A brief introduction to Nuclear Physics

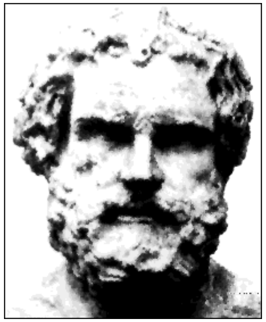
What is Nuclear Physics ?

Properties, Orders of Magnitude, Notations

Radioactive decays
- α-decay
- β-decay
- γ-decay
- Spontaneous fission

Fission / Fusion applications

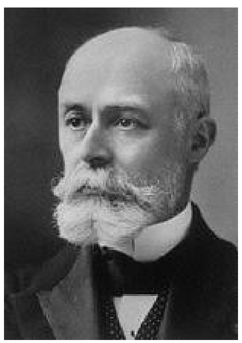
A bit of History…



~400 BC :
Greek Philosopher Democritus believed that each kind of matter could be subdivided into smaller and smaller bits until one reached the very limit beyond which no further division was possible.

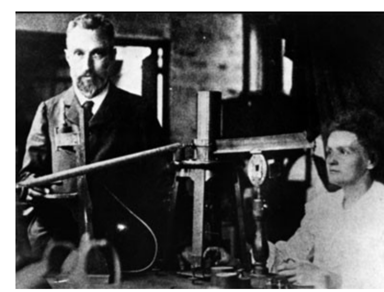
"atomos" = "that cannot be cut"

1895:
Discovery of X-rays by Wilhelm Röntgen



1896:
Discovery of the radioactivity in Uranium by Henri Becquerel

1898:
Isolation of Radium by Pierre et Marie Curie



➔ Around 1896: Birth of Nuclear Physics

The Becquerel Experiment (I)

1895: X-rays are interpreted as a chemical process similar to phosphorescence and fluorescence

→ An external source is required to “trigger” the emission of X-rays

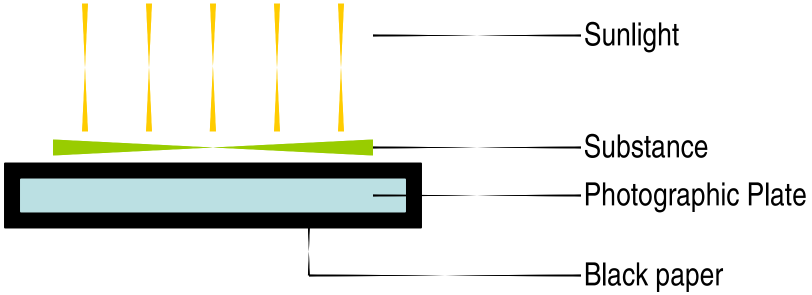
Henri Becquerel’s idea:

look for X-ray emission in known phosphorescent/fluorescent substances.

Experimental procedure:

wrap a photographic plate with thick black paper, place the substance to be tested on the paper and then expose to sunlight for several hours

→ Sunlight = external source



If X-rays were emitted, they would pass through the paper and fog the plate.

Tests are all negative, except for a Uranium Salt.

The Becquerel Experiment (II)

Reproducibility: an experimental result should be reproducible

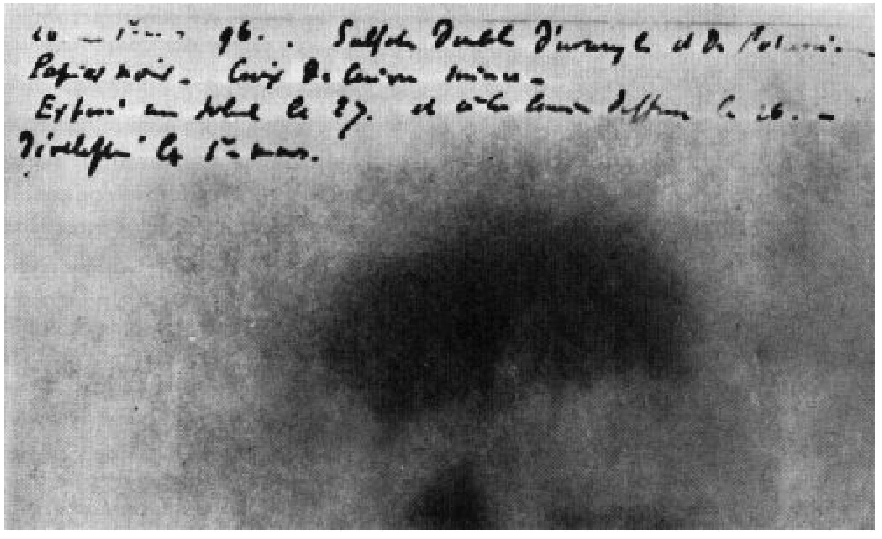
End of February, Henri Becquerel is ready to repeat the experiment.
But it is cloudy over Paris !!!

→ Put his experimental setup in a drawer till March 1st.

When Becquerel develops the plate (not exposed to sunlight), he finds that the fogging is just as intense as when the uranium salt had been exposed to sunlight.

→ No need for external energy source !!!

→ The energy is already available/stored in the material.



Search for other elements with similar properties

Pierre and Marie Curie:	Isolation of Radium and Polonium (1898)
Marie Curie:	PhD & Nobel Prize in Physics in 1903 !
	Nobel Prize in Chemistry (1911)

Radium is so active that it shines brightly in its pure form

Marie Curie about Radium:

"it's active and it radiates" → RADIOACTIVITY

She died of Leukemia at 67 (Exposure to radiations)

Radioactivity ?

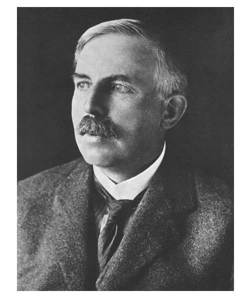
Emission of energy stored in the material by the mean of “mysterious” rays

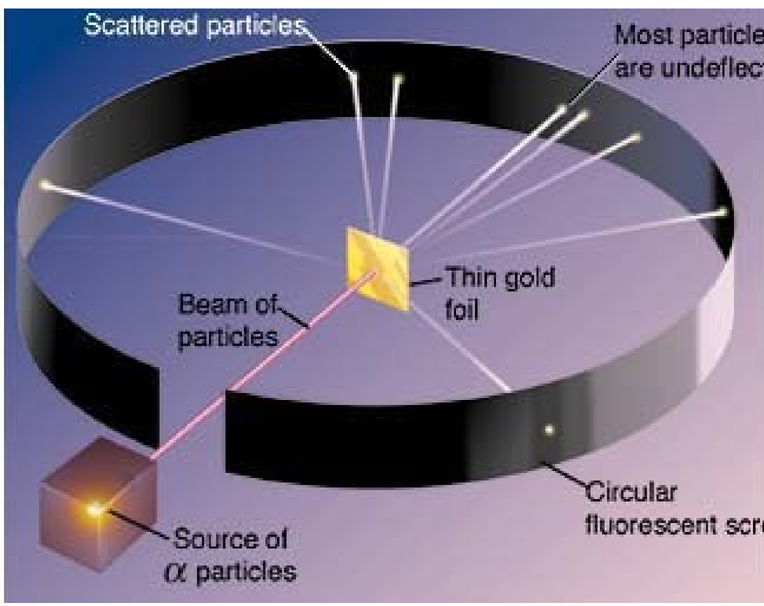
~1900: The structure of the atom is not yet known... But Chemistry is !

(Mendeleiv 1834 – 1907)

The radiation emitted by Radium is identified to be the element Helium

1911: Discovery of the atomic nucleus by Ernest Rutherford





<u>The first experiment with a beam of particles:</u>

The α-particles are most of the time not deflected, but sometimes they are scattered, even in the backward hemisphere.

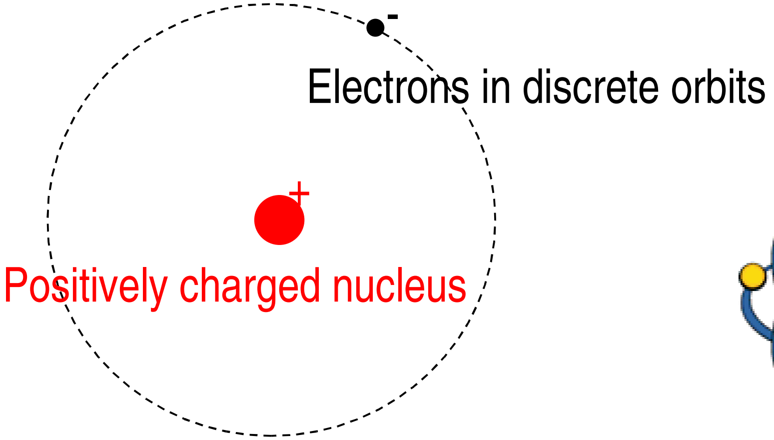
→ the foil is almost “transparent” to the α’s

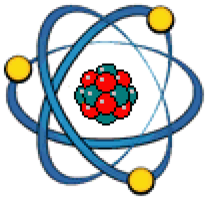
But when interaction occurs, it is on a heavy partner in the foil (the nucleus)

→ full analysis: size of the nucleus, mass, etc…

Nuclear Physics at last !

Niels Bohr: The model of the atom (1913)





α-radiation is positively charged and too energetic to be emitted by the electron cloud → α's are emitted from the atomic nucleus.

NUCLEAR PHYSICS

Rutherford (1919): transmutation of one element into another by α-radiation

α	+	N	→	O	+	p
Helium		Nitrogen		Oxygen		Hydrogen

→ The nucleus has to have exchangeable constituents

Elementary Constituents of the Nucleus

All the nuclei can be made with:

p	proton	positively charge (+q)
n	neutron	neutral (James Chadwick, 1932)

Z	number of protons in the nucleus
N	number of neutrons in the nucleus
A	atomic number = Z + N

The atoms are neutral:

Charge of the nucleus: + Z.q

Electron cloud is made of Z electrons of charge (–q)

The electrons determine the chemical behavior → Z defines the Element

Two nuclei with a same Z but different N (or A) are isotopes (of the same element)

Notations

$^{A}_{Z}X_{N}$

Ex: $^{1}_{1}H_{0}$ Hydrogen

$^{2}_{1}H_{1}$ Deuterium

Isotopes of the same element

Other examples:

$^{12}_{6}C_{6}$ Carbon

$^{235}_{92}U_{143}$ Uranium

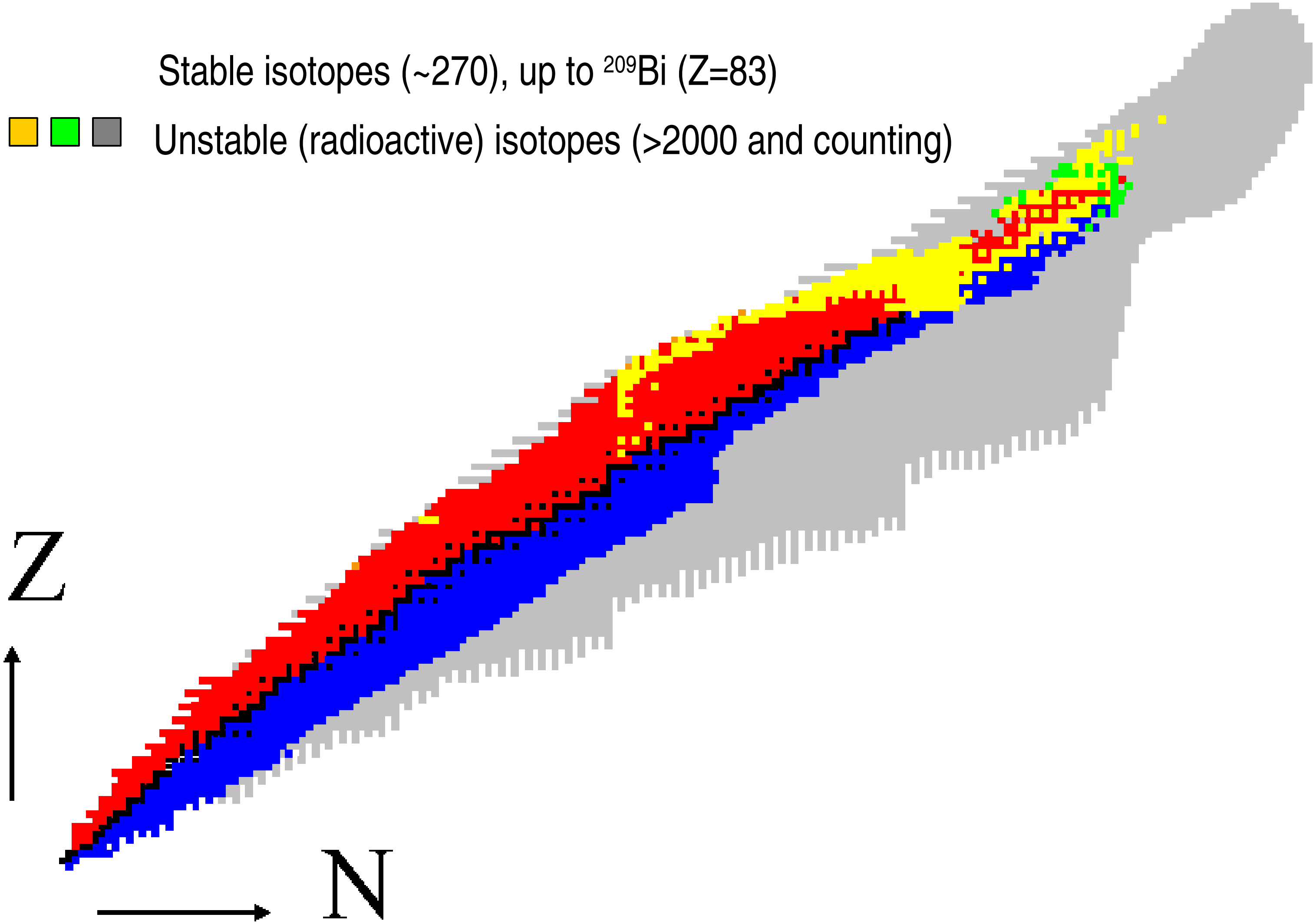
Simplified: ^{12}C ^{235}U

In practice, the Z number is redundant with the element symbol & the N number is obsolete

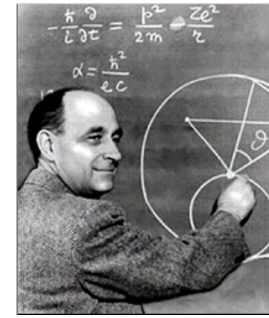
The chart of Nuclei

■ Stable isotopes (~270), up to ^{209}Bi (Z=83)

Unstable (radioactive) isotopes (>2000 and counting)



Units and Dimensions



Enrico Fermi

Size: the order of magnitude is 1fm = 10^{-15}m (a femtometer or fermi)
Radius (assuming nucleus = sphere): $R = R_0.A^{1/3}$ with R_0 = 1.2 fm

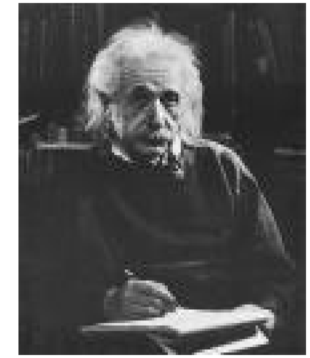
Nuclear Density: 10^{17} kg/m^3 → 100 million tons per cm^3 !!!
density found in the core of a neutron star
Nuclear matter is uncompressible (properties of the strong force)

Energy:
units: 1eV = 1.602 x 10^{-19} J → energy gained by a single unit of electronic charge when accelerated through a potential of one volt

Binding energy: mass of the constituents – mass of the product

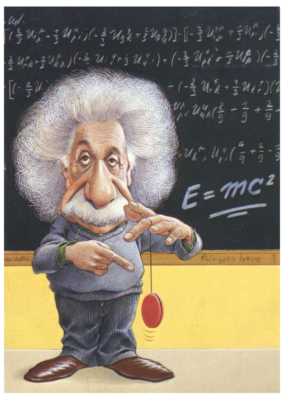
	Atom	Nucleus
Force	Coulomb	Strong
Binding Energy	The hydrogen atom: 13.6 eV	^{2}H: 2.2 x 10^6 eV → 2.2 MeV

How to calculate the binding energy ?



<u>The hydrogen atom:</u>

we win energy by bringing together the proton and the electron (13.6 eV)



Equivalence Energy ←→ Mass: $E = m.c^2$

Binding energy (B) = mass of the constituents – mass of the product

$= (m_p c^2 + m_e c^2) - m_H c^2$

$= 13.6$ eV

with: $m_p c^2$ = rest mass of the proton = 938.28 MeV

$m_e c^2$ = rest mass of the electron = 0.511 MeV = 511 keV

➔ the Hydrogen atom weighs less than its constituents

➔ One needs to provide 13.6 eV to take the hydrogen atom apart

Binding energy is also called Mass deficiency

Any atom (defined by Z): $B = m_{Nucleus} c^2 + Z.\, m_e c^2 - m_{Atom} c^2$

→ How do we calculate $m_{Nucleus} c^2$?

Binding energy of the nucleus

The nucleus:

^1H nucleus = free proton → Binding energy = 0 (but still has a rest mass)

^2H (deuterium) = one proton and one neutron

→ $B = (m_p c^2 + m_n c^2) - m_D c^2 = 2.2$ MeV

$^A_Z X$: $B = (Z.m_p c^2 + N.m_n c^2) - m_X c^2$

Example:

^{56}Fe (Z=26)

$m_{56Fe} = 55.934969$ u (or amu, atomic mass unit = 931.5 MeV/c^2)

with: $m_p = 1.007825$ u & $m_n = 1.008665$ u

$B(^{56}Fe)$ $= 26 \times 1.007825u.c^2 + 30 \times 1.008665u.c^2 - 55.934969u.c^2$

$= 0.528461u.c^2 = 492.3$ MeV

Very large number compared to B's in atomic physics

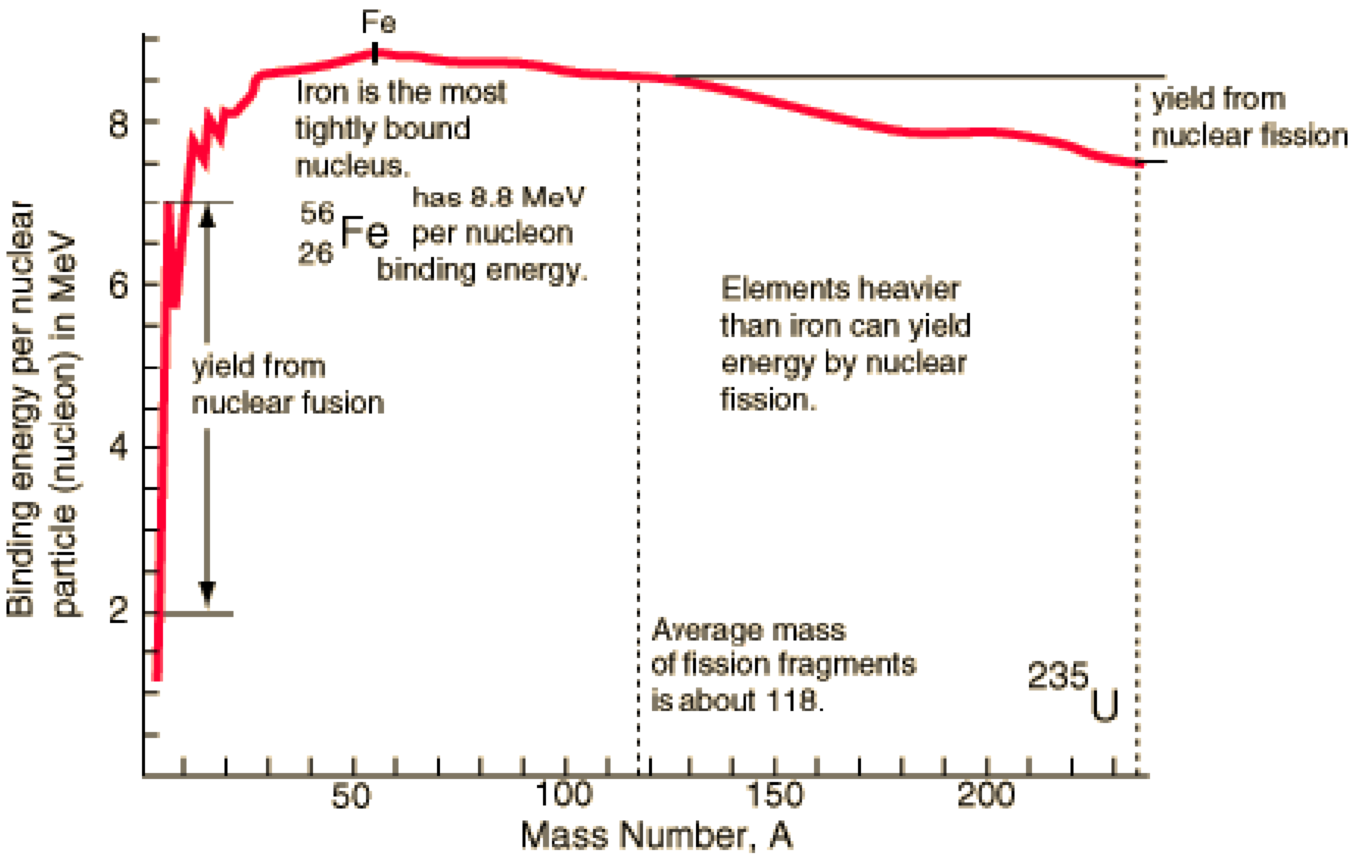
1g of ^{56}Fe broken into protons and neutrons per second would generate $8.5.10^{11}$ Watt !!!

→ 850 GWatt

Average Binding Energy

Average binding energy produced by the strong force can be expressed by dividing the total Binding Energy of the nucleus by its mass number (B/A)

B/A ~ 7-8 MeV is a typical value

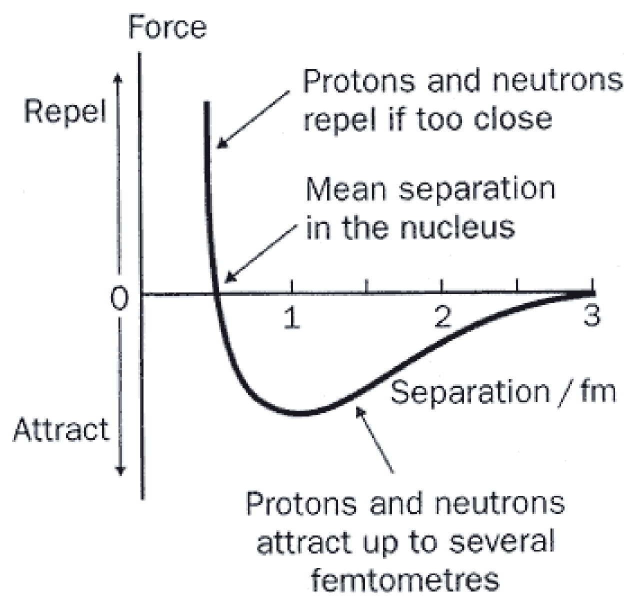


The Nuclear (Strong) Force

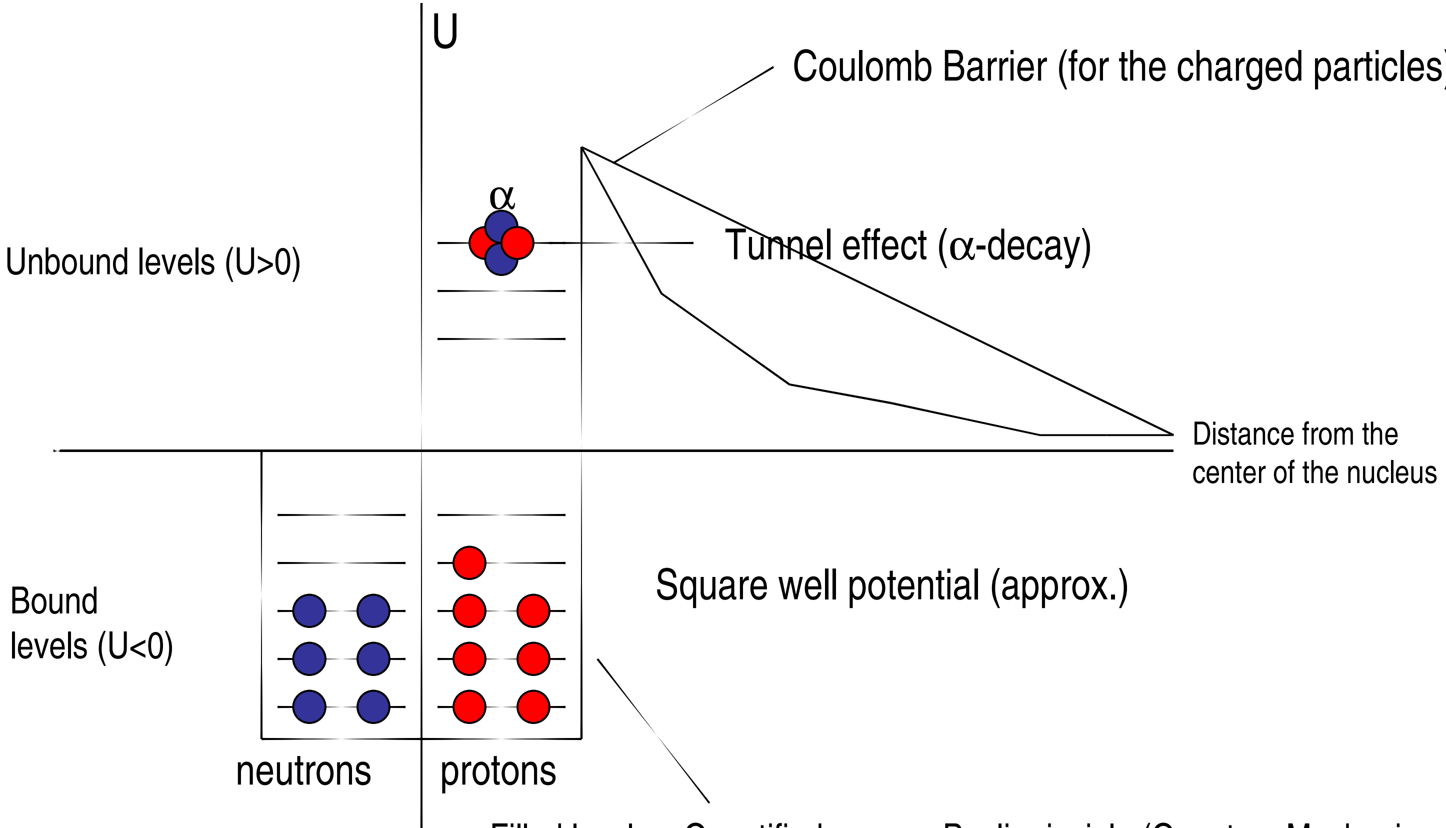
→ Short Range, only a few fm
  Nuclear Matter is uncompressible ; repulsive at very short range (< 1 fm)
  Attractive over a range of a few fm
    a given nucleon only interacts with its next neighbors in the nucleus

→ Negligible at long distances

→ Same force for protons and neutrons



A (simplified) model of the nucleus



Filled levels – Quantified energy, Pauli principle (Quantum Mechanics, Shell Model)

If all nucleons are in U<0, no nucleon can tunnel to the outside

→ Stable nucleus

If unbound levels are filled (U>0), tunneling is possible through the Coulomb barrier

→ Radioactive nucleus

Radioactive Decays

Radioactive (Unstable) nuclei decay if there is an energetically more favorable condition, which it is trying to reach

<u>Change into another element:</u> X → Y + decay particle(s)

- → α-decay: emission of He-nucleus from the unstable nucleus
- → β-decay: emission of electron or positron (antiparticle of the electron) from the unstable nucleus
- → Spontaneous fission: the radioactive nucleus breaks into so-called "fission fragments"

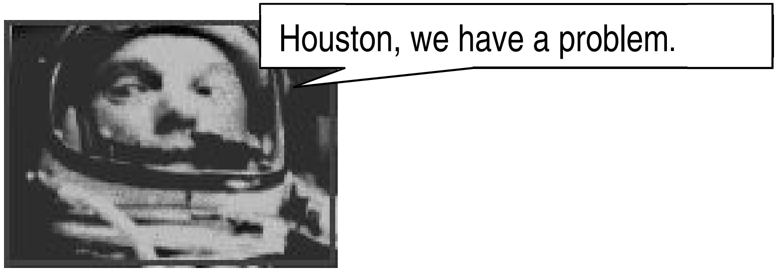
<u>An other decay mode (within the nucleus):</u> X* → X + γ's

- → γ-decay: De-excitation from one excited state to a bound state (…or a less excited one !)

How to describe radioactive decays ?

Radioactive decay represents changes of an individual nucleus.

HOWEVER: quantum mechanics prevents us from describing the decay of a single nucleus !!!



Because, usually one looks at the decay of a large number of nuclei (N>>1), one can describe radioactive decay statistically.

Decay is proceeding at a certain rate → Activity (A) [decays/s]

Units:

1 Becquerel = 1 Bq = 1 decay per second

1 Curie = 1 Ci = 3.7 x 10^{10} decays per second (old unit still widely used)

(activity of 1g of radium)

Formalism (I)

The activity of a certain sample (e.g. source) depends on the number N of radioactive nuclei and on the probability λ for each nucleus to decay:

$$A = \lambda \, . \, N$$

A: [1/s] λ: [1/s]

Evolution with time: $dN = -A.dt$

dN: number of nuclei that decayed during dt

→ $dN = -\lambda.N.dt$, which gives: $$dN/dt = -\lambda.N$$

Solving the differential equation:

➔ Radioactive decay law

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

N_0: N(t=0)

Formalism (II)

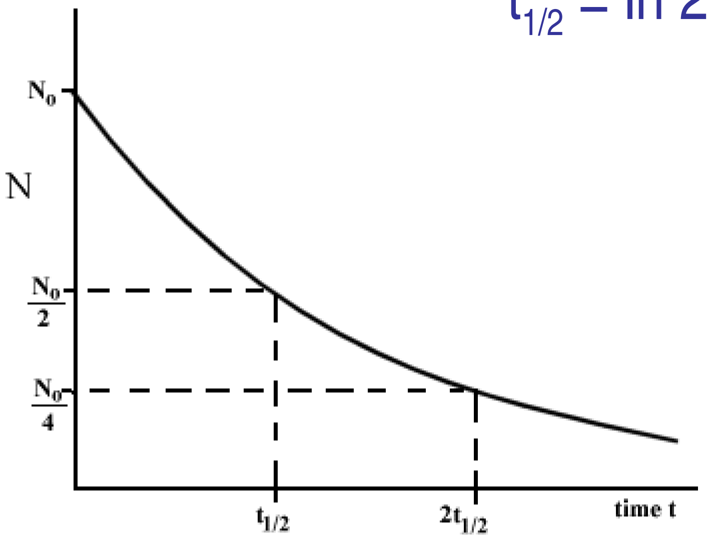
Similarly, we find that the activity of a source change with time:

$$A(t) = A_0.e^{-\lambda.t}$$

From λ = decay constant, one can define $\tau = 1/\lambda$, the mean lifetime

It is usual to define $t_{1/2}$, the half-life, the time after which half of the initial nuclei have decayed:

$$t_{1/2} = \ln 2 / \lambda = \tau \ln 2$$



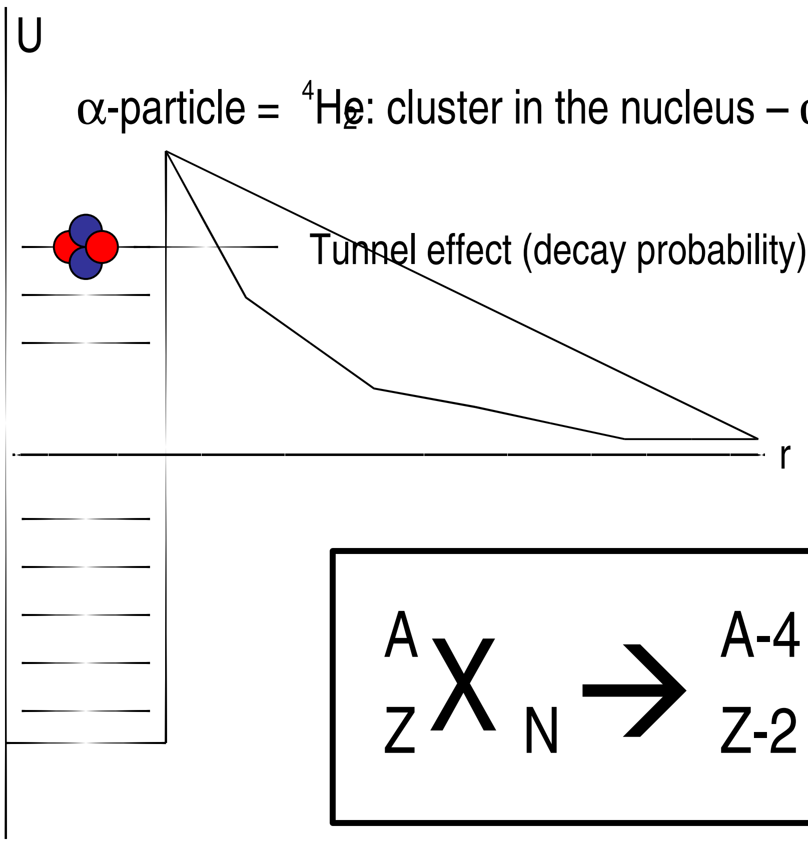
The half-life is characteristic to the decay of a given nucleus. This number (when known) is usually tabulated.

Conservation laws

- Conservation of Energy
- Conservation of linear momentum
- Conservation of angular momentum
- Conservation of electric charge
- Conservation of mass number A
  → e.g. total number of nucleons is conserved, but Z and N can change

α-decay

α-particle = $^{4}He_{2}$: cluster in the nucleus – α: very tightly bound system



$$^{A}_{Z}X_{N} \rightarrow {}^{A-4}_{Z-2}Y_{N-2} + {}^{4}_{2}He_{2} + Q$$

Q-value energy (Q>0, because the decay occurs spontaneously)

$\rightarrow Q = [m_X - m_Y - m_{He}].c^2$

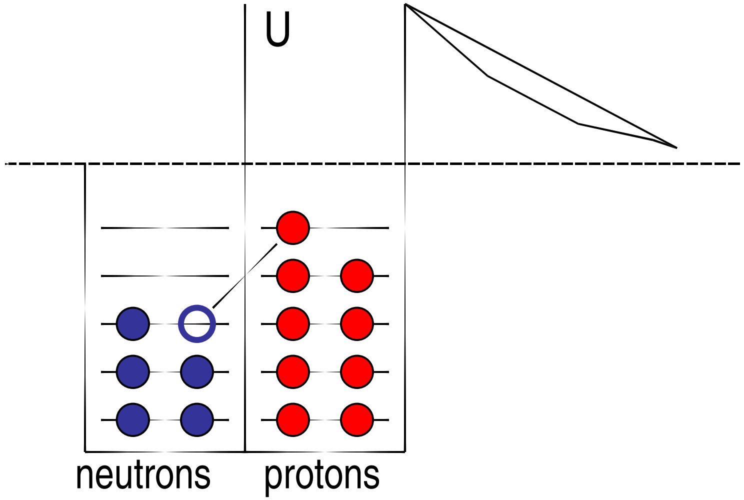
β-decay

Weak interaction can transform a proton into a neutron or a neutron into a proton
(It's actually happening at the quark level)

β^- decay: $n \rightarrow p + e^-$ e^-: electron
β^+ decay: $p \rightarrow n + e^+$ e^+: positron
Electronic Conversion: $p + e^- \rightarrow n$

Experimentally, the β-decay is not a 2-body process → existence of an elusive particle: the neutrino ν and its antiparticle $\bar{\nu}$

Example: β^+ decay
$p \rightarrow n$ leads to a
more stable configuration



β^- decay

Elementary process: $n \rightarrow p + e^- + \bar{\nu}$

Decay of the nucleus: ${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^- + \bar{\nu}$

β^+ decay

Elementary process: $p \rightarrow n + e^+ + \nu$

(only happening inside the nucleus)

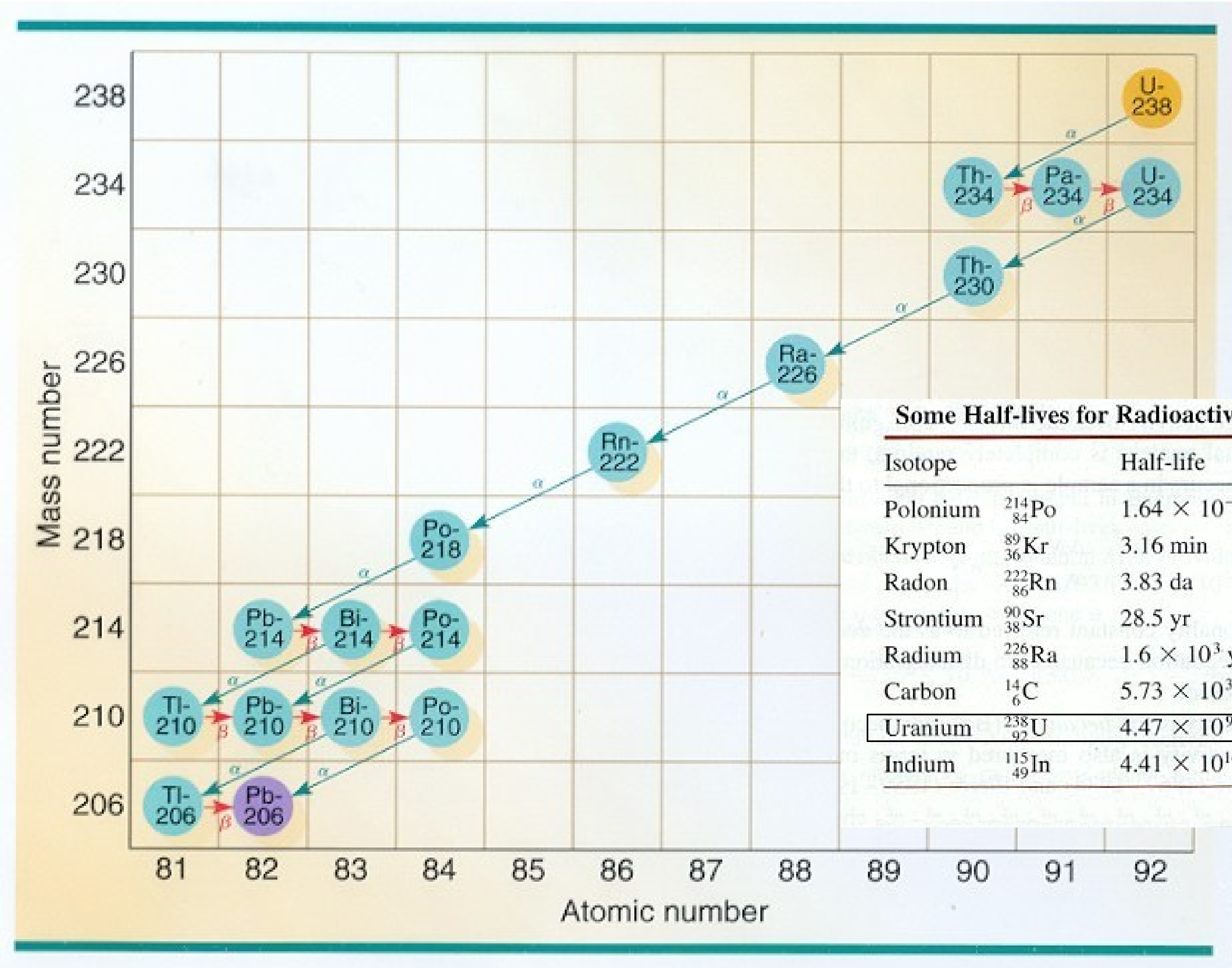
Decay of the nucleus: ${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z-1}Y_{N+1} + e^+ + \nu$

<u>Alternative process:</u> electron capture (from atomic orbit)

$$p + e^- \rightarrow n + \nu$$

$${}^{A}_{Z}X_{N} + e^- \rightarrow {}^{A}_{Z-1}Y_{N+1} + \nu$$

Example: the decay chain of ^{238}U

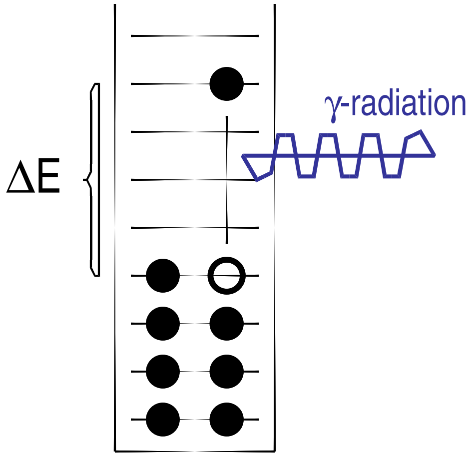


Some Half-lives for Radioactive Decay

Isotope		Half-life	Decay Mode
Polonium	$^{214}_{84}Po$	1.64×10^{-4} s	α, γ
Krypton	$^{89}_{36}Kr$	3.16 min	β^-, γ
Radon	$^{222}_{86}Rn$	3.83 da	α, γ
Strontium	$^{90}_{38}Sr$	28.5 yr	β^-
Radium	$^{226}_{88}Ra$	1.6×10^3 yr	α, γ
Carbon	$^{14}_{6}C$	5.73×10^3 yr	β^-
Uranium	$^{238}_{92}U$	4.47×10^9 yr	α, γ
Indium	$^{115}_{49}In$	4.41×10^{14} yr	β^-

γ-decay

When the nucleus has undergone a α- or β-decay, the daughter nucleus may be in an excited state, e.g. protons, neutrons (or a combination of them) are not on the lowest energy levels possible in the potential well.



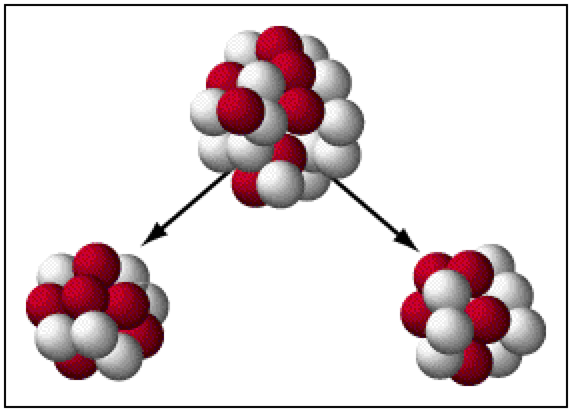
The energy difference ΔE is radiated away by one or more γ-rays (electromagnetic radiation):

$E\gamma$: few keV → few MeV

After β^+ decay, the positron (e^+) can annihilate with an electron (e^-), its antiparticle.
In this case, the energy of the γ-ray is well defined:

$$e^+ + e^- \rightarrow 2\,\gamma\,;\ (2 \times E_\gamma = 2 \times m_e c^2 = 2 \times 511\ \text{keV})$$

Spontaneous Fission



Some heavy isotopes can fission spontaneously into two so-called “fission fragments” (+ possibly some neutrons…)

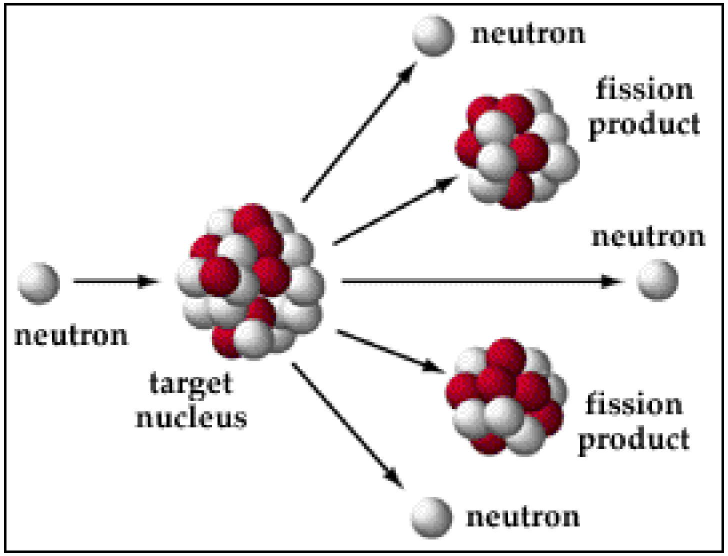
Ex: ^{256}Fm ($t_{1/2}$=2.6 h)

^{254}Cf ($t_{1/2}$=60.5 days)

The fission fragments are statistically distributed over a large range of medium-mass nuclei and are usually radioactive (and β-decay back to stability)

→ How fast depends of the half-lives of the isotopes formed on the way !

Induced Fission



Because the neutron has no charge, it can penetrate the nucleus (no Coulomb barrier)

→ Neutron used as a Probe.

1938-39: Induced fission of ^{238}U

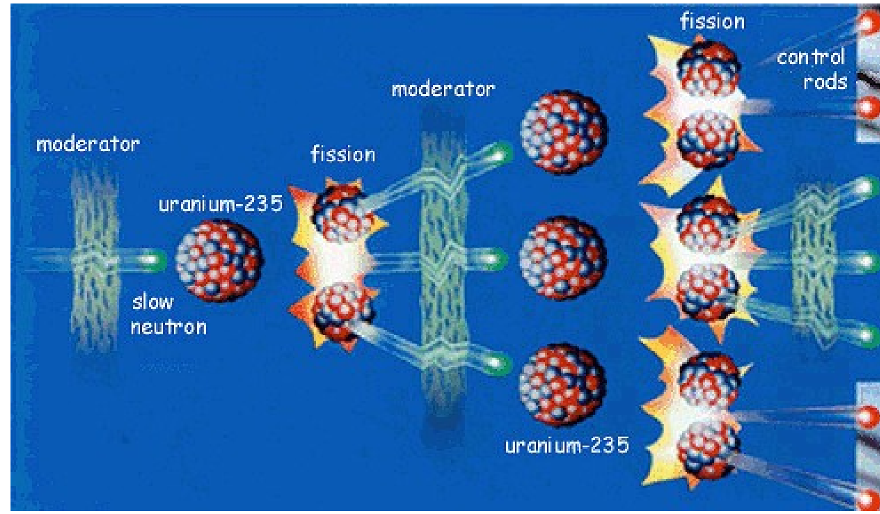
→ large release of energy (~200 MeV)

→ new neutrons are emitted !!!

→ CHAIN REACTION POSSIBLE ?

Leo Szilard

Applications of induced fission



Controlled:

Nuclear Power Plant

Waste: long-lived fission fragments
(ex: ^{90}Sr, ^{137}Cs…)

Uncontrolled:

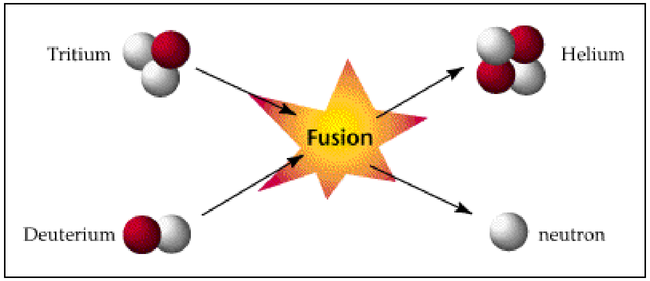
Atomic Bomb (A-bomb)
Hiroshima:
Energy released 10^{14} Joules = 20 kilotons of TNT

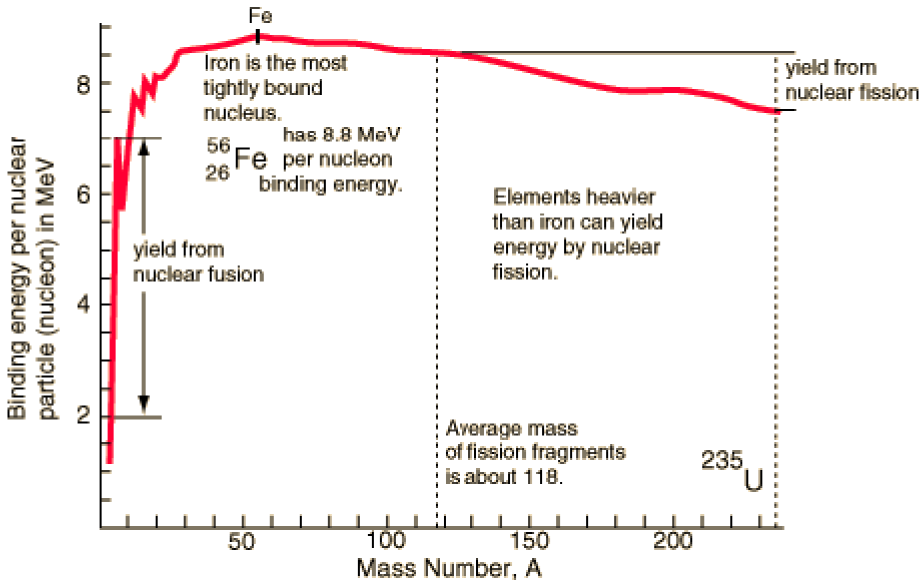
Nasty stuff (after blast): fission fragments !

Reading: “The making of the Atomic Bomb” (Richard Rhodes)

Fusion

Example:



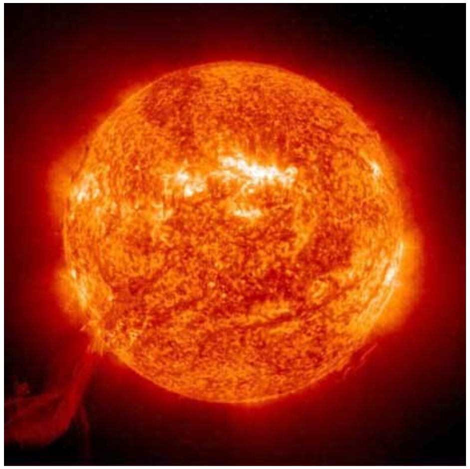


Fusion releases more energy per nucleon than fission. However, this process doesn't occur spontaneously. One needs to ignite the reaction, then the energy produced has to self-sustain the fusion process.

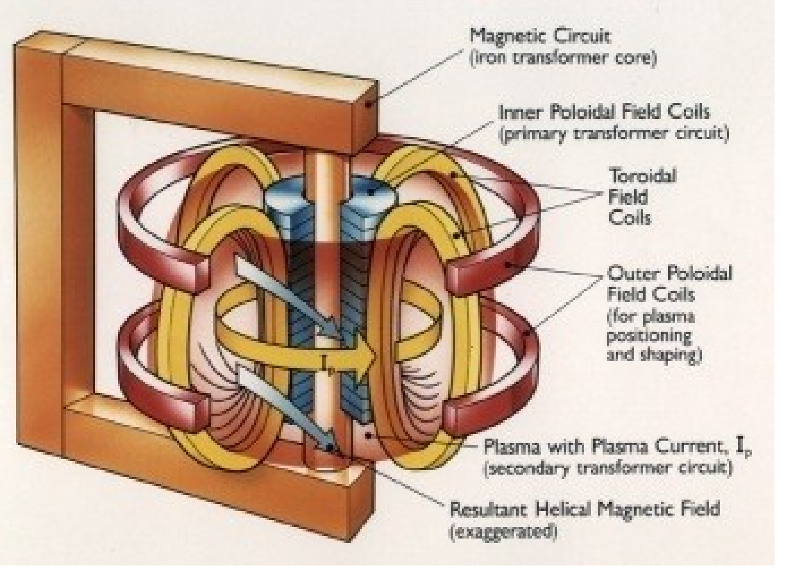
That's what is happening in the Sun !

$4\ {}^{1}H \rightarrow$ (several steps) $\rightarrow {}^{4}He$, Q=26.7 MeV

(then: $3\ {}^{4}He \rightarrow {}^{12}C$, etc…)



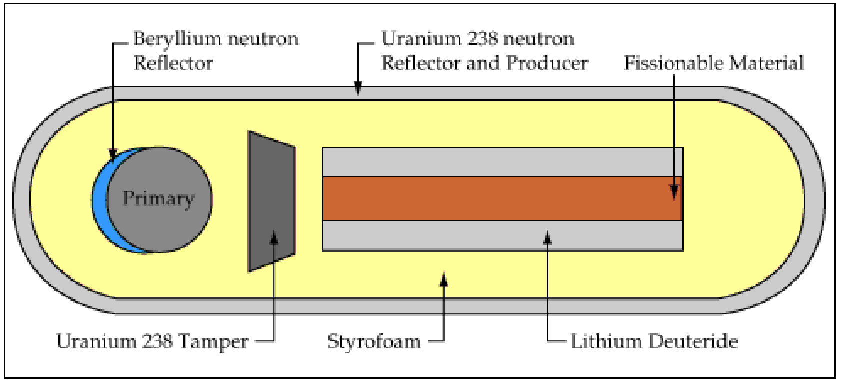
Applications to induced fusion



<u>Controlled:</u>

Nuclear Fusion Power Plant
(projects: tokamaks, laser…)
New initiative: ITER project

Problem: Ignition !



<u>Uncontrolled:</u>

Hydrogen Bomb (H-bomb)
requires an A-bomb to ignite fusion !!!

Enhanced yield:
Hundreds of kilotons → Tens of Megatons !
(Hiroshima, 20 kt)

Reading: "Dark Sun" (Richard Rhodes)

Many more applications

- Archeology: ^{14}C ($t_{1/2}$ ~ 5730 years)

- Medicine: X-rays, radioactive tracers (ex: ^{99m}Tc,…) + imagery, radiotherapy

- Engineering: γ-radiography of material, neutron activation, thickness control…

- Other applications: Smoke detector, Sterilization, …

<u>Example:</u> CAT scan ("Computed Axial Tomography")

→ X-Ray 3D-Imaging

NO !

YES !