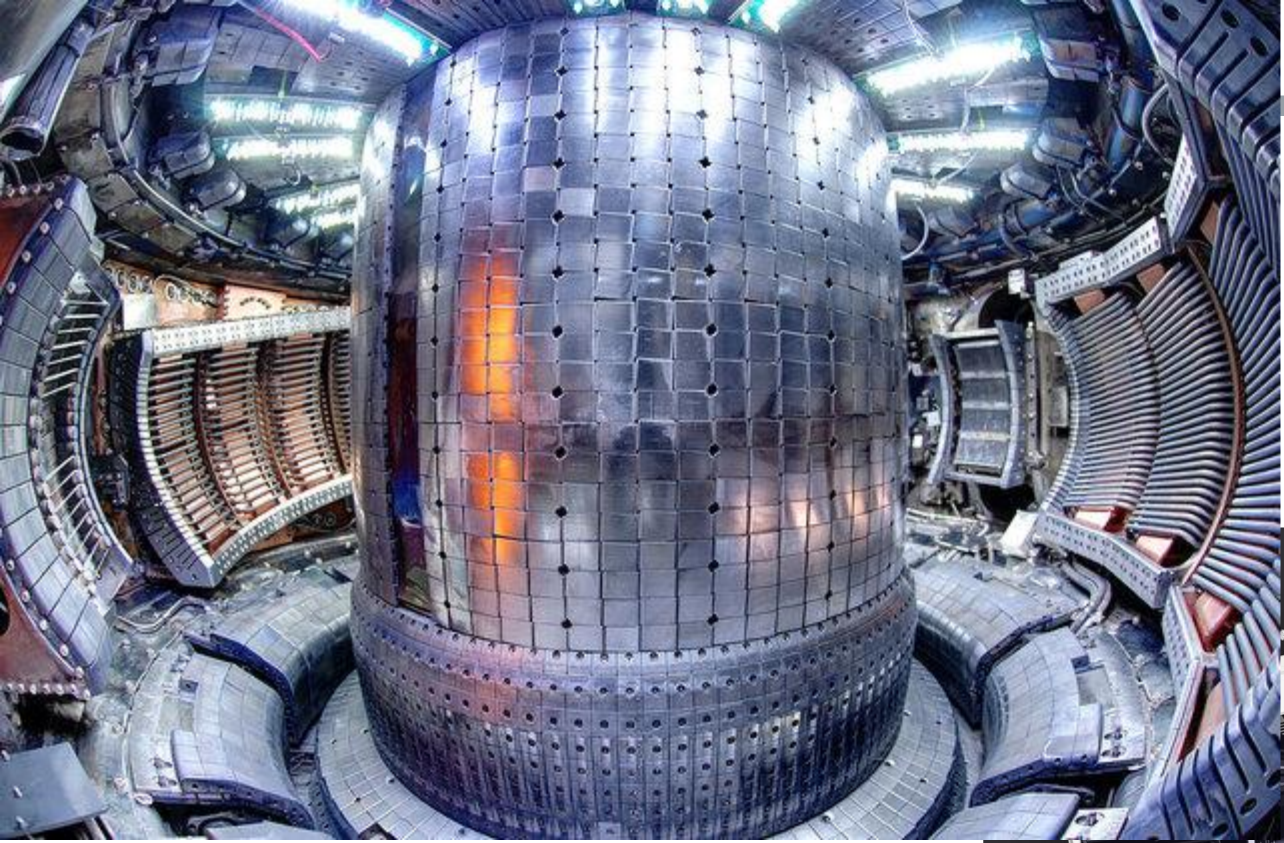
Number of reactions = $25x10^6/2.8881x10^{-12}$

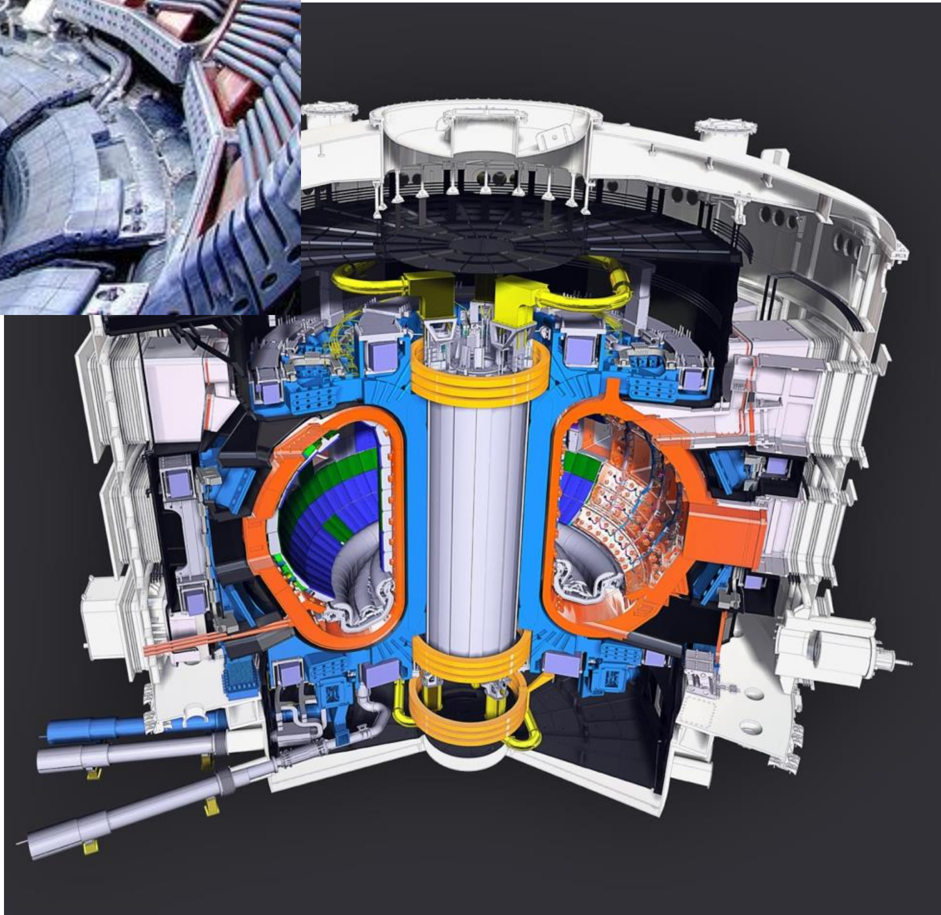
Number of reactions = $8.658x10^{18}$

Review

1. State the composition of an alpha and beta particle.
2. State 3 properties of a gamma ray.
3. Beta radiation is evidence of what?
4. Which has greater mass, the reactants or products?
5. How is energy produced in a fission reaction.
6. If the mass difference is 8.0345×10^{-29} kg calculate the energy produced.

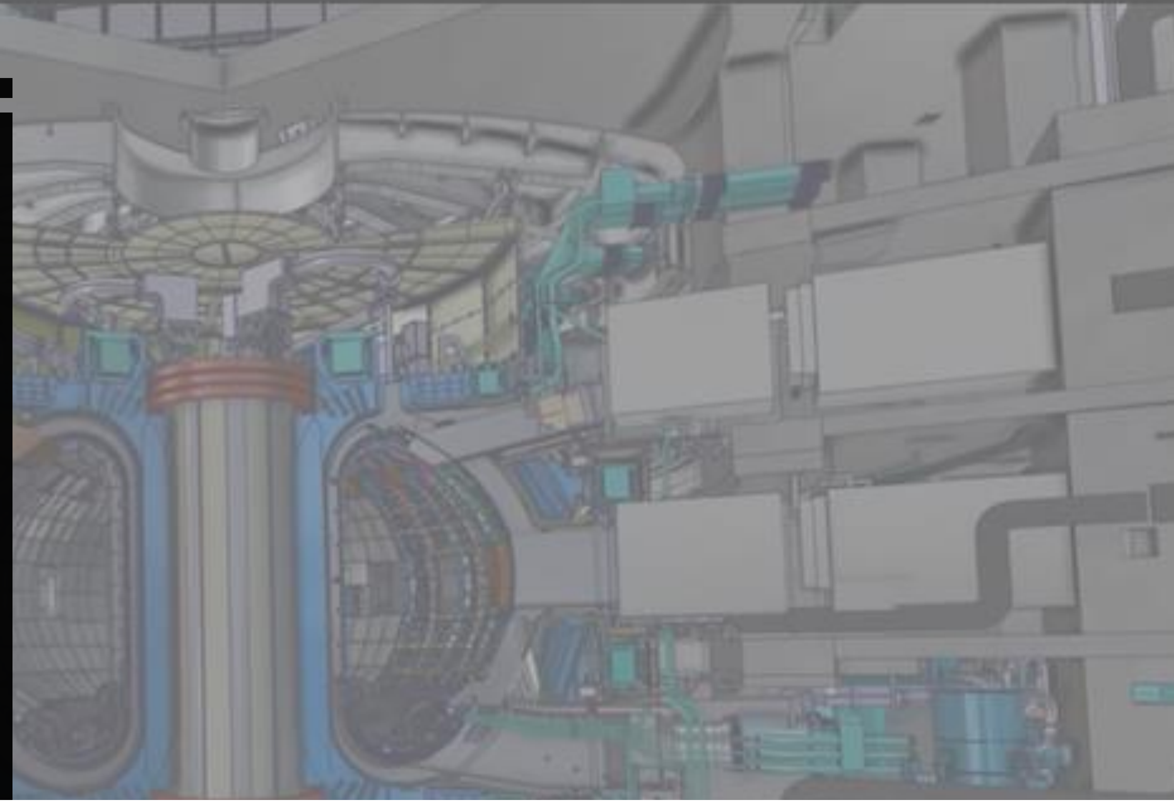
FUSION REACTORS



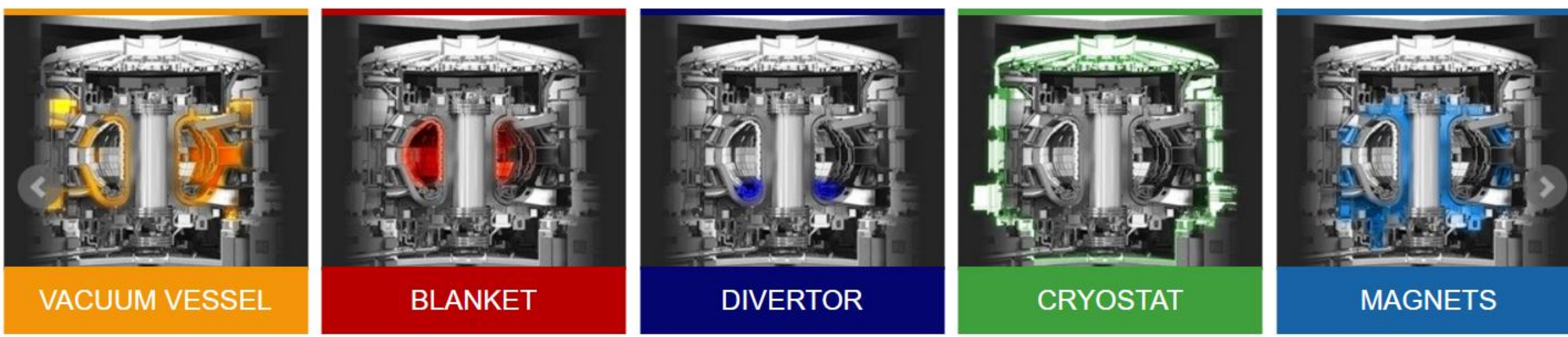


https://www.businessinsider.com/plasma-fusion-reactor-noises-2015-10?r=US&IR=T
https://www.iter.org/mach/tokamak

- [Watch the walkthrough of the TOKAMAK https://www.youtube.com/watch?v= IP7Vuqz-MAE](https://www.youtube.com/watch?v=IP7Vuqz-MAE)



THE OTHER COMPONENTS



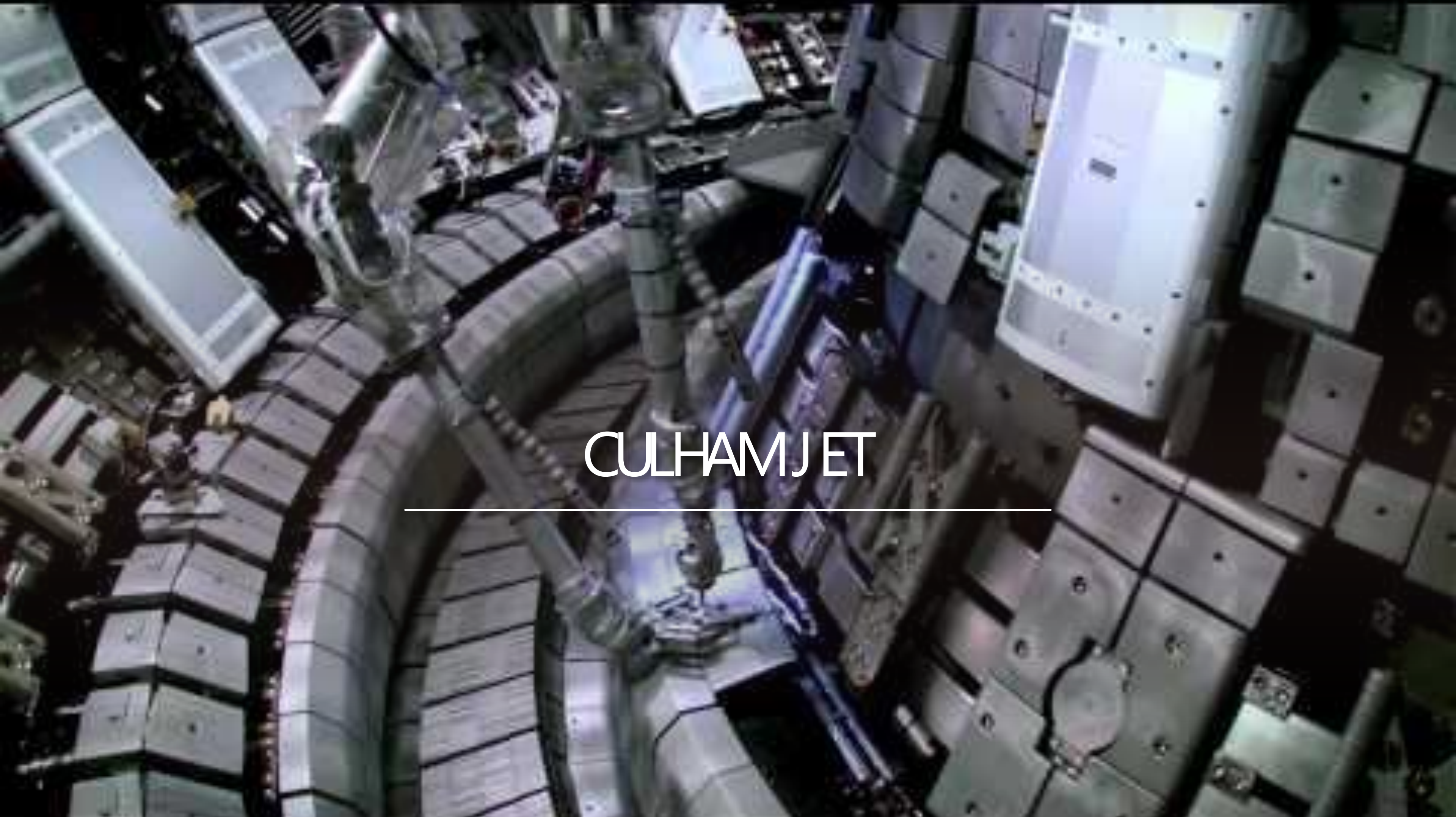
Please note that all images are for illustrative purposes only

MAIN PROBLEMS WITH FUSION

- Plasma at very high temperatures requires no contact with container
- Containment by magnetic field
- Very high levels of radiation


ITER TOKAMAK
TEST REACTOR

CULHAM JET



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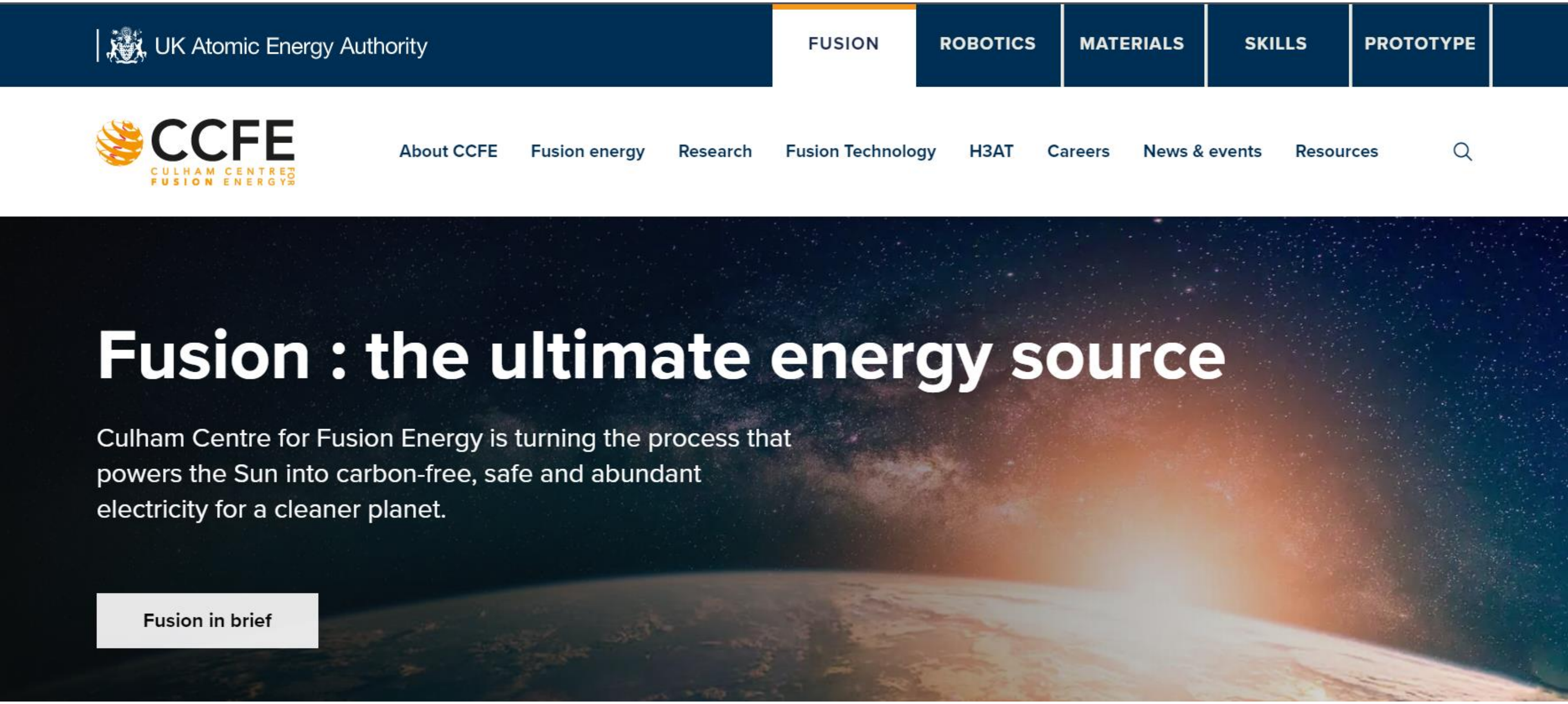

RESEARCH 1 FISSION

Summarise Nuclear Reactors in a 1-page infographic using

https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

RESEARCH 2- FUSION

Summarise Fusion as a potential source of energy in a 1-page infographic using

https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

SQA content

- Use of nuclear equations to describe radioactive decay, fission (spontaneous and induced) and fusion reactions, with reference to mass and energy equivalence.

- Use of an appropriate relationship to solve problems involving the mass loss and the energy released by a nuclear reaction.

$$E = mc^2$$

- Knowledge that nuclear fusion reactors require charged particles at a very high temperature (plasma) which have to be contained by magnetic fields.