Nuclear reactions, reactors

szerző: PGY

Energy from fusion

When you join small atoms together, you can also get energy.

The Sun fuses hydrogen to make helium.

We're currently trying to fuse two isotopes of hydrogen - it's easier.

$$^{3}H + {}^{2}H \longrightarrow {}^{4}He + {}^{1}n + 14.6\ \text{MeV}$$

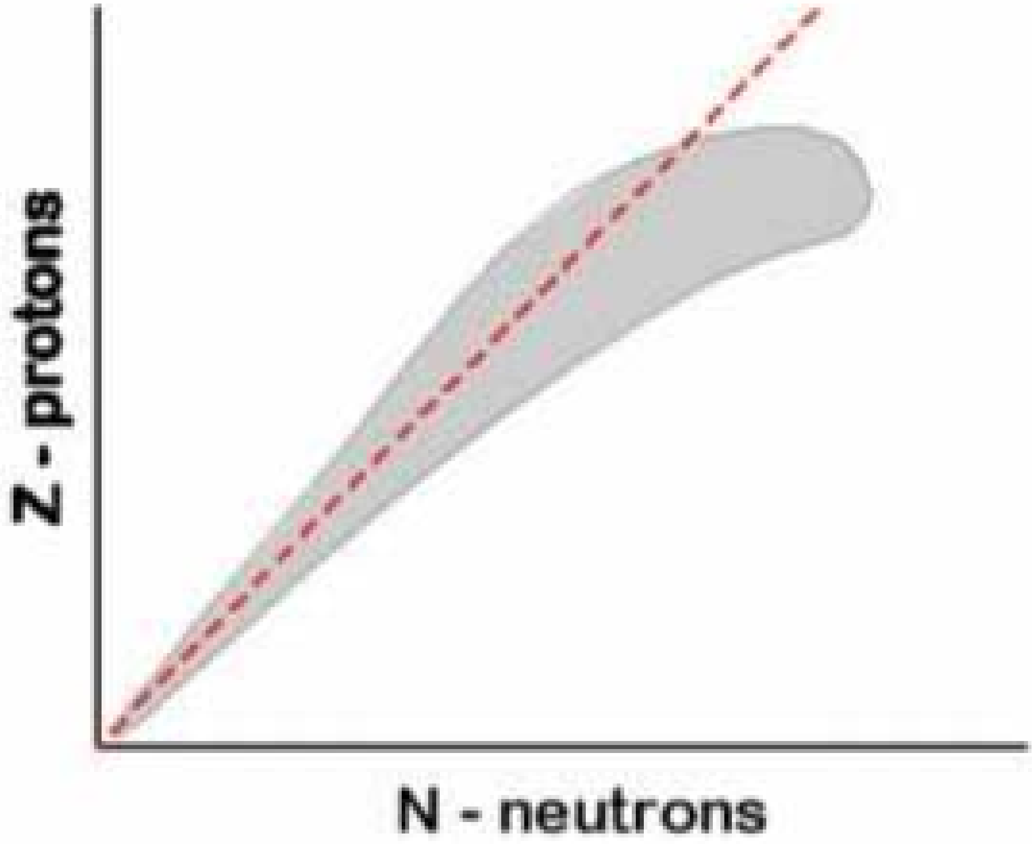
It will be great when it works. Fuel would come from the oceans - almost free.

Chart of the Nuclides

The radiochemist's version of the Periodic Table, listing all known nuclear isotopes.

- There are more than 2300 known nuclides and over 400 isomers.
- Only 287 isotopes are stable or naturally occurring radioactive forms.
- The chart lists this information along with other valuable data.

Chart of the Nuclides



The chart is arranged as a plot of neutron number Vs. atomic number.

Stable isotopes run at ~ 45o slope then slope down at Z = 20 (Ca).

Due to the size, the chart is often split up into several pages.

Information obtained from the chart

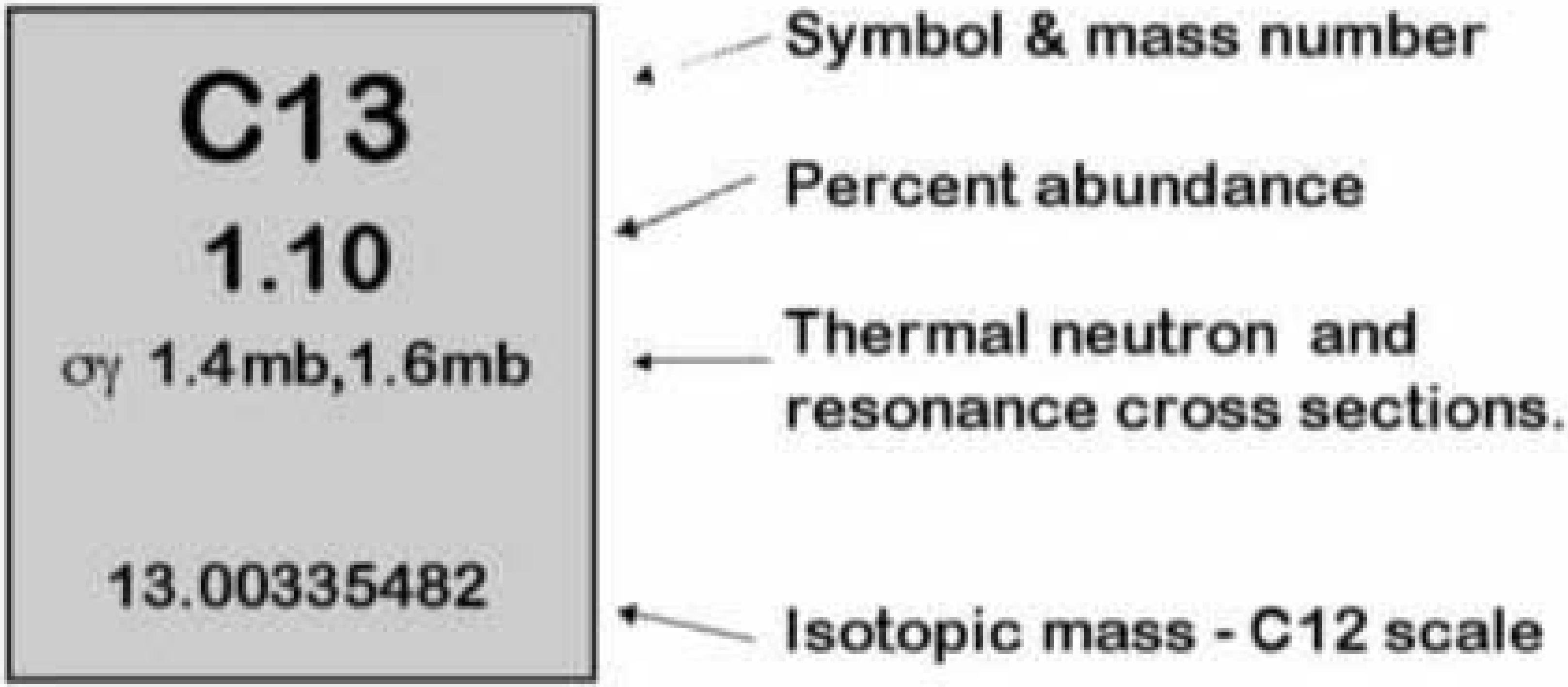
Each chart 'box' lists appropriate types of physical data for a specific nuclide.

The style and color of the box also gives you a fair amount of information.

Since there is so much information, lets look at some examples.

Stable isotope

Stable isotopes are listed in gray boxes.



C13

1.10

$\sigma\gamma$ 1.4mb,1.6mb

13.00335482

Symbol & mass number

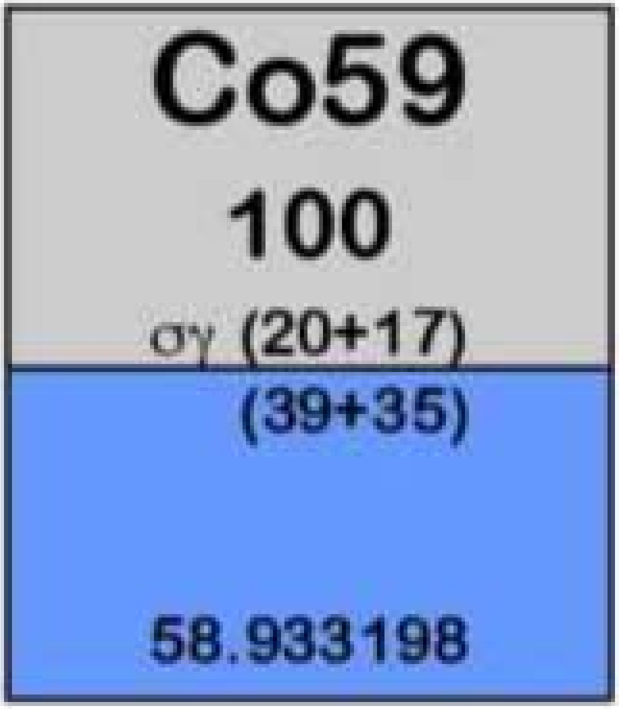
Percent abundance

Thermal neutron and resonance cross sections.

Isotopic mass - C12 scale

Other information might be listed for other isotopes.

Stable isotope



Co59

100

$\sigma\gamma$ (20+17)

(39+35)

58.933198

This stable isotope also has a color code

A color on the bottom half of the box is used to indicate its relative large neutron cross section.

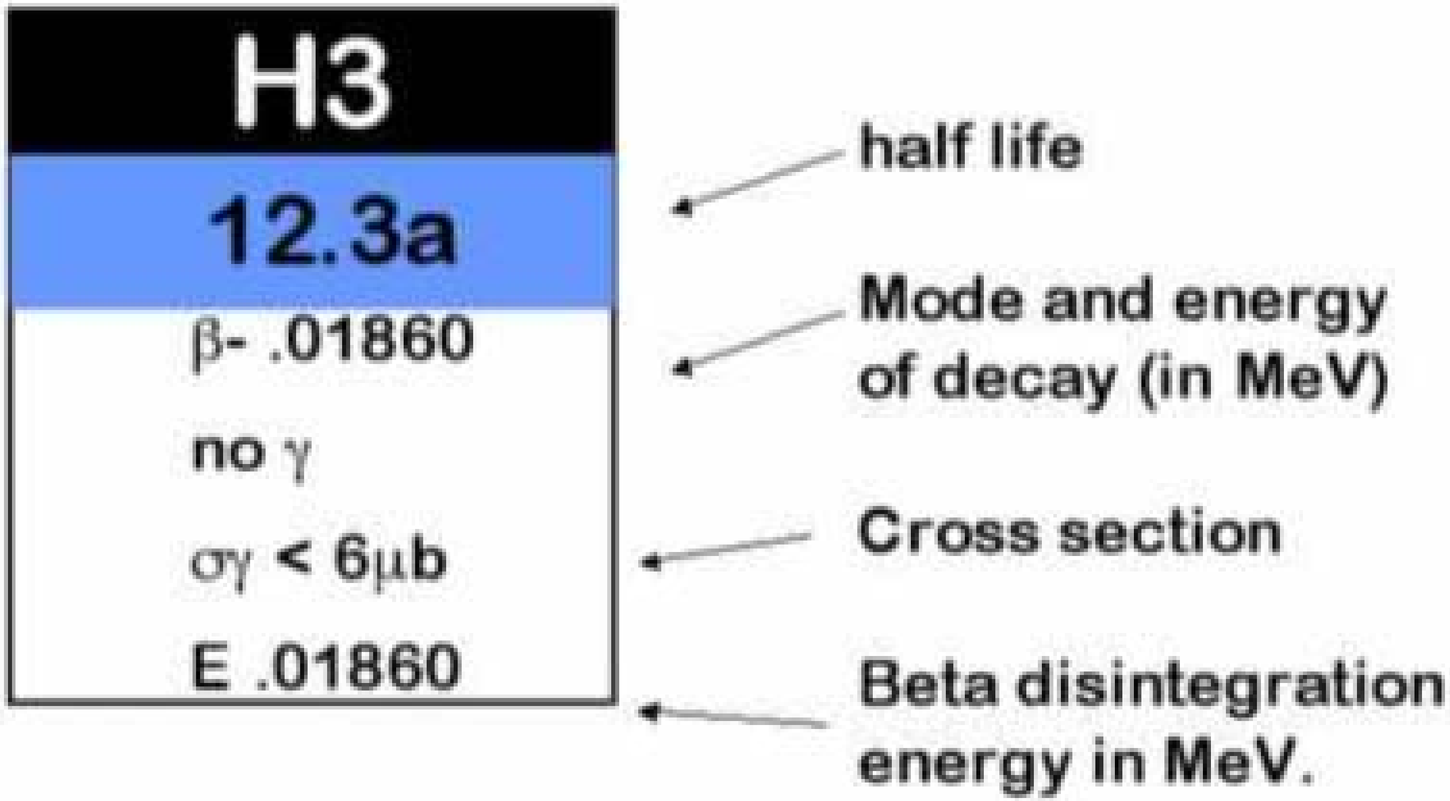
Cross section color coding.

🟦	10 - 100 barns
🟩	100 - 500 barns
🟨	500 - 1000 barns
🟧	>1000 barns

This is a measure of neutron absorption by a nuclide.

We'll cover in detail later when we discuss neutron activation.

Naturally occurring radioisotope



H3

12.3a

β- .01860

no γ

$\sigma\gamma < 6\mu b$

E .01860

half life

Mode and energy of decay (in MeV)

Cross section

Beta disintegration energy in MeV.

Note: Color coding is also used to indicate relative half life values.

Half life color coding.

🟧	1 - 10 days
🟨	10 - 100 days
🟩	100 - 10 years
🟦	10 years - 10,000 years

Color coding of the top half of the box is used for half life

< 1 day and
> 10,000 years
are not color coded.

Artificially radioactive

Ca47

4.54 d

β- .69, ...
γ 1.297, ...

E 1.988

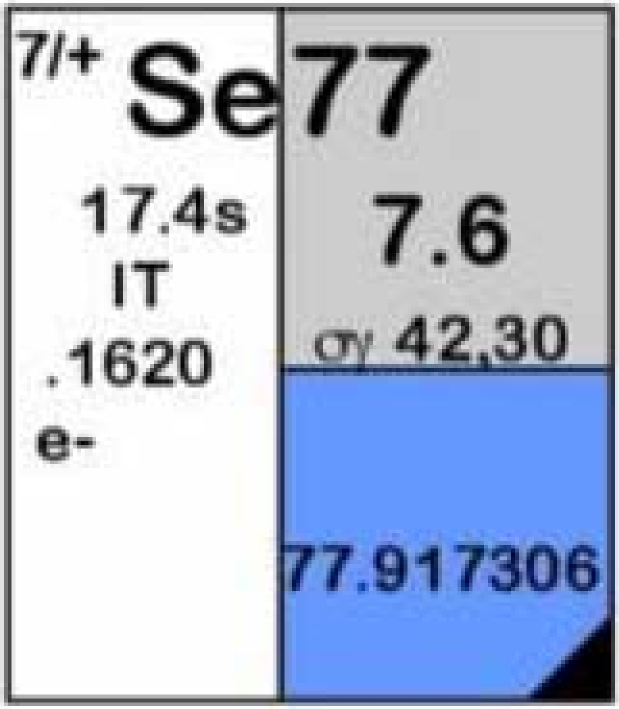
This example show the most common modes of decay.

Others may be present.

Symbols used in chart.

Radiations and decay		Time	
α	alpha	μs	microseconds
β^-	negative e-	ms	milliseconds
β^+	positron	s	seconds
γ	gamma	m	minutes
n	neutron	h	hours
p	proton	d	days
ε	electron capture	a	years
IT	isomeric transition		
SF	spontaneous fission		
$\beta^-\beta^+$	double beta decay		

Two isomeric states - one stable



spin/parity

Used to indicate that it is a fission product

metastable isotopic form

Spin information

Each neutron and proton has an intrinsic angular momentum of 1/2 h/2π. h is Plank's constant.

These combine with their orbital angular momentum to produce a resultant angular momentum called the **nuclear spin**.

Orbital angular momentum is always zero, so nuclear spin has an integer or half-odd-integer value depending on the nucleons. even - integer, odd - 1/2 odd integer

Parity information

Mathematical formalism of quantum theory.

even parity (+)
odd parity (-)

Example: Al-27 has a value of 5/+

This is actually 5/2+ but the 2 has been omitted to improve readability.

The ground states of all even-even nuclides is 0+ so they are omitted from the chart.

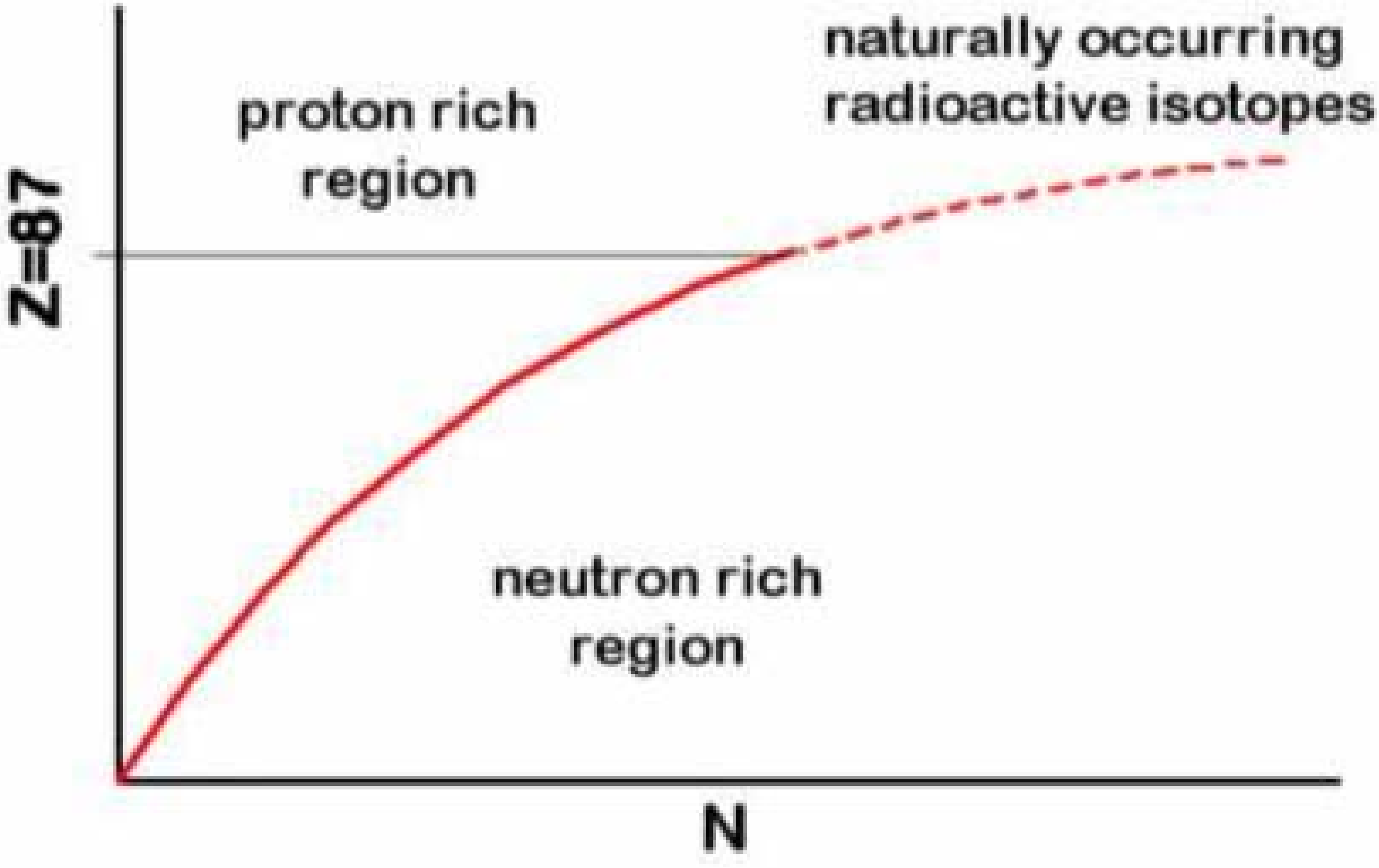
So What!

A large angular momentum or spin change is required for gamma-ray transition between energy states of a nuclide

If the spin change is large and the energy of the transition is small, you end up with relatively long half lives for the transition.

As a result, you are able to see metastable states.

Decay trends and the chart



Decay trends

Naturally occurring radioactive isotopes

All are alpha emitters.

Too many nucleons.

$$ {}^{A}_{Z}X \longrightarrow \alpha + {}^{A-4}_{Z-2}A $$

This is a quick way to reduce the number by 4. Multiple steps may be required to complete the process -**decay series**.

Decay trends

Proton rich isotopes

Prefer β^+ or ε emission

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

$${}^{A}_{Z}X \xrightarrow{\text{EC}} {}^{A}_{Z-1}A$$

In essence, we are converting a p to an n
- trying to get back to the zone of stability.

Decay trends

Neutron rich isotopes

Prefer β^- emission

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

In essence, we are converting a neutron to a proton.

Nuclear transmutations and the chart

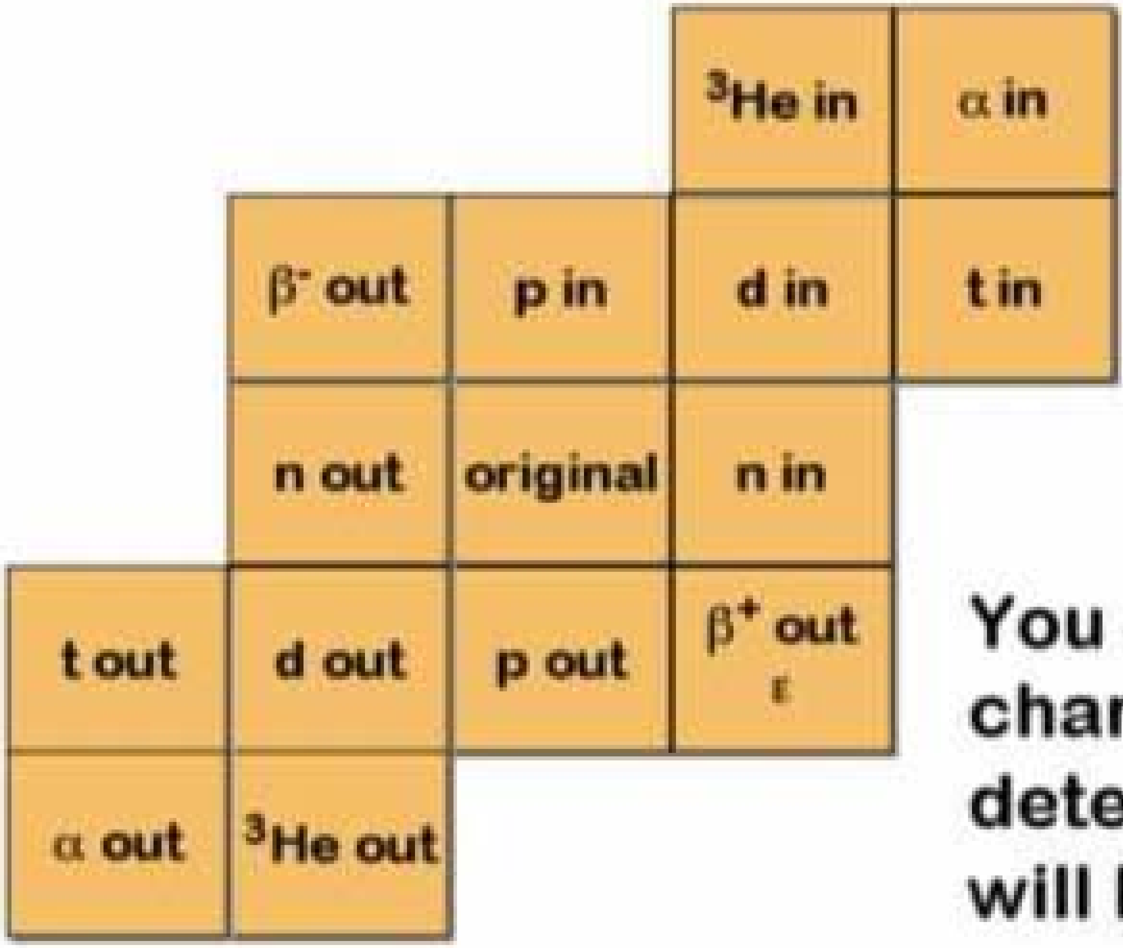
Due to its arrangement, the chart can assist in determining what will form as a result of a nuclear reaction or decay.

Symbols used:

n - neutron
p - proton
d - deuteron
t - tritium

α - alpha
β^- - beta
β^+ - positron
ε - electron capture

Nuclear transmutations



			^{3}He in	α in
	β^- out	p in	d in	t in
	n out	original	n in	
t out	d out	p out	β^+ out ε	
α out	^{3}He out			

You can use the chart to rapidly determine what will be produced.

Nuclear transmutations

			^{3}He in	α in
	β⁻ out	p in	d in	t in
	n out	original	n in	
t out	d out	p out	β⁺ out ε	
α out	^{3}He out			

O15	O16	O17	O17
N13	N14	N15	N15
C12	C13	C14	C14
B11	B12	C13	C13

What would result from the

β⁻ decay of C12?

Inserting a deuterium into B12?

Nuclear transmutations

Many nuclear reactions involve bombarding a nucleus with a particle to obtain a new species.

We use a form of ‘nuclear short hand’ to describe the reaction.

X (particles in , particles out) Y

We omit gamma rays from the reaction since they don’t affect the outcome.

Nuclear transmutations

The (in,out) pattern can be used with the chart to predict what could be formed. This does not tell you if it will actually occur.

Common bombardment patterns

(n,γ) (p,α) (γ,n)

(n,p) (γ,n) (p,γ)

Nuclear transformations

	α,3n	α,2n	α,n	
	p,n	p,γ d,n	α, np t,n	
	γ,n n,2n	original n,n	d,p n,γ	t,p
p,α	n,t	γ,p	n,p	
	n,α	n,pd		

This is a partial list of nuclear reactions.

Example

Starting with Mg-26, predict what will be formed by the following reactions.

$^{26}\text{Mg}(n, \gamma)$

$^{26}\text{Mg}(n, p)$

$^{26}\text{Mg}(p, \alpha)$

$^{26}\text{Mg}(\gamma, n)$

$^{26}\text{Mg}(\alpha, n)$

$^{26}\text{Mg}(p, g)$

Example

$^{26}\mathrm{Mg}$	(n, γ)	$^{27}\mathrm{Mg}$
$^{26}\mathrm{Mg}$	(n, p)	
$^{26}\mathrm{Mg}$	(p, α)	
$^{26}\mathrm{Mg}$	(γ, n)	
$^{26}\mathrm{Mg}$	(α, n)	
$^{26}\mathrm{Mg}$	(p, g)	

Example

$^{26}\mathrm{Mg}$	(n, γ)	$^{27}\mathrm{Mg}$
$^{26}\mathrm{Mg}$	(n, p)	$^{27}\mathrm{Al}$
$^{26}\mathrm{Mg}$	(p, α)	
$^{26}\mathrm{Mg}$	(γ, n)	
$^{26}\mathrm{Mg}$	(α, n)	
$^{26}\mathrm{Mg}$	(p, g)	

Example

^{26}Mg	(n, γ)	^{27}Mg
^{26}Mg	(n, p)	^{27}Al
^{26}Mg	(p, α)	^{23}Na
^{26}Mg	(γ, n)	
^{26}Mg	(α, n)	
^{26}Mg	(p, g)	

Example

^{26}Mg	(n, γ)	^{27}Mg
^{26}Mg	(n, p)	^{27}Al
^{26}Mg	(p, α)	^{23}Na
^{26}Mg	(γ, n)	^{25}Mg
^{26}Mg	(α, n)	
^{26}Mg	(p, g)	

Example

^{26}Mg	(n, γ)	^{27}Mg
^{26}Mg	(n, p)	^{27}Al
^{26}Mg	(p, α)	^{23}Na
^{26}Mg	(γ, n)	^{25}Mg
^{26}Mg	(α, n)	^{29}Si
^{26}Mg	(p, g)	

Example

$^{26}\mathrm{Mg}$	(n, γ)	$^{27}\mathrm{Mg}$
$^{26}\mathrm{Mg}$	(n, p)	$^{27}\mathrm{Al}$
$^{26}\mathrm{Mg}$	(p, α)	$^{23}\mathrm{Na}$
$^{26}\mathrm{Mg}$	(γ, n)	$^{25}\mathrm{Mg}$
$^{26}\mathrm{Mg}$	(α, n)	$^{29}\mathrm{Si}$
$^{26}\mathrm{Mg}$	(p, g)	$^{27}\mathrm{Al}$

Binding energy and the chart

When protons and neutrons combine, mass is lost to energy - Binding energy.

If the nucleus was not more stable than the separate nucleons it would not have formed (or stay formed)

The binding energy of a nucleus can be found based on:

$$E = mC^2$$

Binding energy and the chart

A more useful version of the equation is

$$\Delta E = \Delta m C^2$$

where:

ΔE = the binding energy

Δm = mass difference between the nucleus and the separate nucleons.

Since 1 amu = 931MeV

Binding energy $= \Delta m_{(amu)} \times 931$ MeV/amu

Example

Determine the binding energy of ^{16}O.

First, look up the masses of ^{16}O, p and n.

^{16}O	15.9949146 amu
n	1.00866497 amu
p	1.00782504 amu

Example

Next, determine the total mass for the separate protons and neutrons.

^{16}O - 8 protons and 8 neutrons

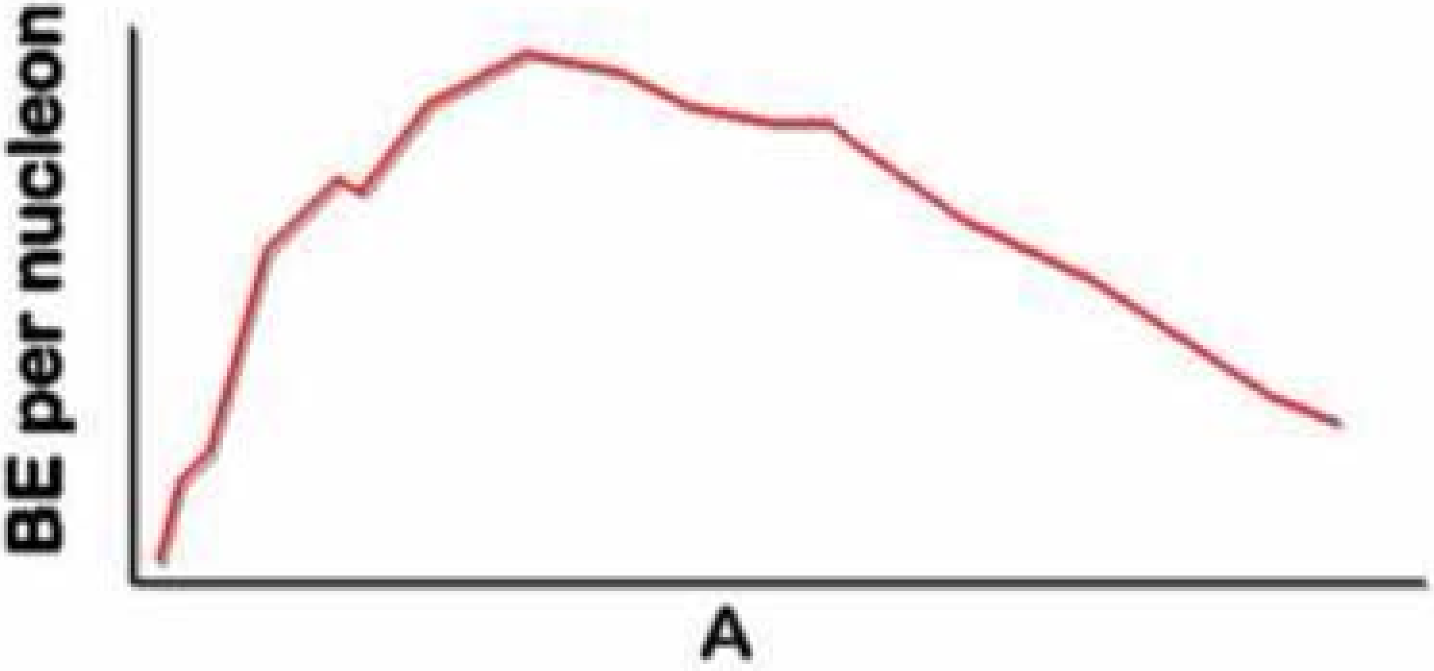
8 n   8 x 1.00866497 = 8.0693197

8 p   8 x 1.00782504 = 8.0620032

Total 16.13192008

Binding energy

We can calculate the binding energy for all of the stable isotopes and end up with the following plot.

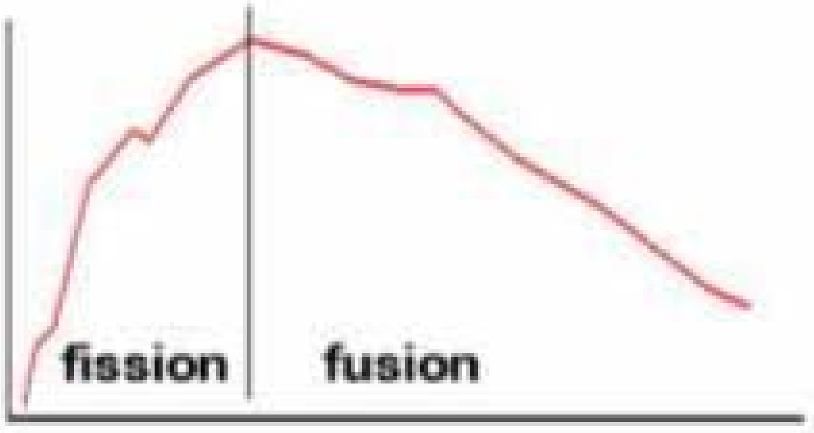


Binding energy

As the total number of nucleons increases, we reach a point where we reach a maximum.

Higher mass nucleons are less stable.

This is why we can obtain energy from both and fusion and why alpha emission is common for heavier isotopes.



Nuclear power

Power can be obtained two ways.

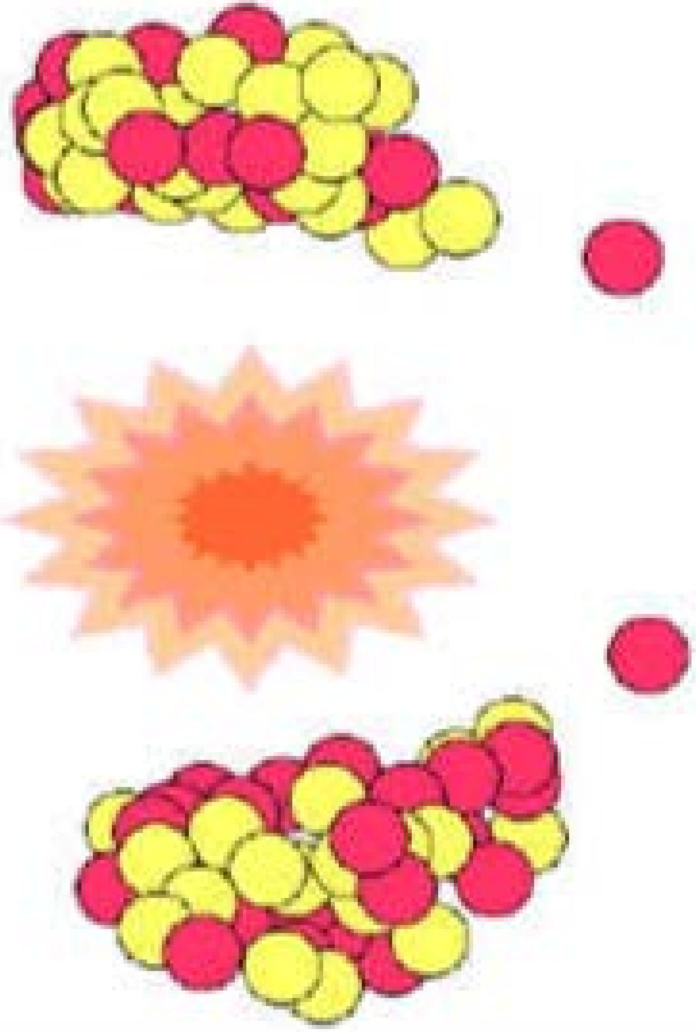
Fission Splitting atoms

- Get energy if the nucleus is big.
- The smaller ones are more stable.
- What we do in nuclear reactors.

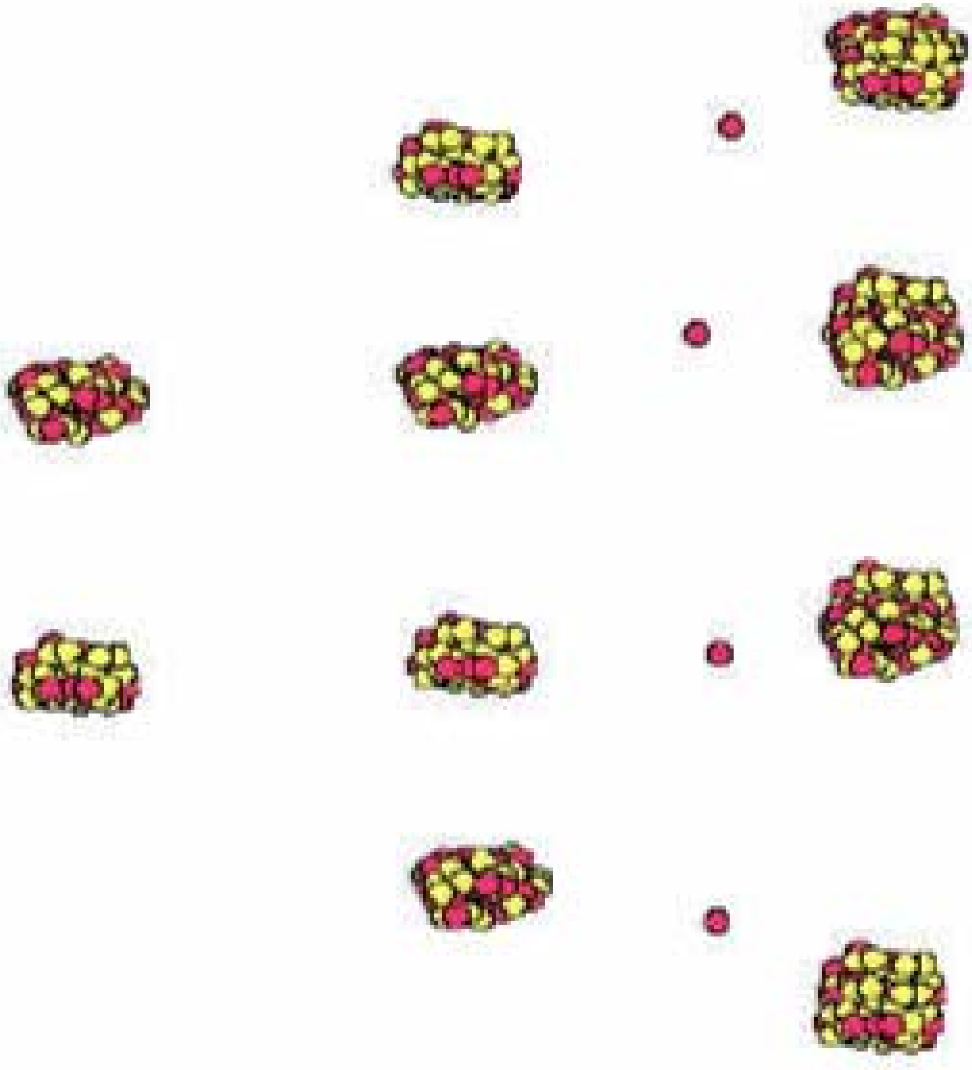
Fusion Joining atoms

- Get energy if the nuclei are small.
- The larger one is more stable.
- This is how the sun works.

Nuclear Fission



Chain reaction



Chain reactions

Critical Reaction

When just enough fissions occur to keep the chain reaction reaction going.

- nuclear power

Supercritical Reaction

When excess neutrons are produced and the rate of fission keeps increasing.

- nuclear bombs

Energy from fission

Uranium-235 is used as a ‘fuel’ in a reactor.

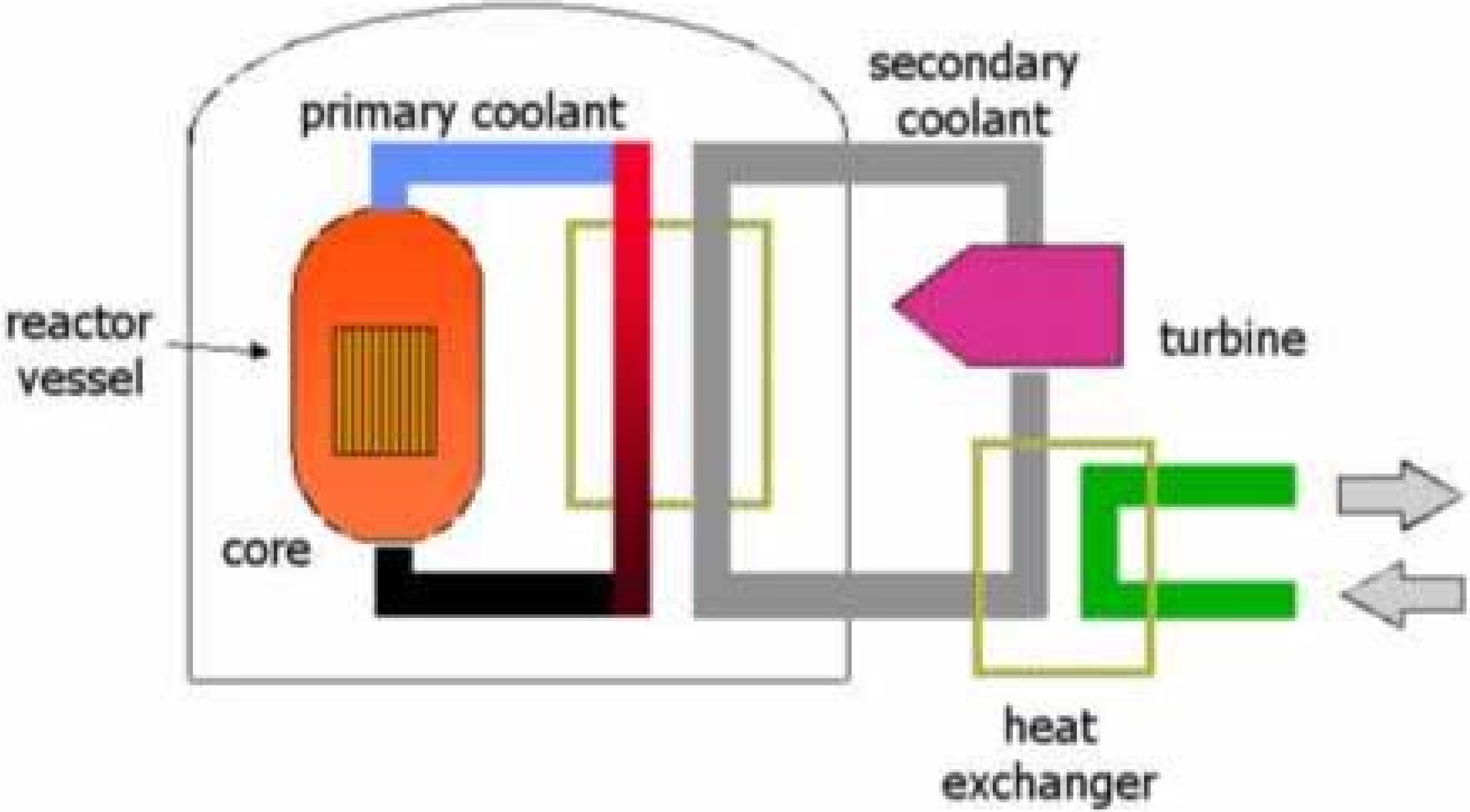
One common reaction is

$$^{1}n + {}^{235}U \longrightarrow {}^{92}Kr + {}^{141}Ba + 3\,{}^{1}n + \text{energy}$$

The energy produced by splitting one atom is approximately 200 million electron volts.

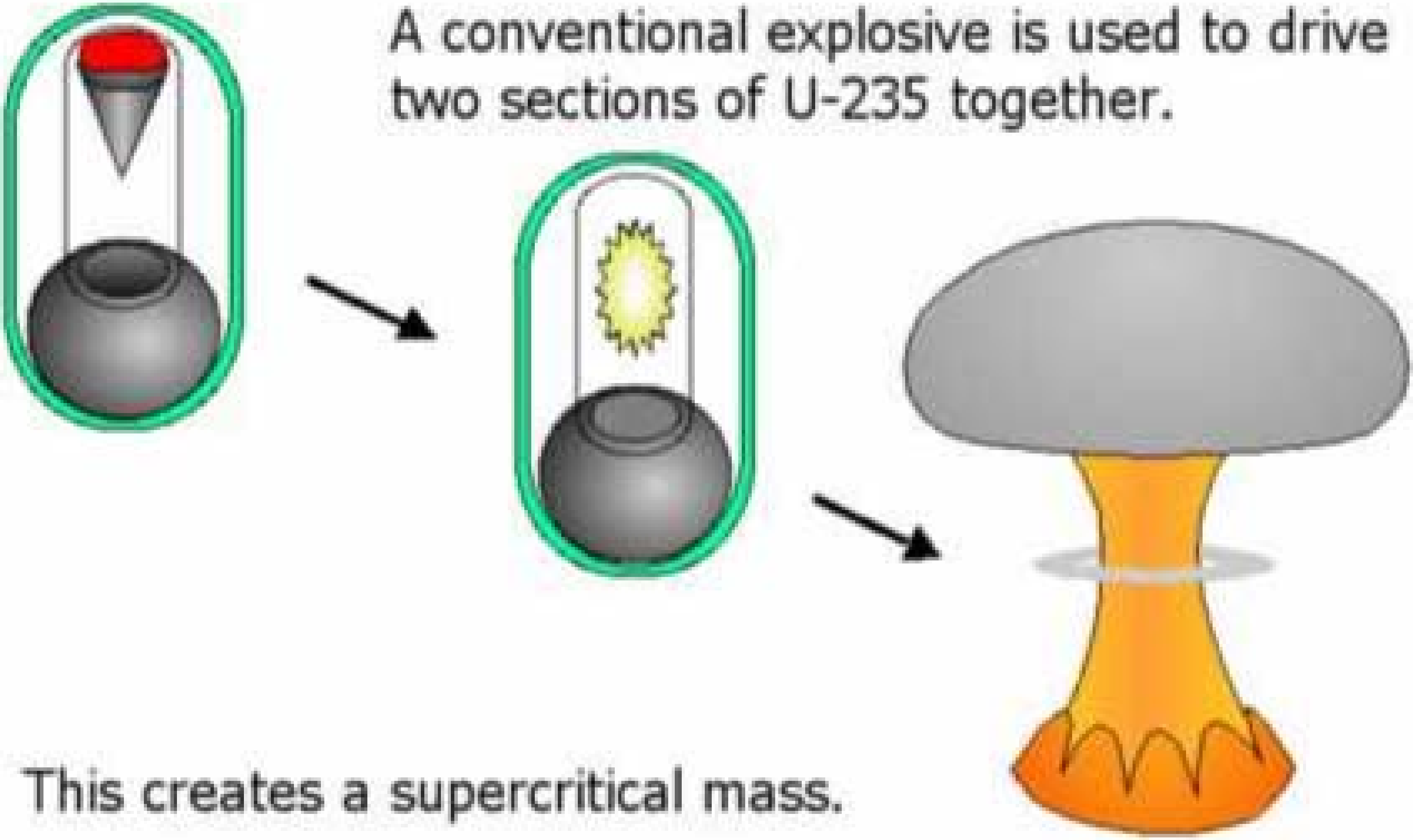
100 grams of ^{235}U could produce as much energy as 80 trillion tons of TNT.

Nuclear reactors



Nuclear bombs

A conventional explosive is used to drive two sections of U-235 together.



This creates a supercritical mass.