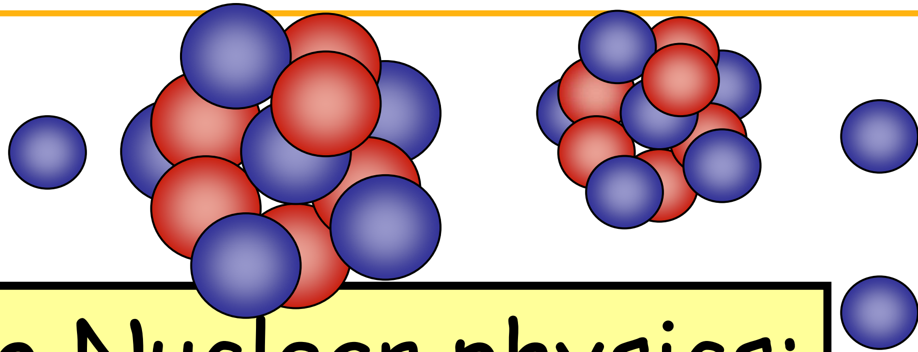
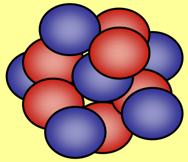


Introduction to Nuclear physics;



The nucleus a complex system

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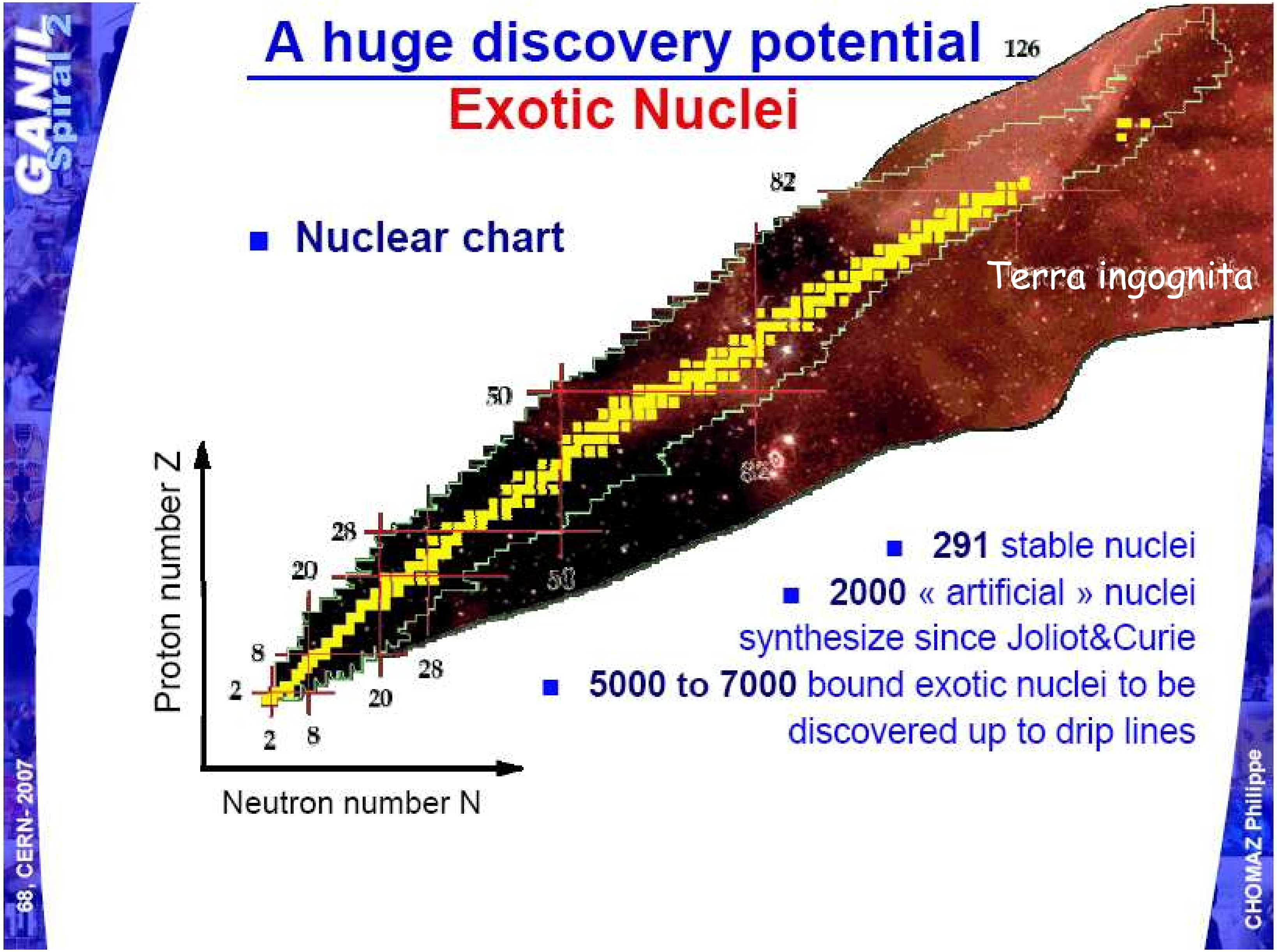
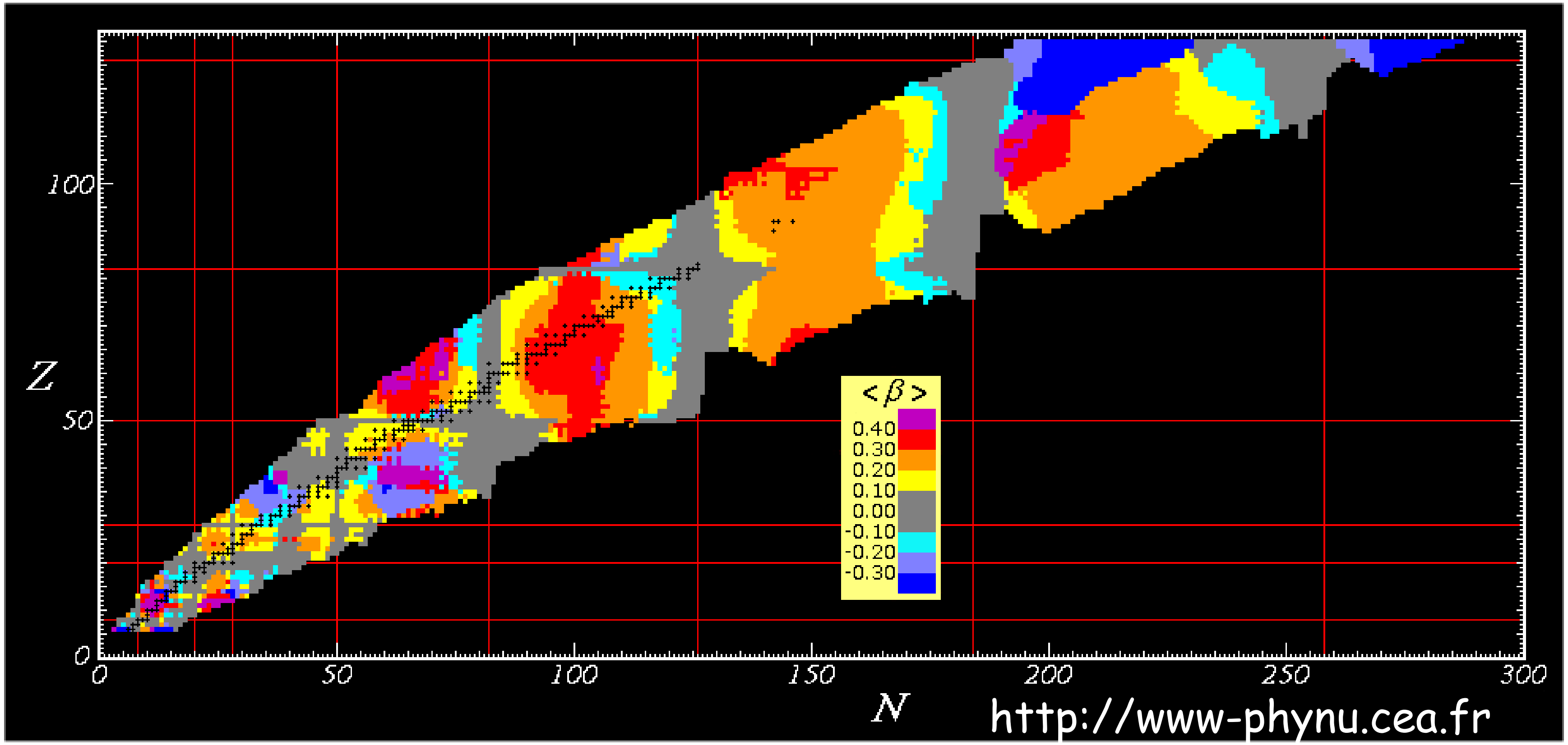
CEA, DAM, DIF

Heloise.goutte@cea.fr

- What is the heaviest nucleus ?
- How many nuclei do exist ?
- What are the shapes of the nuclei ?

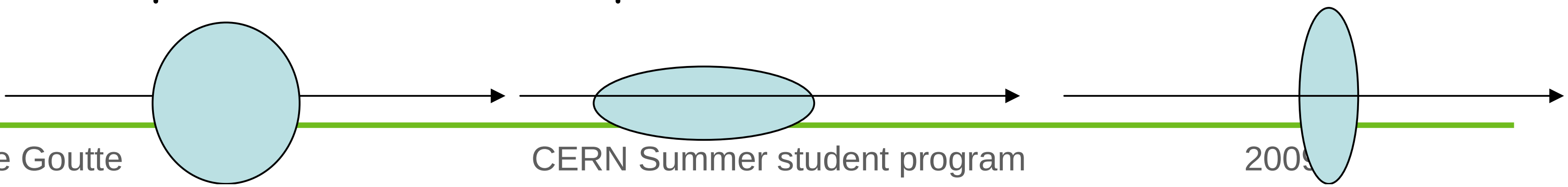

A huge discovery potential
Exotic Nuclei
Nuclear chart
Terra ingognita
126
82
50
28
20
8
2
291 stable nuclei
2000 « artificial » nuclei synthesize since Joliot&Curie
5000 to 7000 bound exotic nuclei to be discovered up to drip lines
Proton number Z
Neutron number N
GANIL Spiral 2
68, CERN- 2007
CHOMAZ Philippe

Ground -state nuclear deformation predicted with the Hartree-Fock-Bogoliubov approach with the Gogny force



Nuclei are predicted to be either:

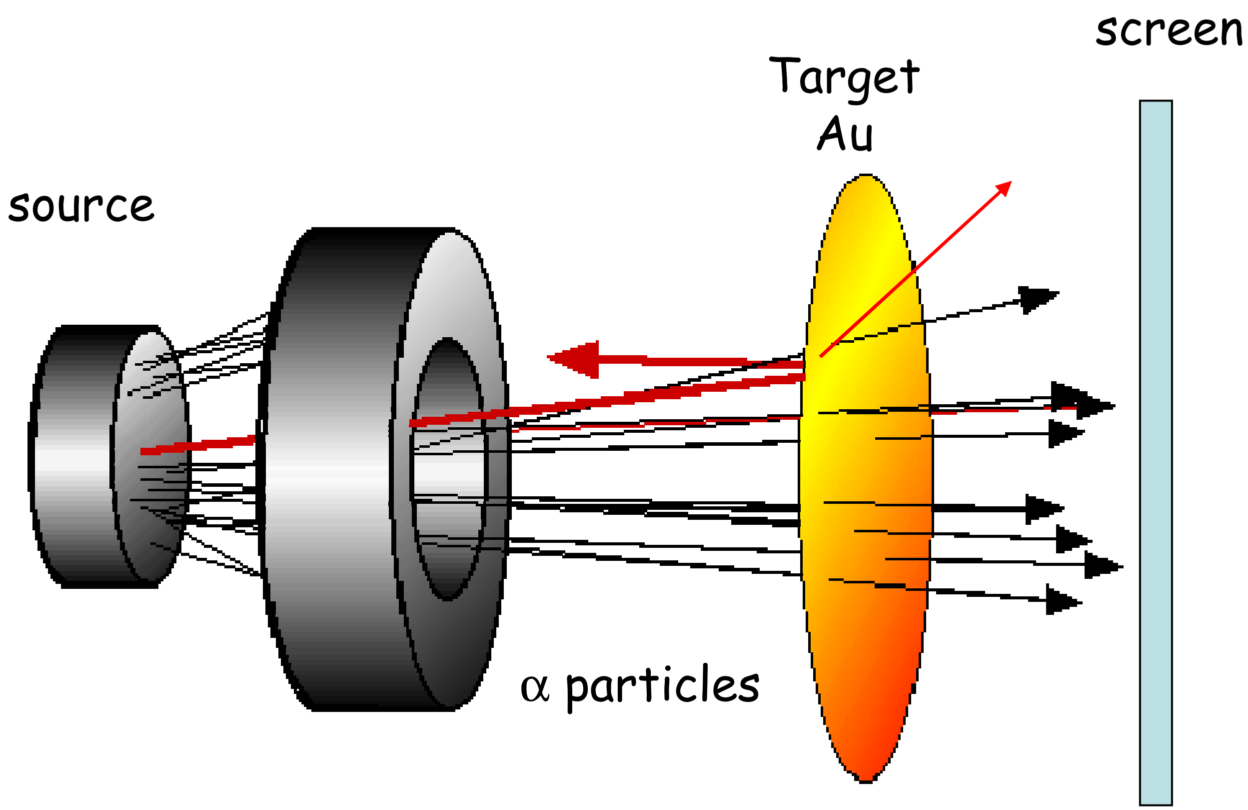
spherical prolate or oblate



I) Some features of the nucleus

The discovery of the nucleus

The structure of the atom was first probed by the Rutherford experiment in 1909. A beam of α particles generated by the radioactive decay of radium was directed onto a sheet of a very thin gold foil.



The unexpected results demonstrated the existence of the atomic nuclei.

The nucleus : a complex system

I) Some features about the nucleus

- discovery
- radius
- binding energy
- nucleon-nucleon interaction
- life time
- applications

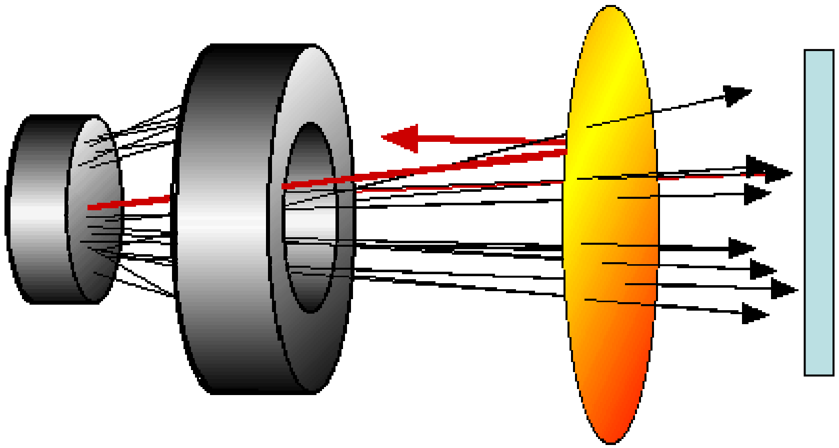
II) Modeling of the nucleus

- liquid drop
- shell model
- mean field

III) Examples of recent studies

- exotic nuclei
- isomers
- shape coexistence
- super heavy

IV) Toward a microscopic description of the fission process

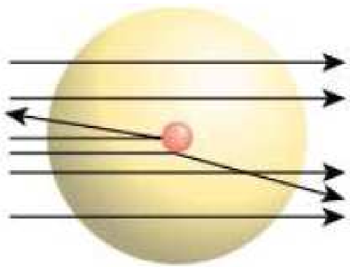


Before this exp. people thought that α particles should all be deflected by at most a few degrees.

But some α 's were deflected through angles much larger than 90 degrees !!

→The results suggest that the greater part of the mass of the atom was concentrated into a very small region.

→Atoms are almost empty except a hard scattering center: the atomic nuclei



Some questions about the Rutherford experiment

- Why a thin target ?
- What about electrons ?
- Why in the vacuum ?
- How can we determine the size of the atomic nucleus from this experiment ?

Some tracks about the Rutherford experiment

- Why a thin target ?

To be sure that the projectile do interact with only one nucleus

- What about electrons ?

Electrons do not affect the trajectory of the projectile which is much heavier

- Why in the vacuum ?

In the air, the slowing down of the beam and of the scattered α make the analysis more complicated and can even stop the particles before detection.

- How can we determine the size of the atomic nucleus from this experiment ?

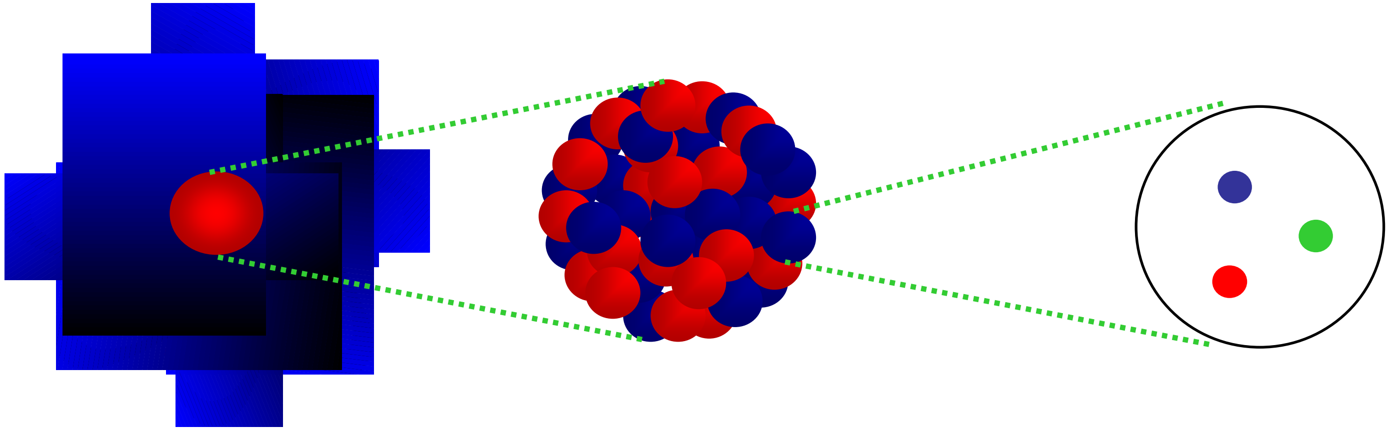
At the distance « a_0 » from the center of the nucleus, when the α particle go back :
Coulomb repulsion = kinetic energy of the α particle

$$\frac{1}{2}mv^2 = \frac{1}{4\pi\epsilon_0} \cdot \frac{q_1 q_2}{a_0}$$

The size of the gold nucleus is 2.8 10^{-14} m

The scale of a nucleus

A nucleus is almost 100000 times smaller than an atom



ATOM (10^{-9} m)

NUCLEUS (10^{-14} m)

NUCLEON (10^{-15} m)

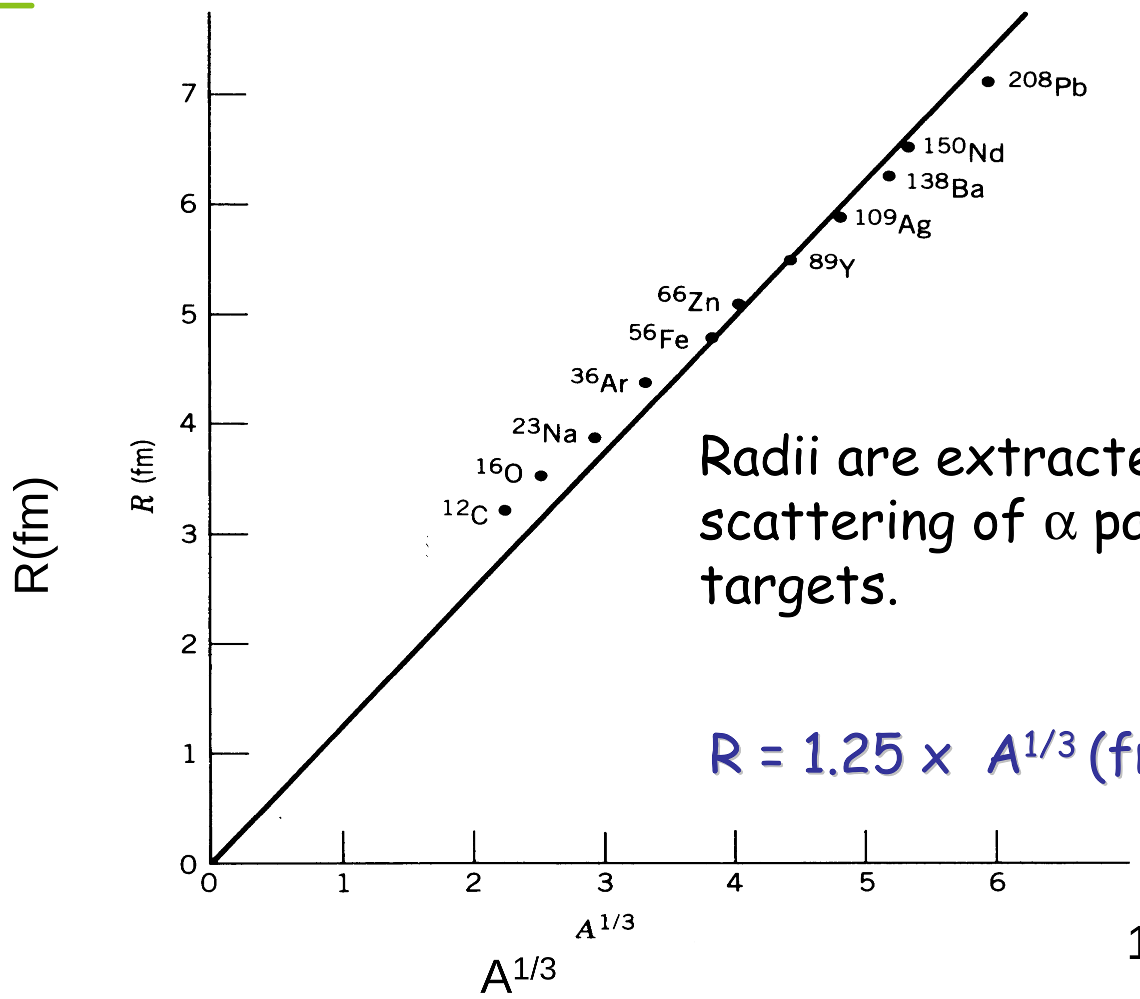
A nucleus is made of Z protons and N neutrons (the nucleons).

A nucleus is characterized by its mass number $A = N + Z$
and its atomic number Z.

It is written ^{A}X.

Do all the nuclei have the same radius ?

Nuclear radius



Radii are extracted from elastic scattering of α particles on different targets.

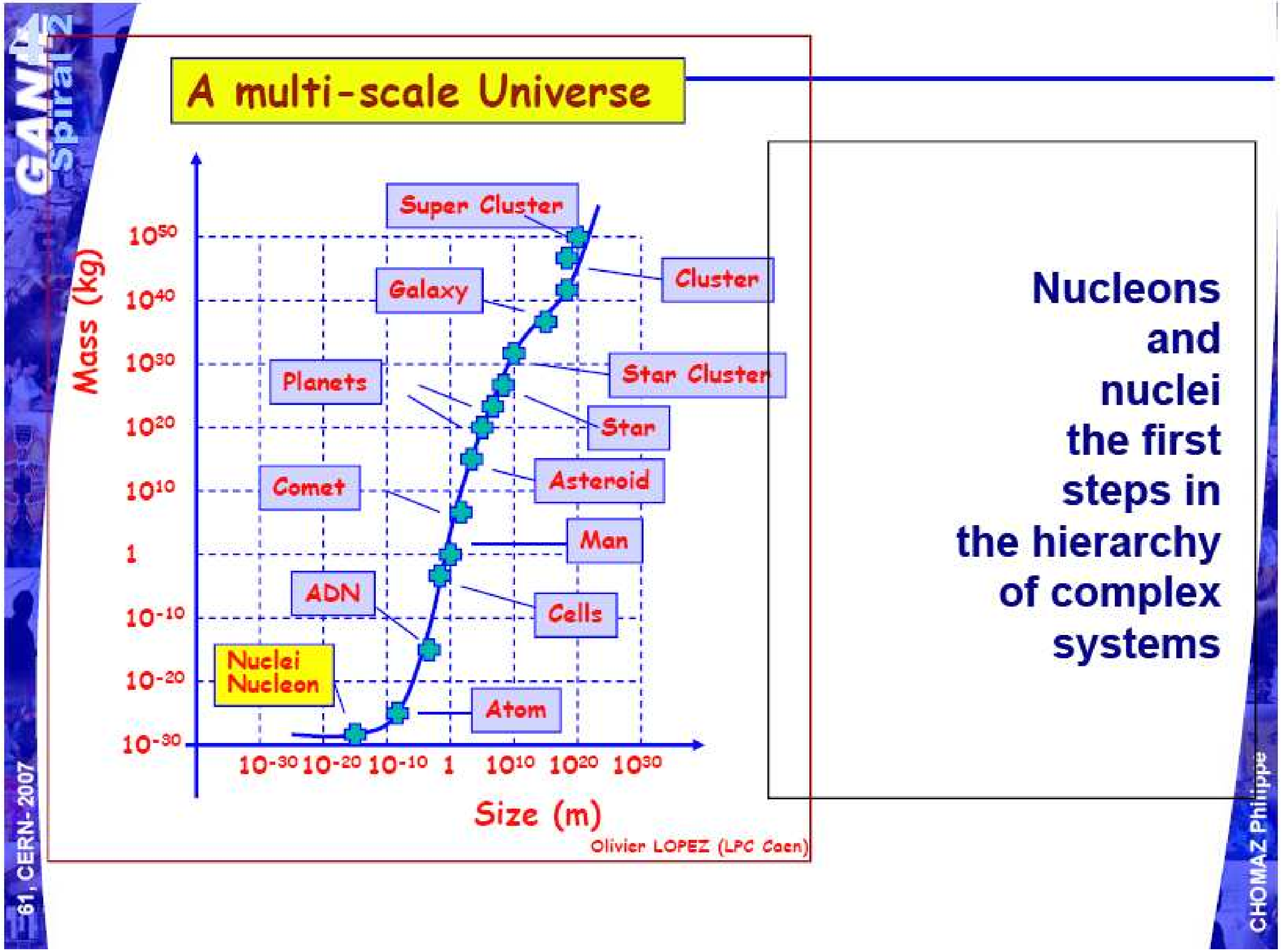
$$R = 1.25 \times A^{1/3} \text{ (fm)}$$

$1\text{fm} = 10^{-15}$ m

The radius increases with $A^{1/3}$

→ The volume increases with the number of particles

From infinitely small to infinitely large



Nuclear masses

Proton and neutrons are:

hadron particles (particles governed by the strong interaction)

They are baryons (made of 3 quarks)

Proton	uud	(charge +e)
Neutron	udd	(charge 0)

Proton and neutron have almost the same mass

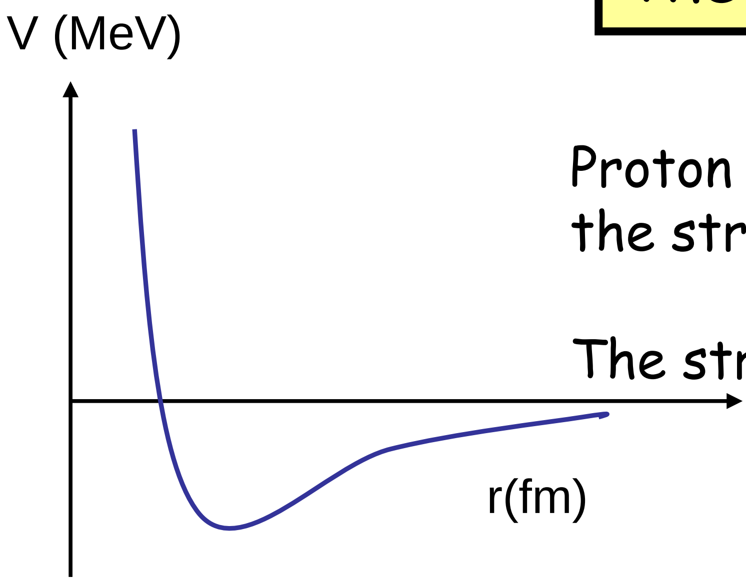
$M_p c^2 = 938.272$ MeV
$M_n c^2 = 939.565$ MeV

2000 times the mass of the e^- :

$M_e c^2 = 0.511$ MeV

1 MeV = 10^6 eV
$M_p = 1.7\ 10^{-27}$ kg

The nucleon-nucleon interaction



Proton and neutron interact through the strong interaction.

The strong interaction is
very intense
of short range

The nuclear interaction is stabilizing the nucleus

Proton –neutron interaction : Vpn > Vnn
Vpp ≅Vnn

PLUS

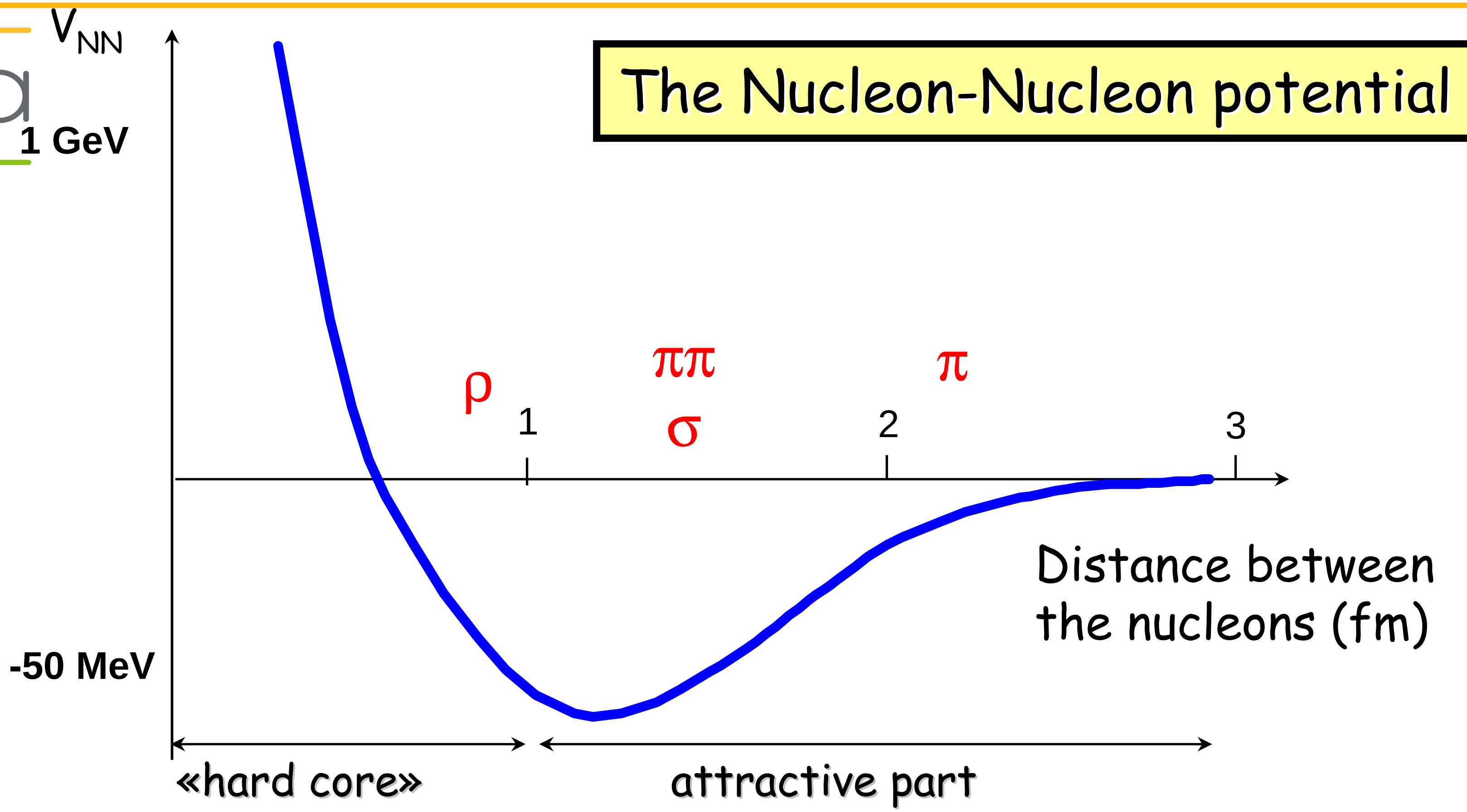
Coulomb interaction between protons (repulsive)

What about gravitation in a nucleus ?

The four elementary interactions

Name	Intensity	bosons	range
strong	1	Gluons	1 fm $=10^{-15}$m
Electro magnetic	10^{-2}	Photons	infinity
faible	10^{-5}, 10^{-6}	Leptons	contact
gravitation	10^{-34}	Gravitons ?	long

The Nucleon-Nucleon potential



There is no derivation of the nucleon-nucleon interaction from the first principles of the Quanta Chromo Dynamics theory.

Phenomenological parameterization of the interaction ;

THIS IS ONE OF THE MOST IMPORTANT PROBLEM NOWADAYS

Binding energy

A stable nucleus is a bound system
i.e. its mass is lower than the mass of its components.

(if not the nucleus would release its excess of energy by spontaneously evolving to a state of lower energy composed of free particles)

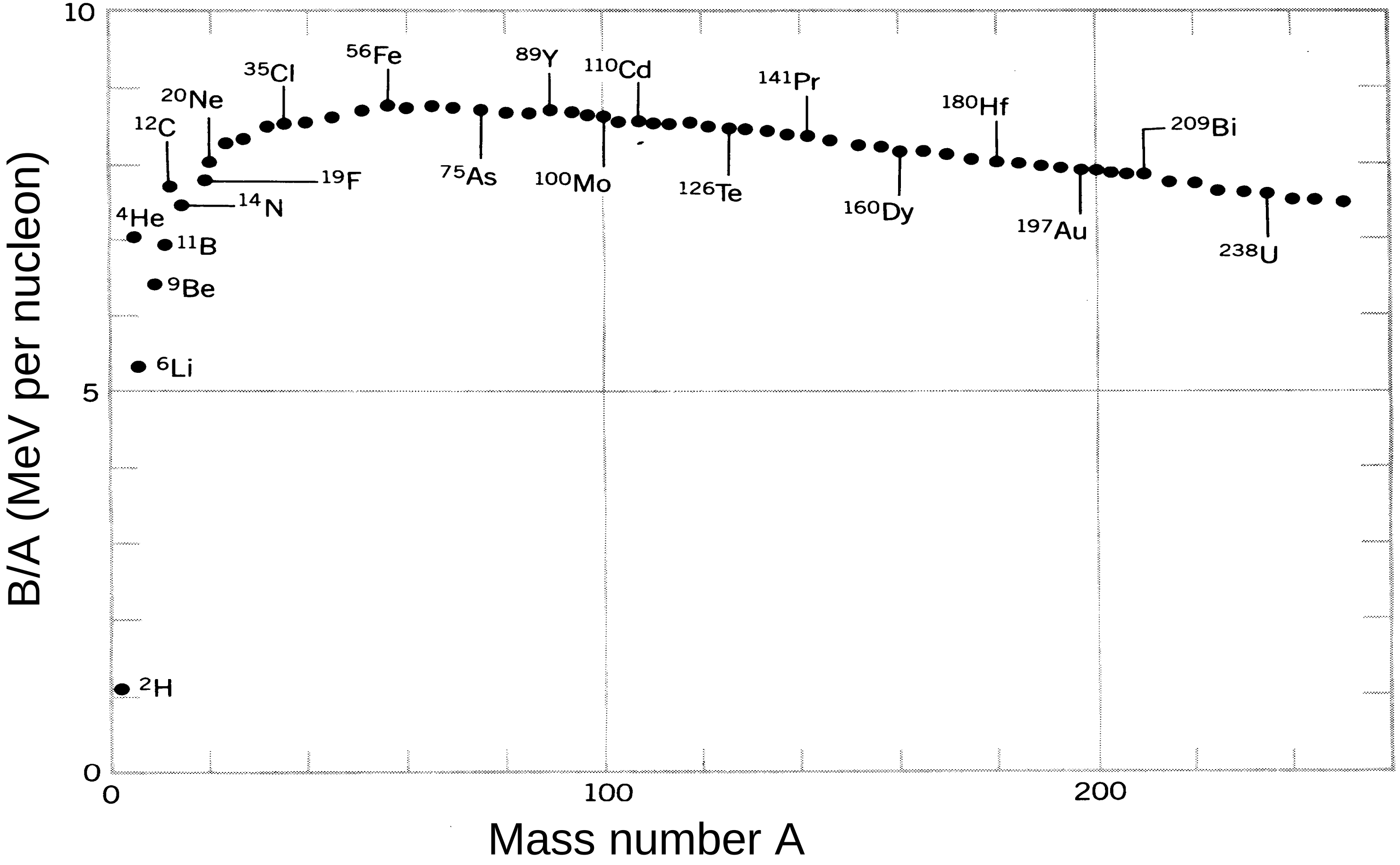
Mass of a given nucleus : $\mathbf{M(A,Z) = N\,M_n + Z\,M_p - B(A,Z)}$

B(A,Z) : binding energy

Stable bound system for B > 0

Binding energy per nucleon: $B(A,Z)/A \approx 8$ MeV

Binding energy per nucleon



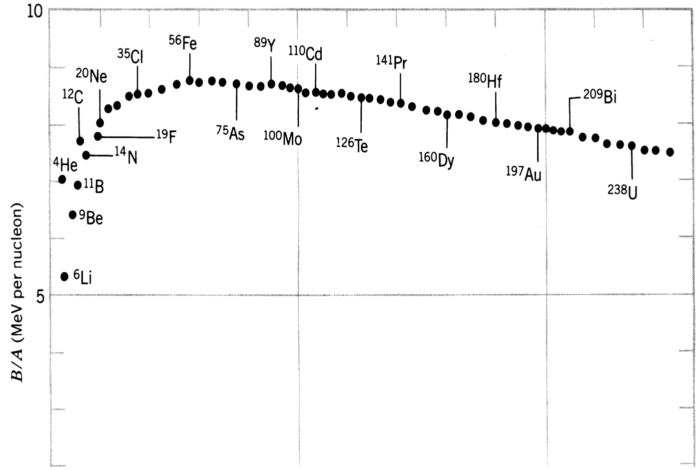
Which nuclei could fission spontaneously ?

FISSION A $\longrightarrow$ B + C + ΔE

$(M_p = M_n = M_N)$

Energy balance : $A\,M_N - B_A = B\,M_N - B_B + C\,M_N - B_C + \Delta E$

Energy difference : $\Delta E = B_B + B_C - B_A$



FUSION A + B $\longrightarrow$ C + ΔE

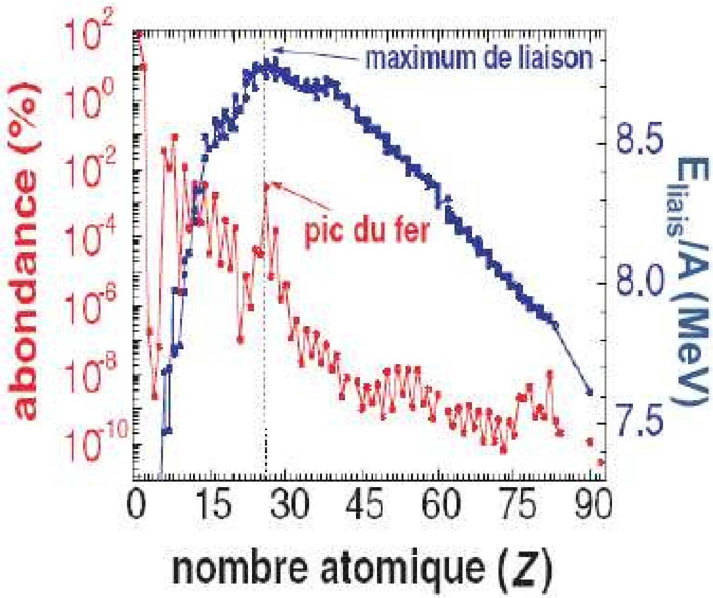
Energy balance : $A\,M_N - B_A + B\,M_N - B_B = C\,M_N - B_C + \Delta E$

Energy difference : $\Delta E = B_C - B_B - B_A$

Energetic features : fission possible only for elements heavier than Fe.
fusion possible for elements lower than Fe;

Some results on stellar nucleosynthesis

Correlation between B/A and abundance



• The abundance of the elements in the Univers depends on their stability

• The abundance of the elements in the Univers reflects the nuclear interaction.

• The most abundant element (hydrogen) is also the lighter one

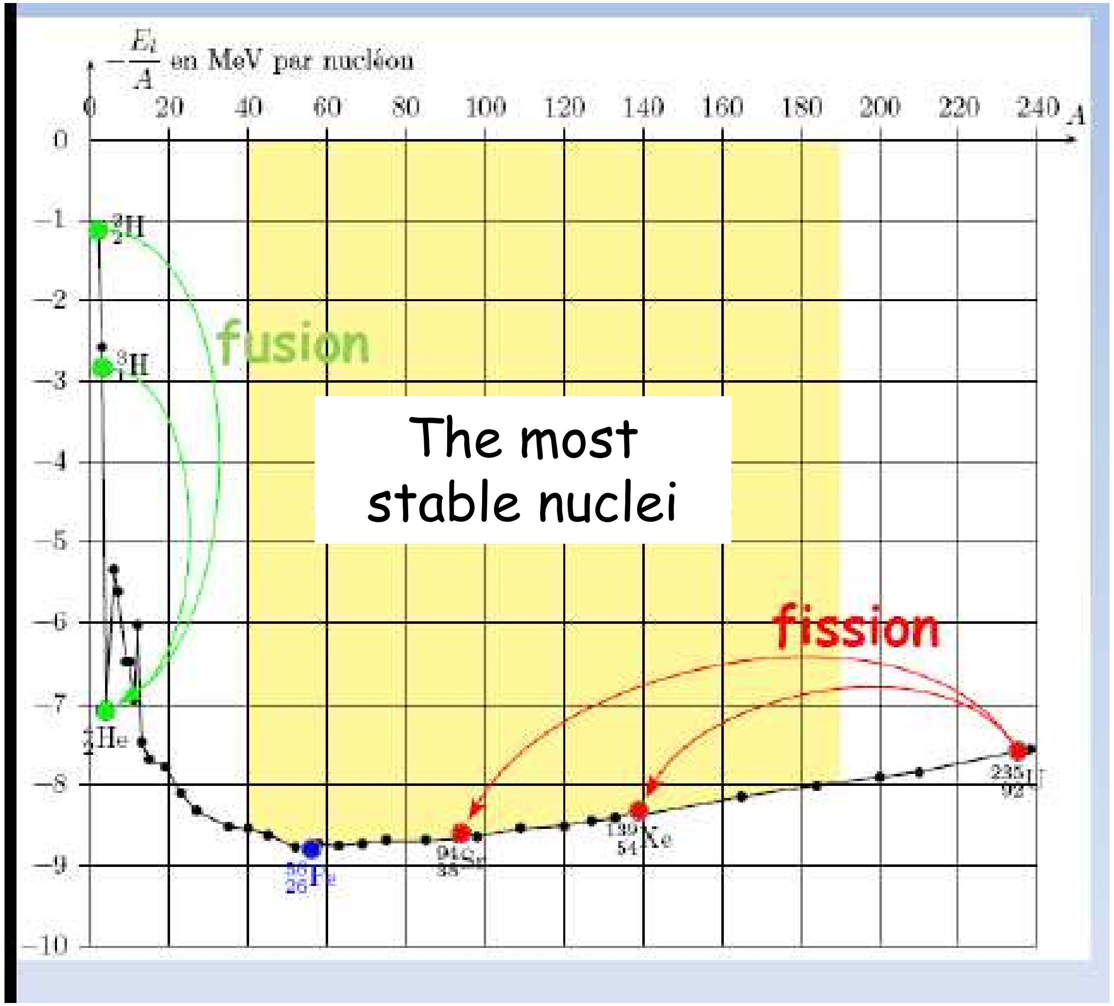
• Fe (the most stable and abundant) is the nucleus at the limit between :

 * the burning by fusion for the elements lighter than Fe

 * the radiative capture of neutrons by elements heavier than Fe.

From E. Gallichet

ITER project



Nuclear powerplant

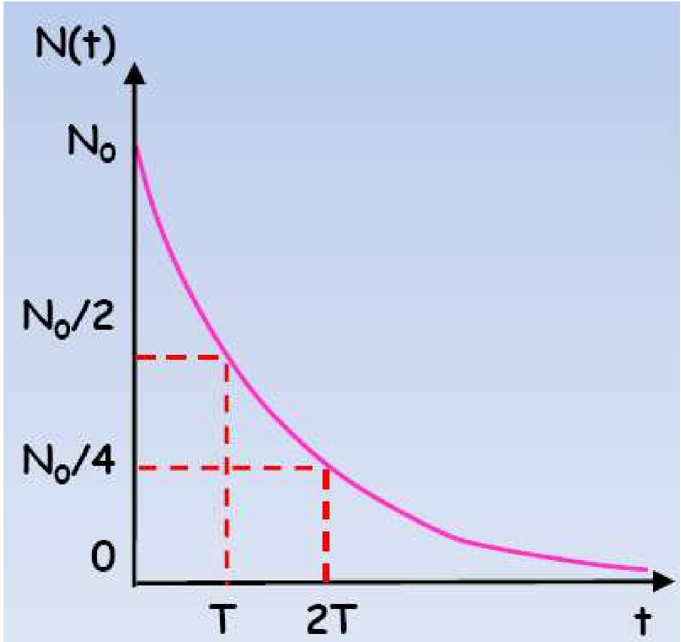
Nuclear Life times

A few nuclei are stable : their lifetimes are infinite (comparable to the lifetime of the proton 10^{33} years.)

The others are unstable : they transform into more stable nuclei

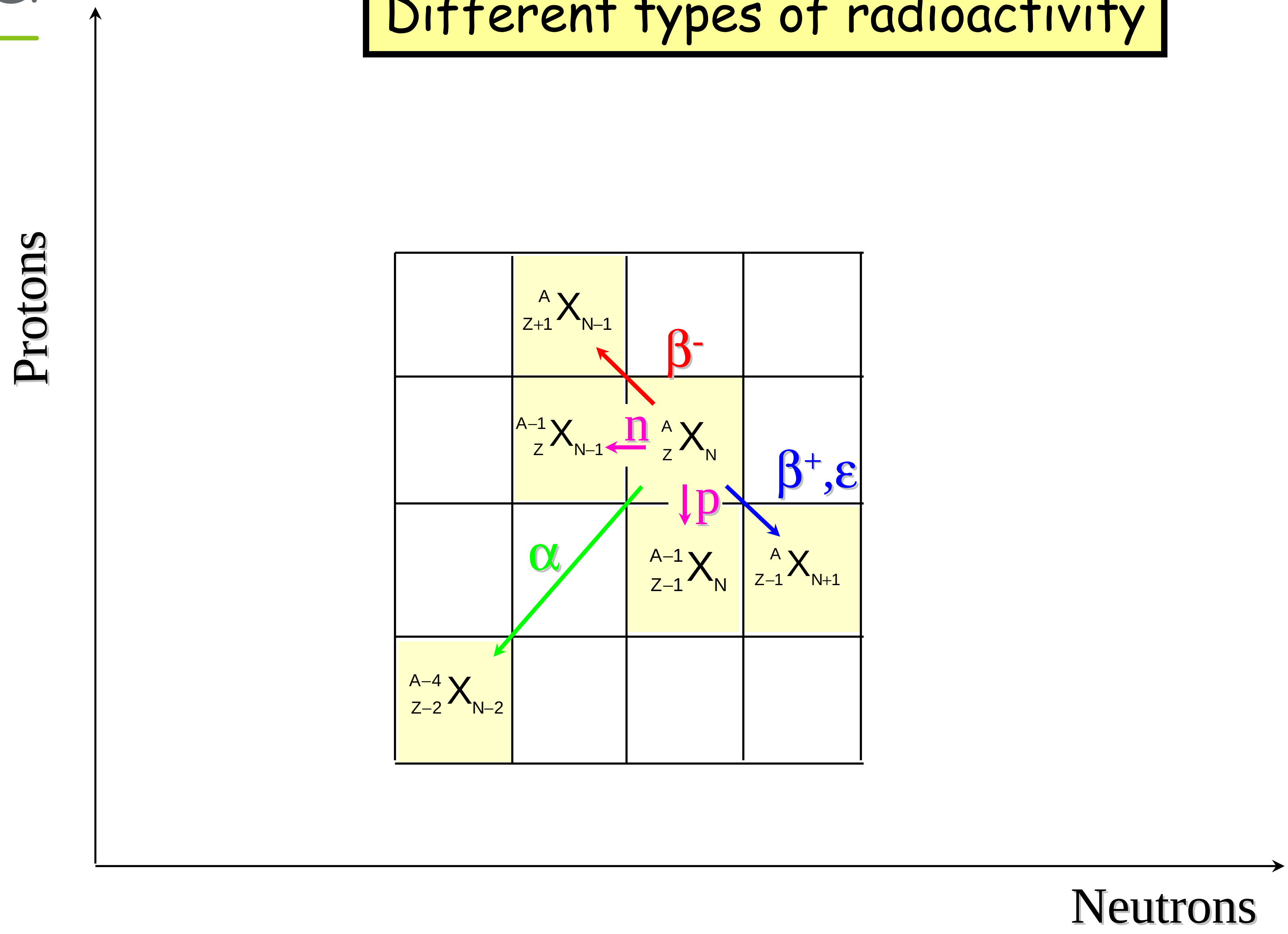
Exponential decay

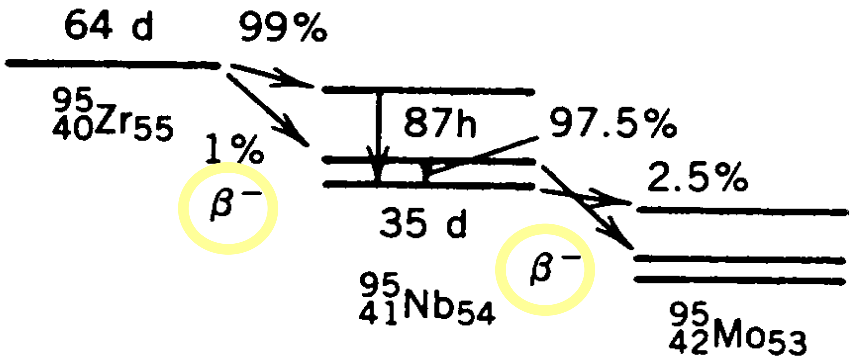
$$\frac{dN}{dt} = -\lambda N(t)$$

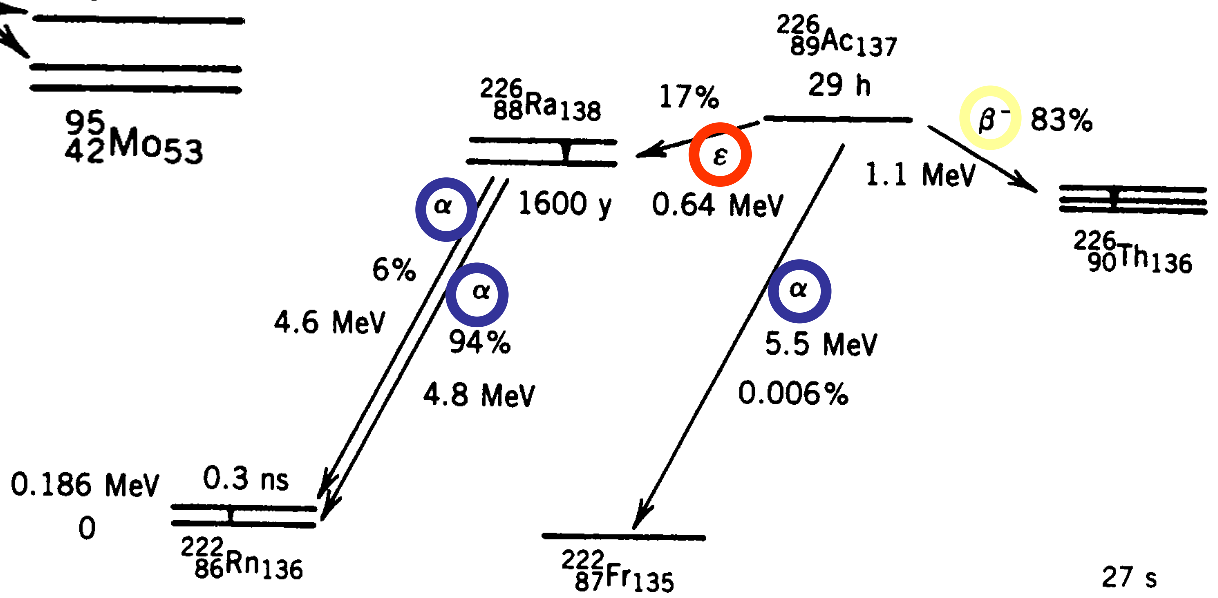


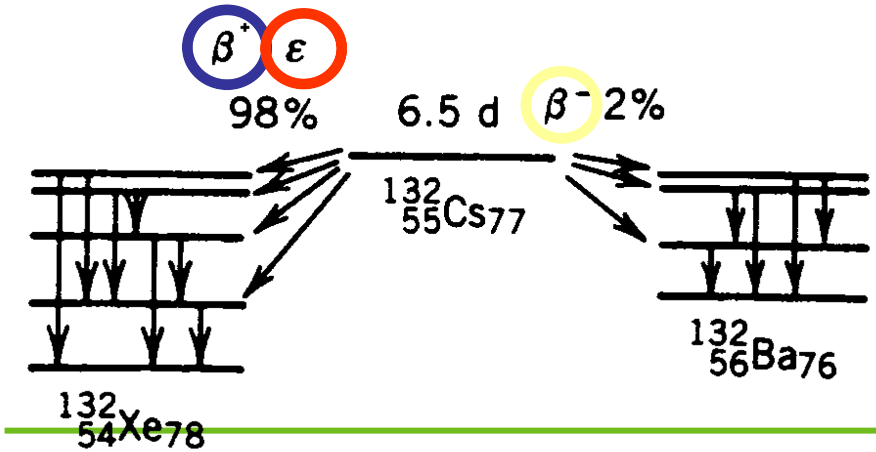
Half -life T defined as the time for which the number of remaining nuclei is half of its the initial value.

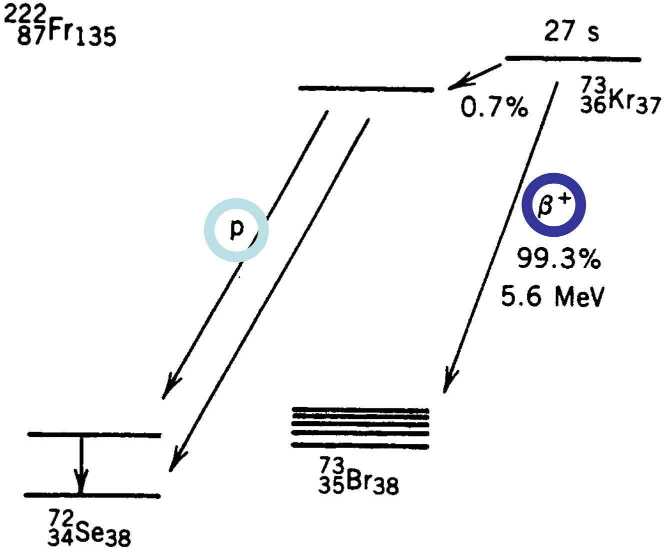
Different types of radioactivity



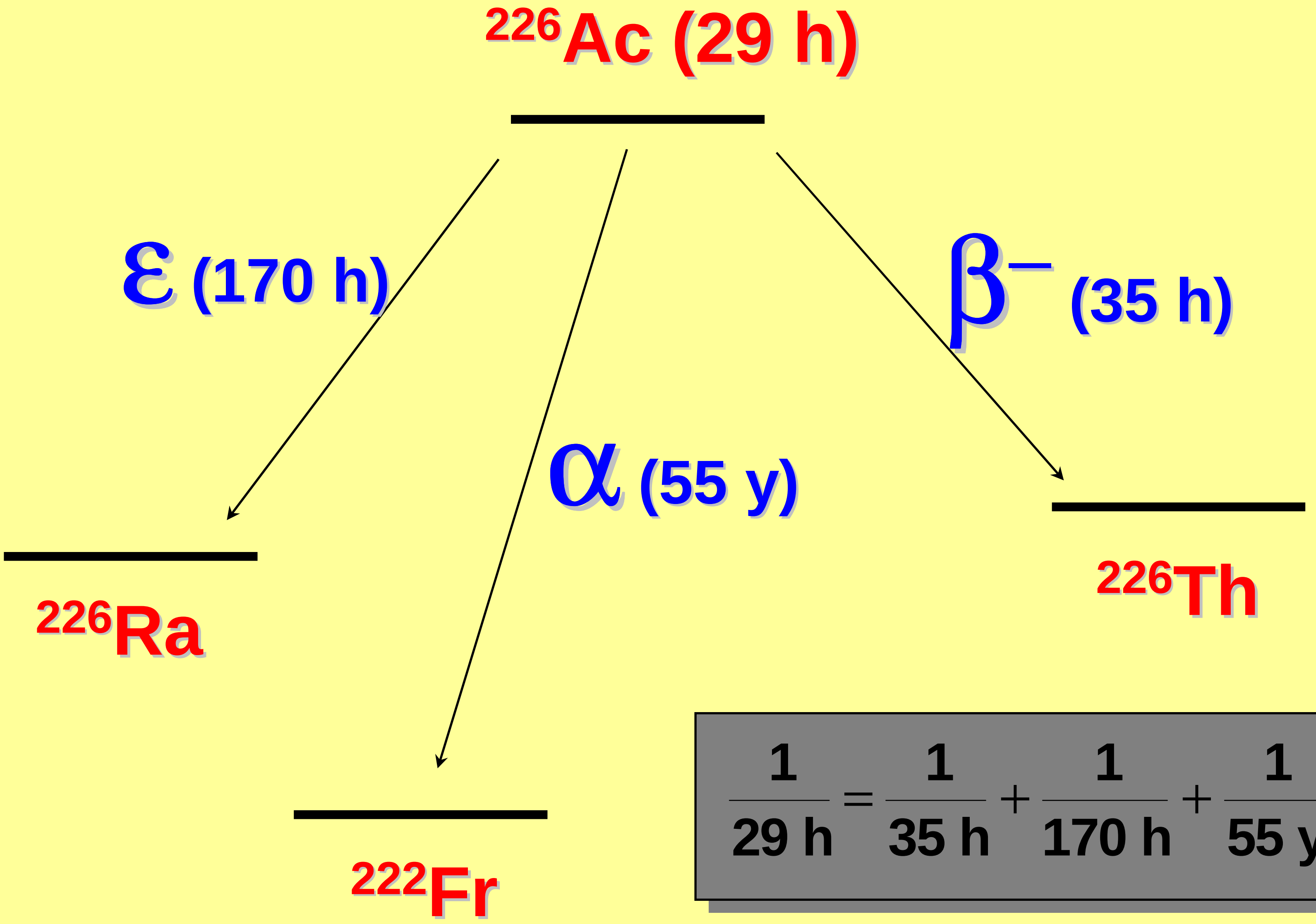

64 d
99%
$^{95}_{40}Zr_{55}$
1%
β⁻
87h
97.5%
2.5%
35 d
β⁻
$^{95}_{41}Nb_{54}$
$^{95}_{42}Mo_{53}$


$^{226}_{89}Ac_{137}$
29 h
17%
ε
0.64 MeV
β⁻
83%
1.1 MeV
$^{226}_{90}Th_{136}$
$^{226}_{88}Ra_{138}$
1600 y
α
6%
4.6 MeV
α
94%
4.8 MeV
α
5.5 MeV
0.006%
0.186 MeV
0.3 ns
0
$^{222}_{86}Rn_{136}$
$^{222}_{87}Fr_{135}$


β⁺
ε
98%
6.5 d
β⁻
2%
$^{132}_{55}Cs_{77}$
$^{132}_{54}Xe_{78}$
$^{132}_{56}Ba_{76}$


27 s
0.7%
$^{73}_{36}Kr_{37}$
p
β⁺
99.3%
5.6 MeV
$^{72}_{34}Se_{38}$
$^{73}_{35}Br_{38}$

Total versus partial life times

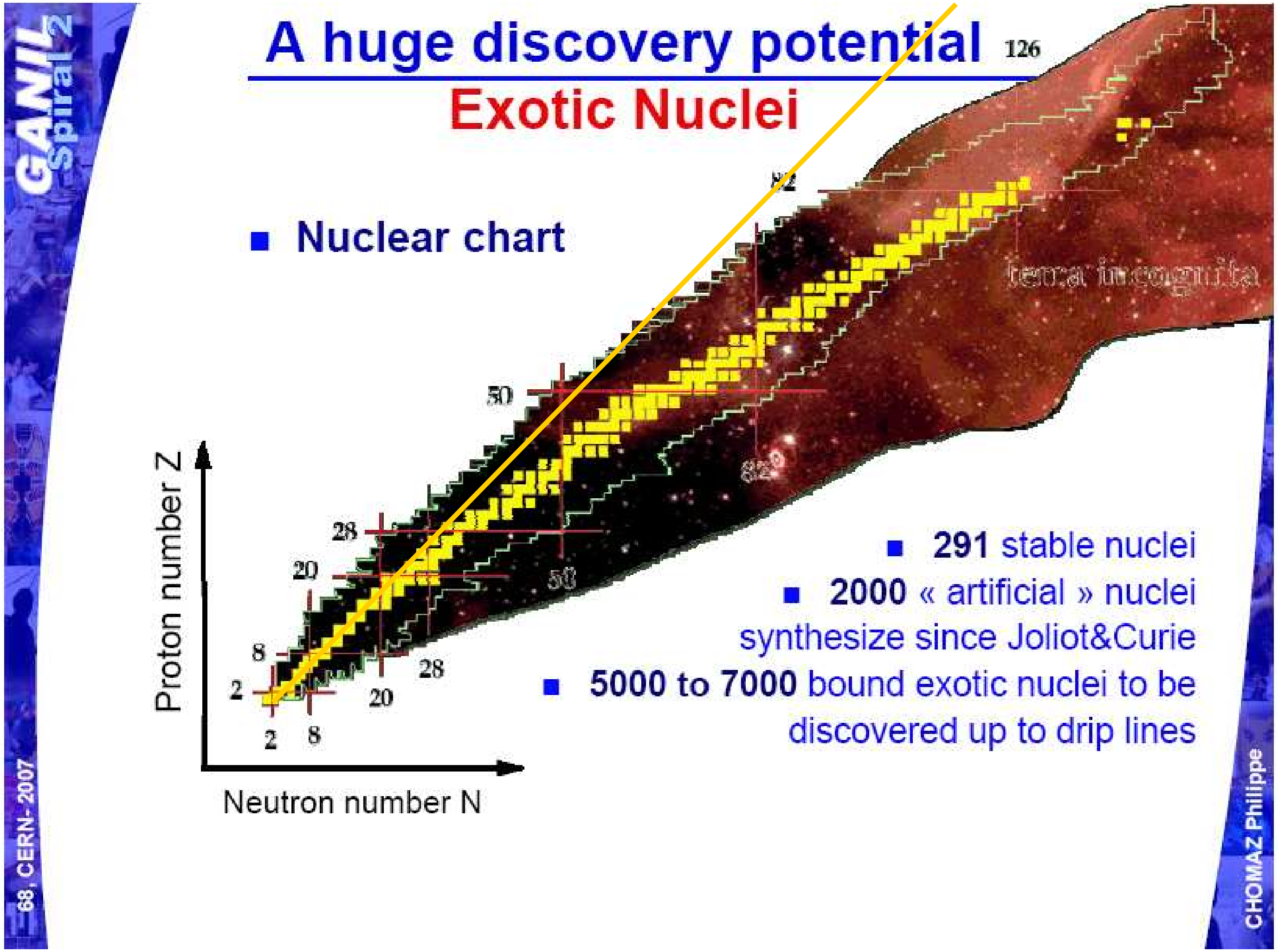


$$\frac{1}{29\ \text{h}} = \frac{1}{35\ \text{h}} + \frac{1}{170\ \text{h}} + \frac{1}{55\ \text{y}}$$

Examples : half lives

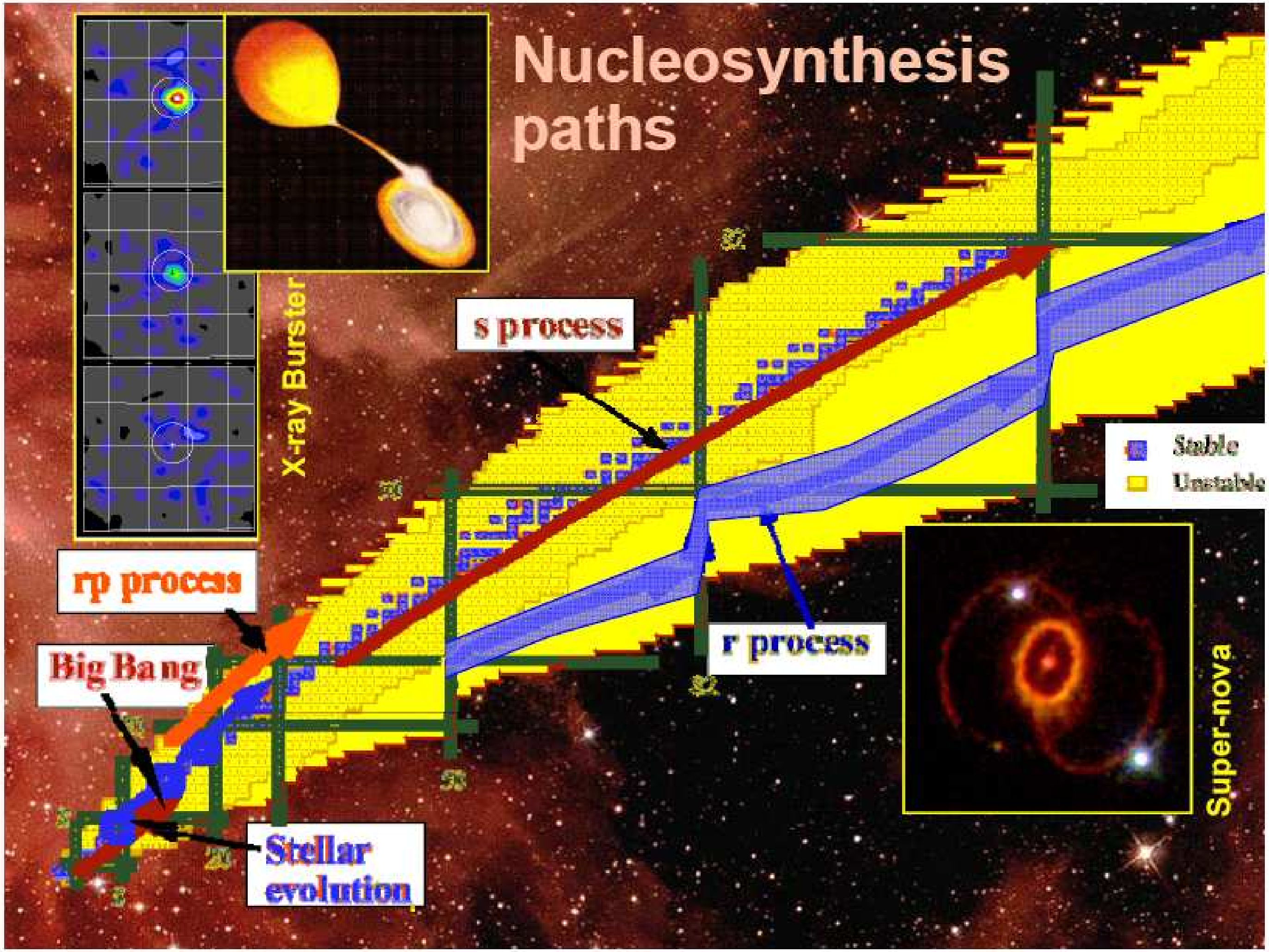
Life times span many orders of magnitude:

Nitrogen 16	$T_{1/2}$ = 7.13 s
Oxygen 15	= 2.037 mn
Radium 224	= 3.62 d
Carbon 14	= 5730 y
Molybdenum 100	= 10^{19} y
Tellurium 124	= 2.2 10^{28} y

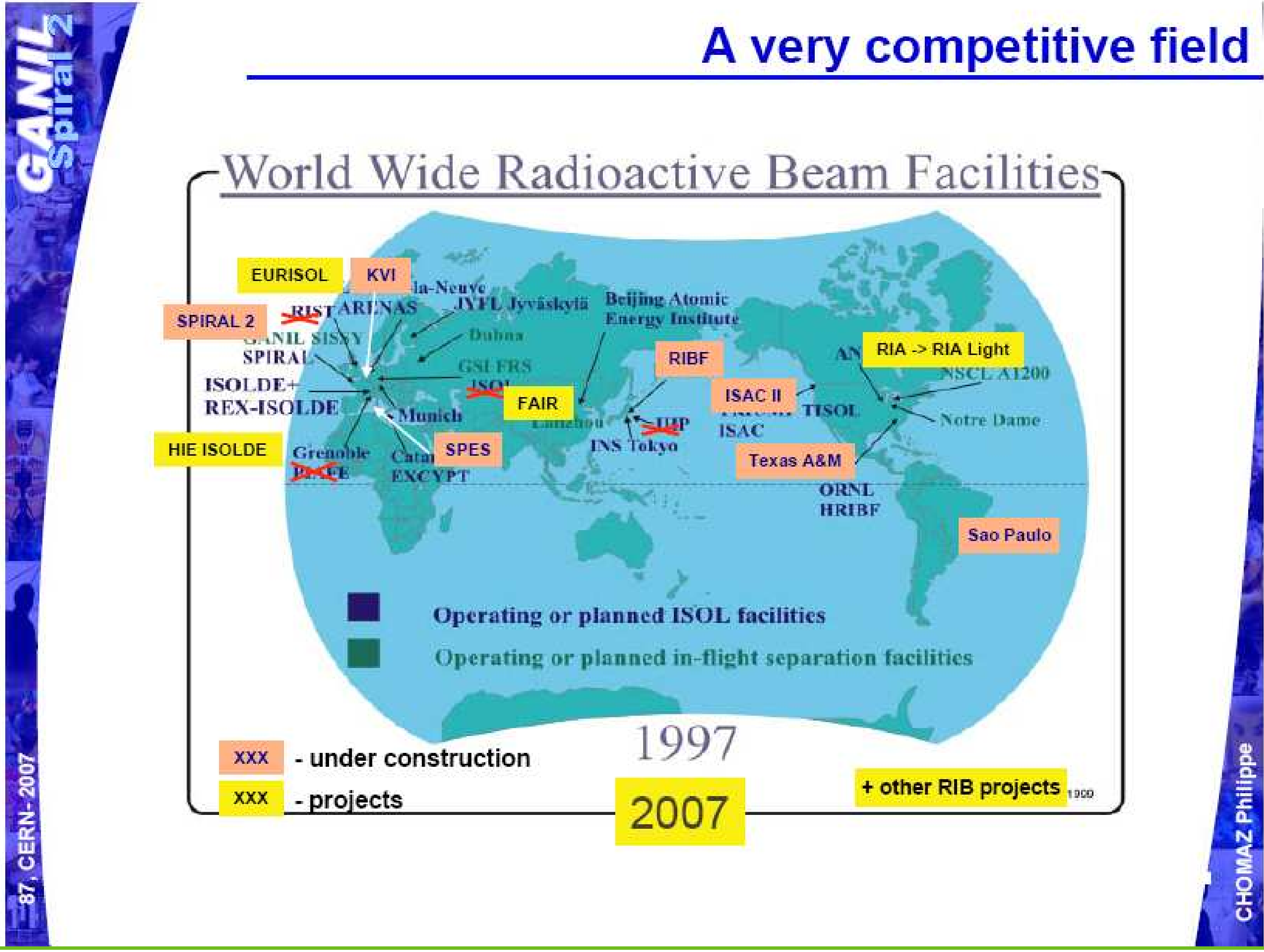


Why do the stable nuclei do not follow the N= Z line ?

Why do we search for new nuclei ?

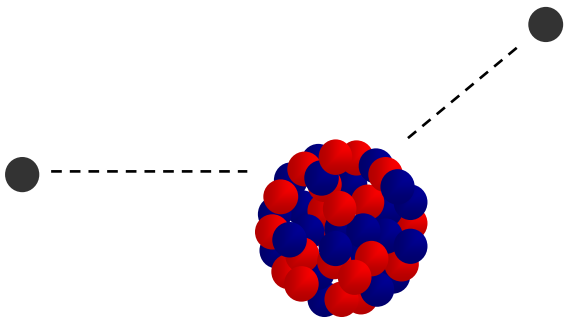

Nucleosynthesis paths
X-ray Burster
s process
rp process
Big Bang
Stellar evolution
r process
Stable
Unstable
Super-nova

A very competitive field



How do we experimentally study a nucleus ?

I) Elastic and inelastic scattering



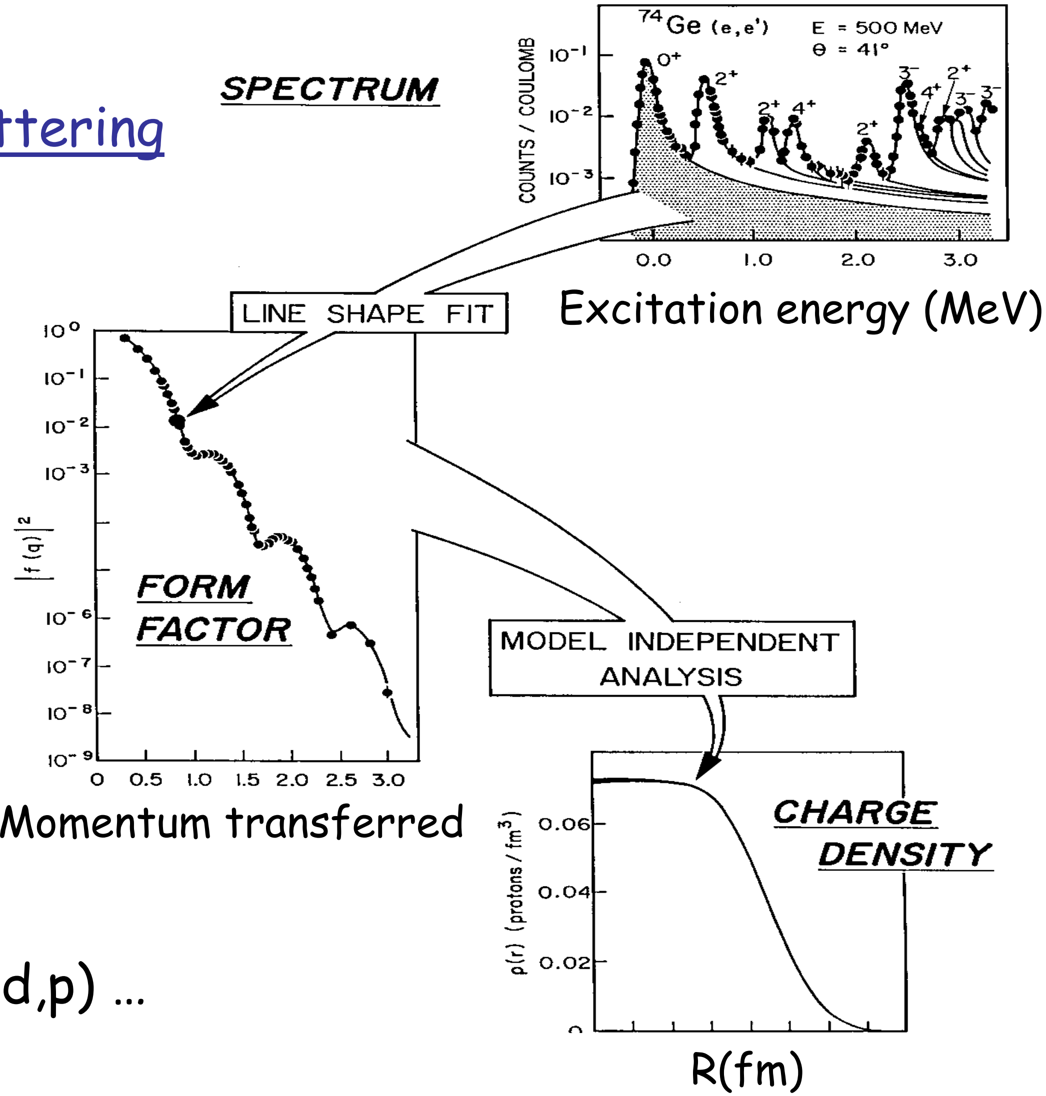
e^- ,e^+

p

n

Heavy ions

……..

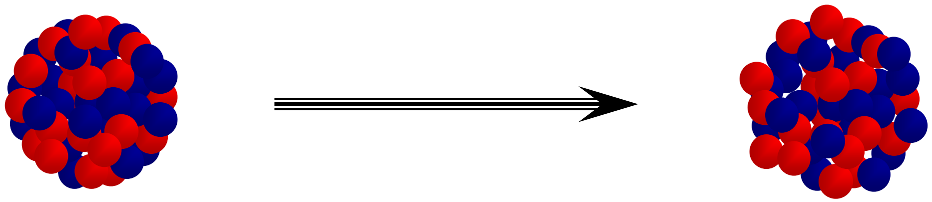


II) Transfer ex : (p,n), (d,p) …

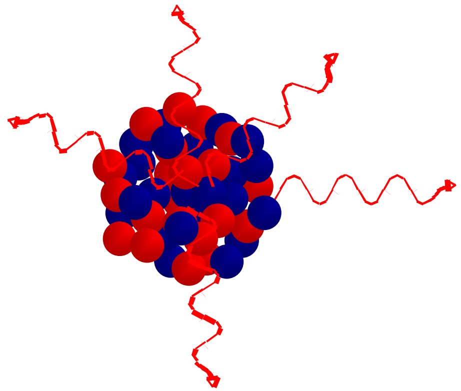
Knock out …

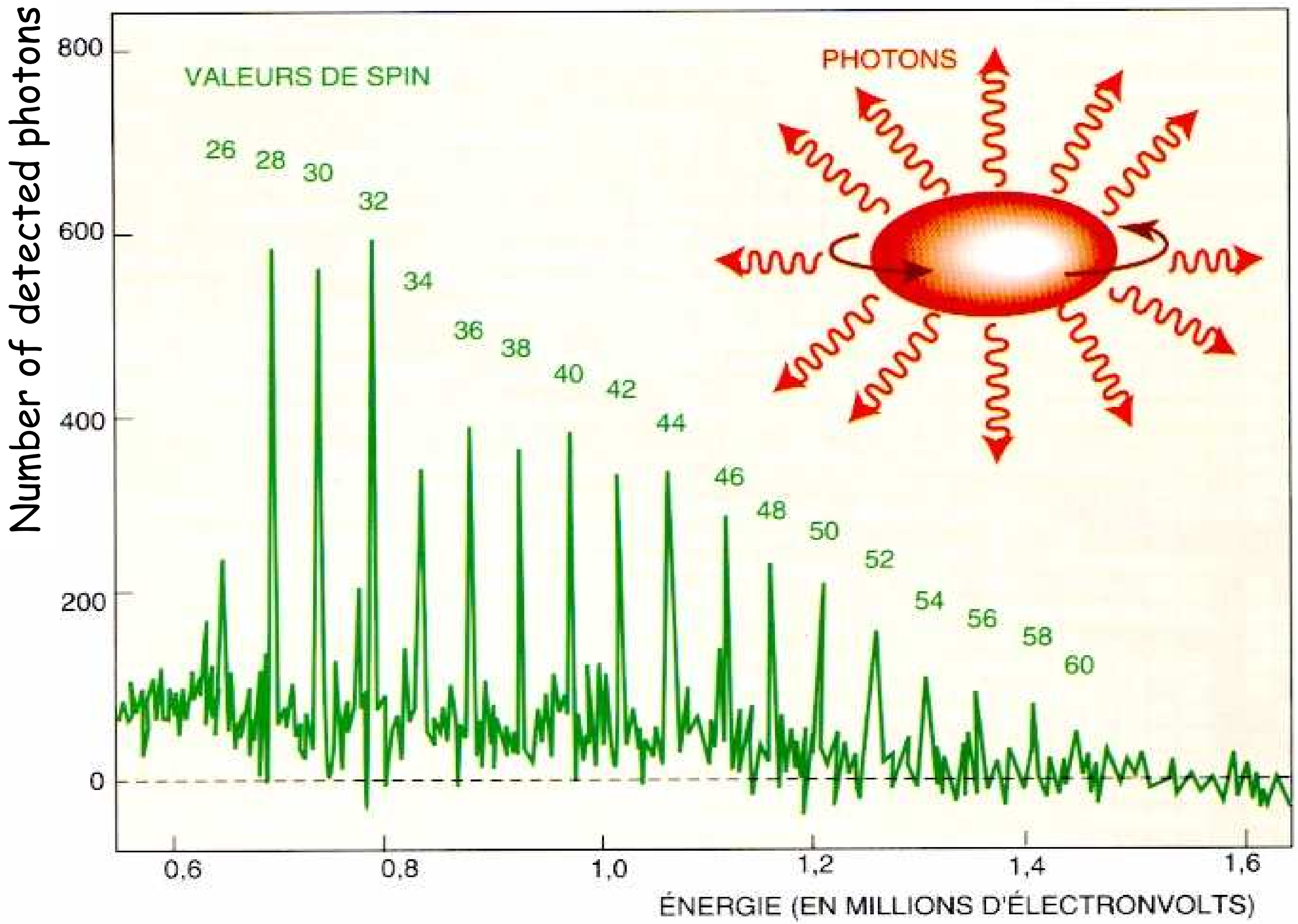
III) Gamma spectroscopy

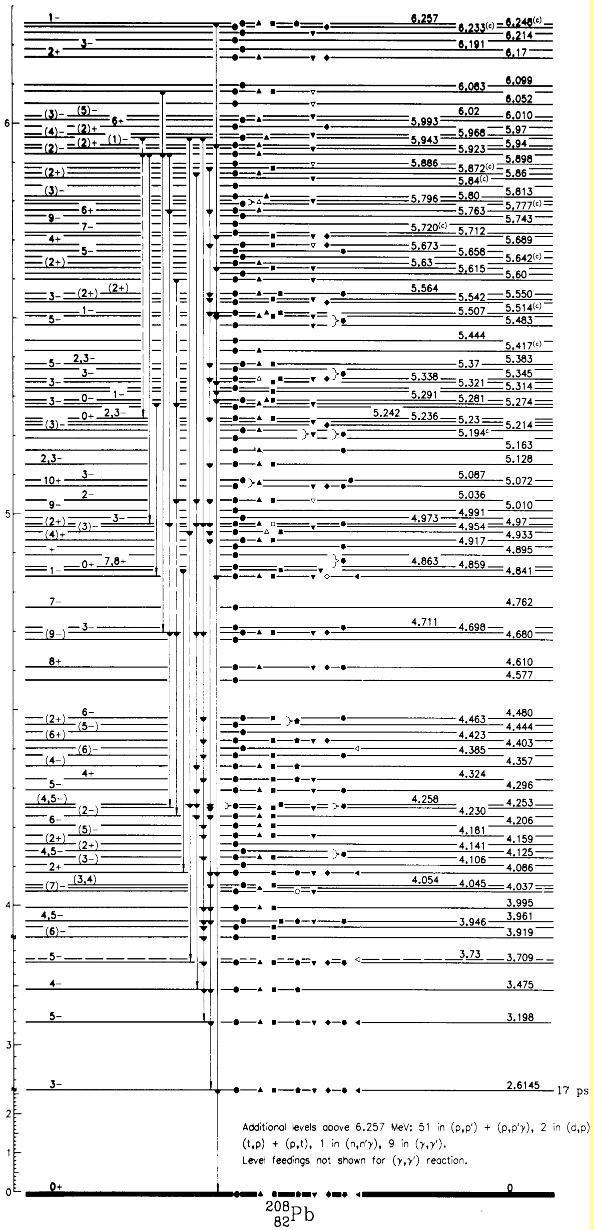
1) To excite the nucleus



2) To observe its decay




Number of detected photons
VALEURS DE SPIN
PHOTONS
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
800
600
400
200
0
0,6
0,8
1,0
1,2
1,4
1,6
ÉNERGIE (EN MILLIONS D'ÉLECTRONVOLTS)

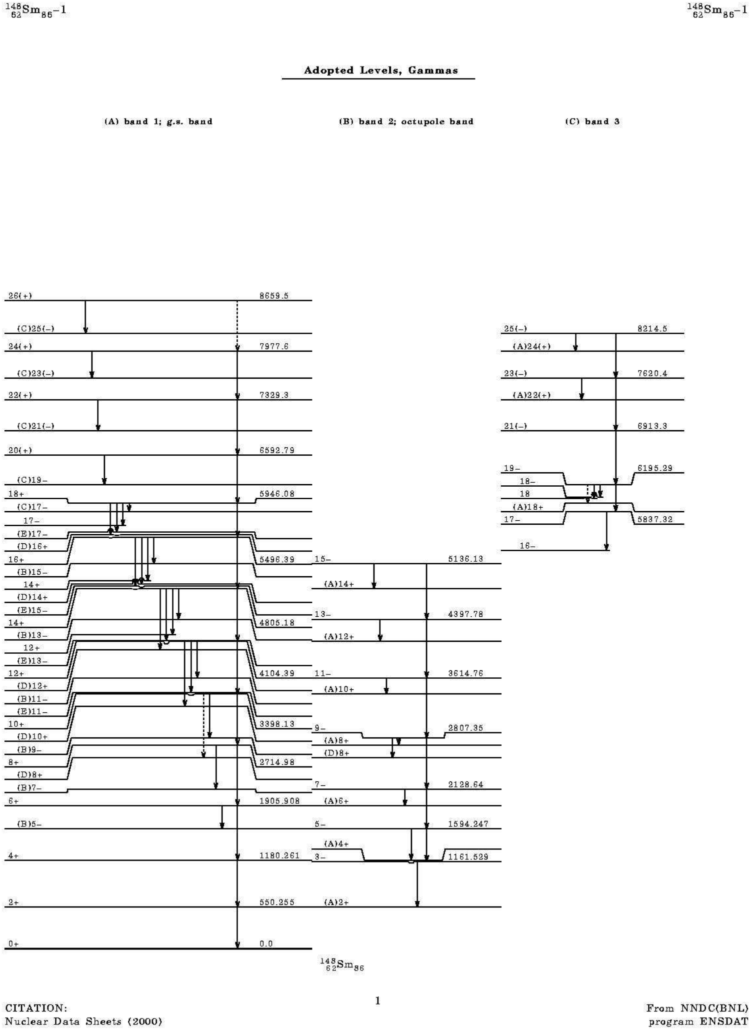


Example of a level scheme

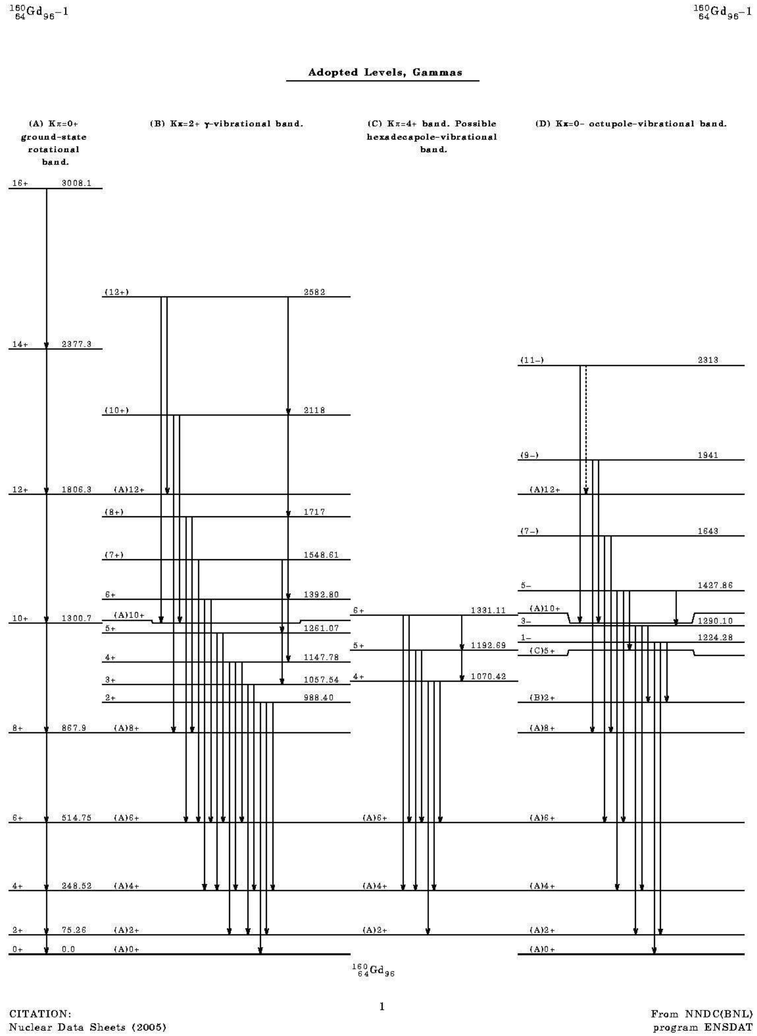
The barcode of a nucleus

^{148}Sm

^{160}Gd



Adopted Levels, Gammas
(A) band 1; g.s. band
(B) band 2; octupole band
(C) band 3
CITATION:
Nuclear Data Sheets (2000)
From NNDC(BNL)
program ENSDAT



Adopted Levels, Gammas
(A) Kπ=0+ ground-state rotational band.
(B) Kπ=2+ γ-vibrational band.
(C) Kπ=4+ band. Possible hexadecapole-vibrational band.
(D) Kπ=0− octupole-vibrational band.
CITATION:
Nuclear Data Sheets (2005)
From NNDC(BNL)
program ENSDAT

Some applications of Nuclear Science

Nuclear physics makes indeed many essential contributions to

- Energy production
  - * Electricity generation
    - * fission : research on
      - * new generations of power plants, new fuel cycles
      - * reduction by transmutation of the long – term impact of the nuclear wastes produced (ADS or GEN IV reactors)
    - * fusion for the far future : (ITER project)
- Medicine
  - * diagnostic
    - * detection of the decay of radioactive isotopes
      SPECT Single Photon Emission Computer Tomography
      PET Positron Emission Tomography
    - * IRM Imaging by Magnetic Resonance
  - * therapy (proton-, hadron-therapy …)

Some applications of Nuclear Science (2)

- Art and archaeology
  - * datation
  - * identification of constituent materials
  (ex : AGLAE Accélérateur Grand Louvre pour l'Analyse Elémentaire)

- Environmental studies
  - * ex : observation of modification of ocean circulation patterns (measurement of ^{129}I / ^{127}I in seawater as a function of depth and distance to the coast)

- …

From NuPECC long Range Plan 2004

Some features of the nuclei : Summary

- The existence of the atomic nuclei : the Rutherford experiment in 1909
- The nucleon-nucleon interaction is not precisely known.
- Many nuclei are predicted but not observed up to now
- Most of them are neutron rich, and are supposed to have played a role during the nucleosynthesis.
- Nuclei are characterized by their level scheme : their barecode.
- Many applications of the nuclear physics