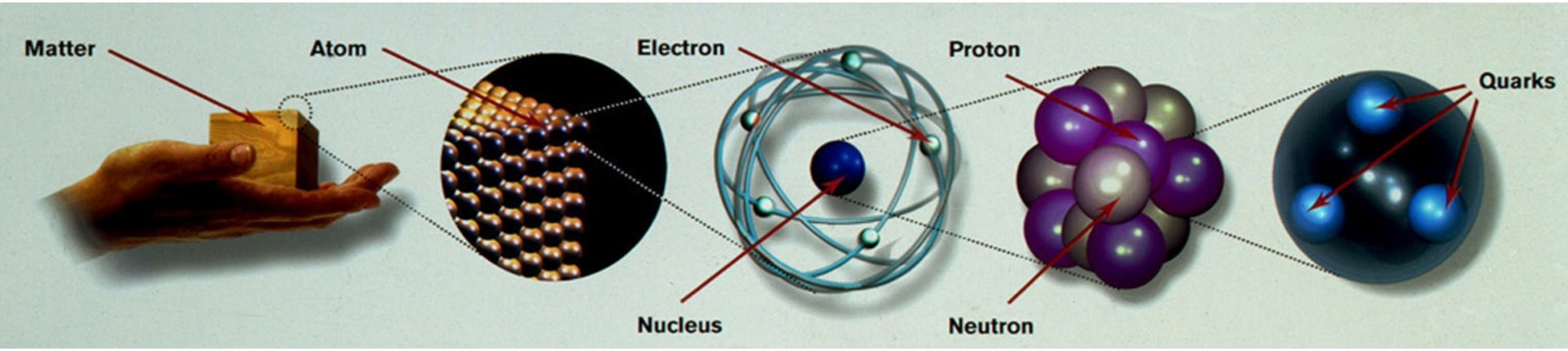
Chapter I
Introduction



These lectures will cover the core topics of Nuclear and Particle Physics

Particle physics is the study of :

Matter : Elementary Particles

Forces : Basic forces in nature
Electromagnetic, Weak, Strong

Theoretical Framework :
The current understanding is described by
The Standard Model
Excellent agreement with experimental data but does not include gravity

Nuclear physics is the study of :

Matter : Complex Nuclei (protons and neutrons)

Forces : Strong nuclear force
(underlying strong force)
Weak and Electromagnetic in decays

Theoretical Framework :
Complex many-body problem and effective interactions
→requires semi-empirical approach.
→Several models of nuclear physics.
Agreement with experimental data less convincing

Historically, Nuclear physics preceded and led to Particle Physics. This course will discuss Nuclear Physics first and then Particle Physics

Experimental point of view

✓ Invisibility of the constituents (even with a microscope)
→ Detectors (= "eyes" to see the particles)

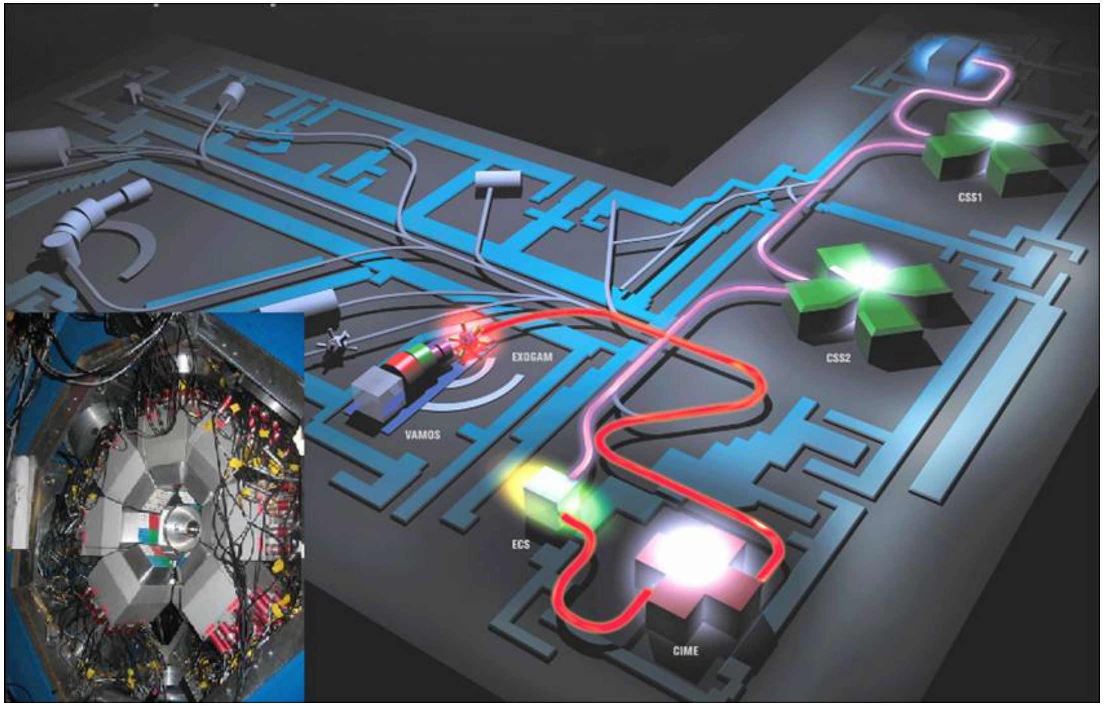
✓ Probing the matter to very small scale
→ Accelerators

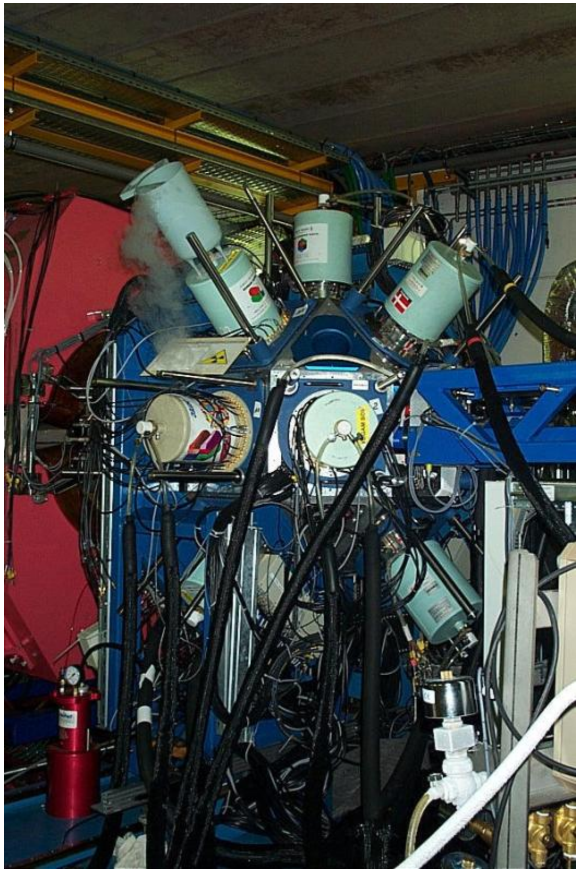
Accelerators and detectors are the common tools of nuclear and particle physics

Historic example : Rutherford experiment

An example of nuclear physics facility: the GANIL (Caen)

Accelerator : SPIRAL (radioactive beam on a fixed target)

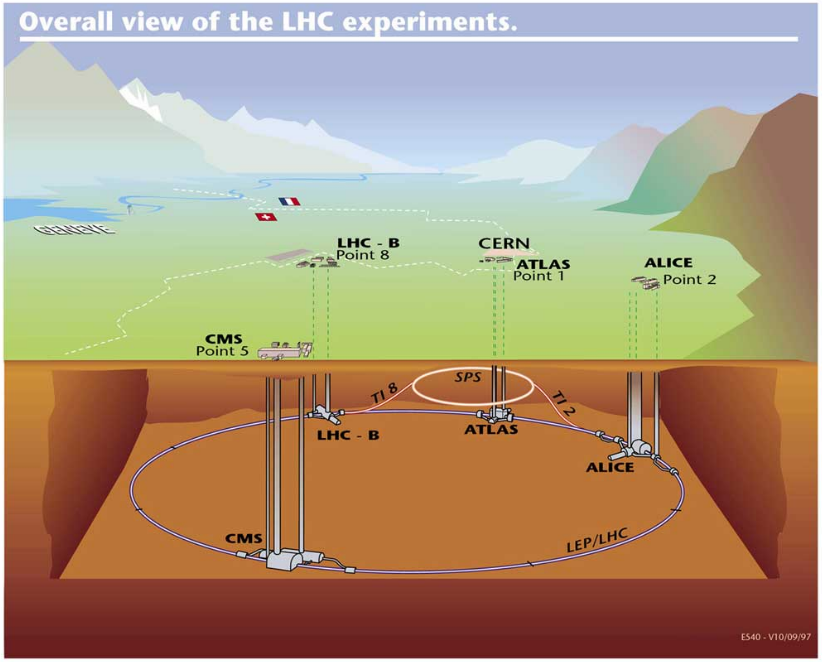




Detector: EXOGAM (amongst others)

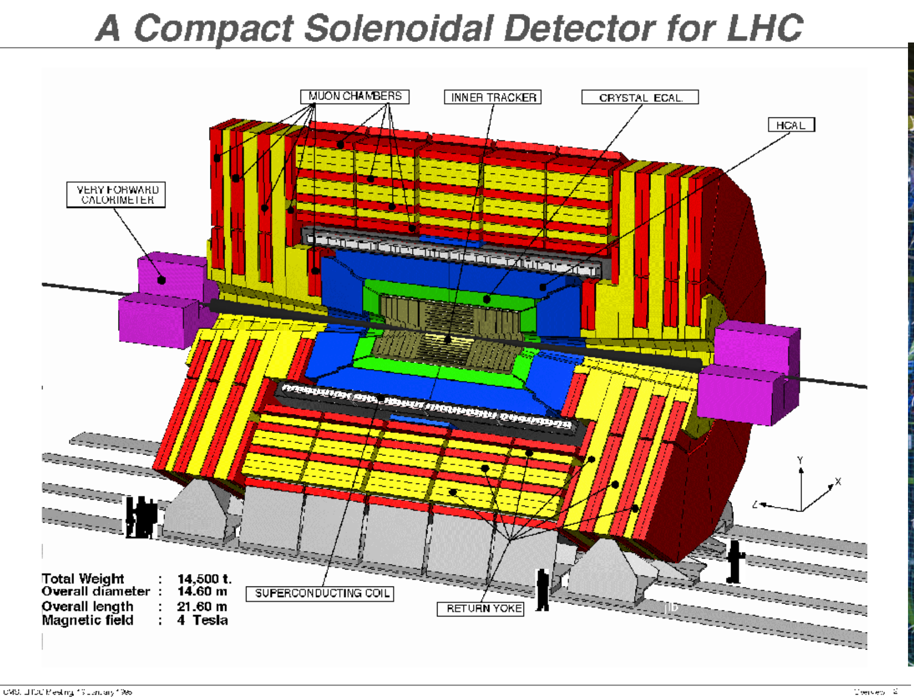
An example of particle physics facility: CERN (Genève)

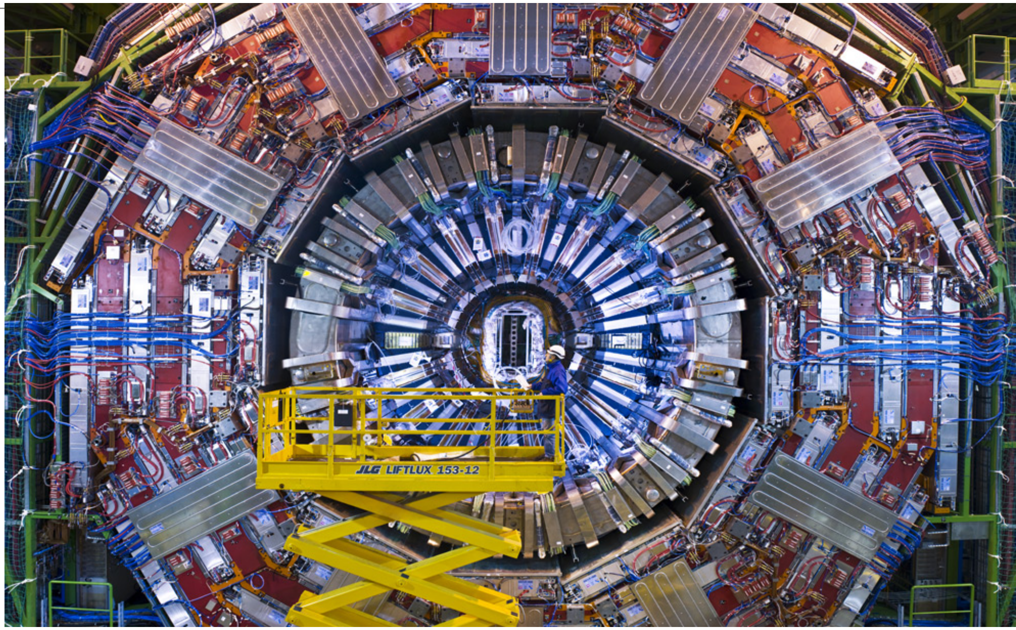
Accelerator : LHC (Large Hadron Collider)



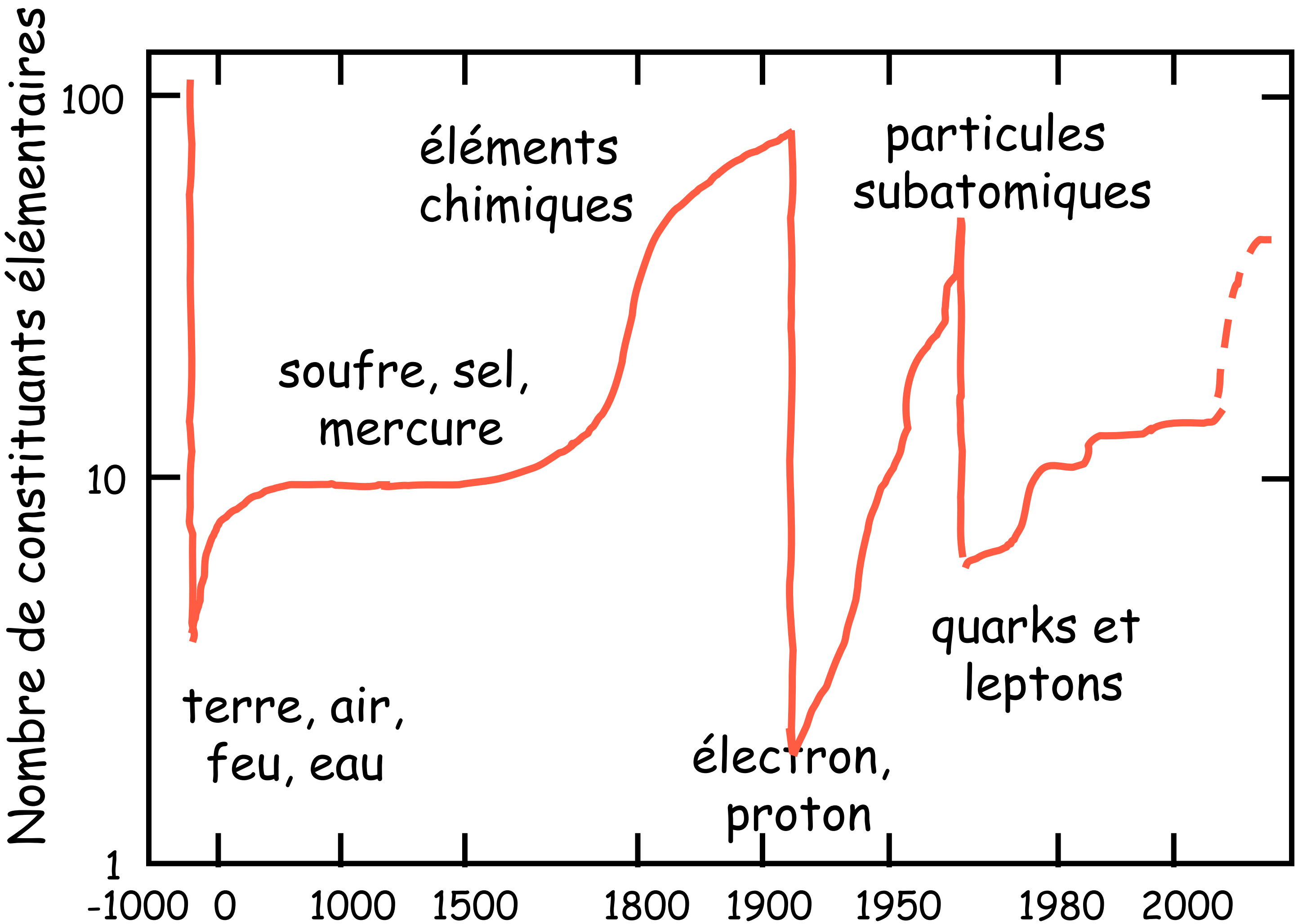
An example of particle physics facility: the CERN

CMS Detector (Compact Muon Solenoid)

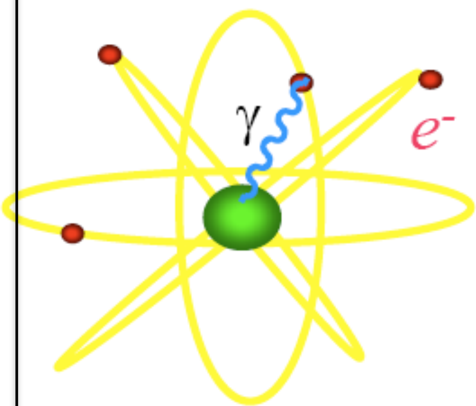




Elementary constituents ?



Binding energy ~10 eV



ATOM

Electrons bound to atom by electromagnetic force

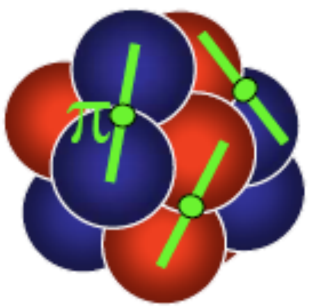
Size : Atom ~10^{-10} m, e^{-}<10^{-19} m

Charge : Atom is neutral, electron –e=1.6 10^{-19} C

Mass : Atom Mass ~ Nucleus Mass, m_e=0.511 MeV/c^2

Chemical Properties depend on Atomic Number Z

Binding energy ~10 MeV/nucleon



NUCLEUS

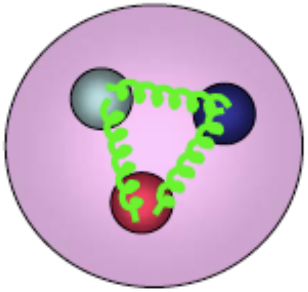
Nuclei held together by strong nuclear force

Size : Nucleus (medium A) ~ 5 fm (1 fm= 10^{-15} m)

Charge : Ze

Mass : from few GeV/c^2 to about a hundred GeV/c^2

Binding energy ~1 GeV



NUCLEON

Proton (p) and neutrons (n) : held together by the strong force

Size : p,n ~1 fm

Charge : proton +e; neutron uncharged

Mass : p=938.27 GeV/c^2, n = 939.57 MeV/c^2 ~1836 Me

Matter

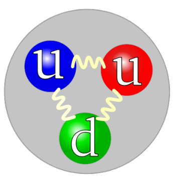
All ordinary matter can be described by the interaction [illegible] ur elementary fermions (spin ½) :

Particle	Symbol	Type	Char[illegible]
Electron	e^-	Lepton	[illegible]
Electronic neutrino	ν_e	Lept[illegible]	0
Up quark	u	[illegible]ark	2/3
Down quark	d	Quark	-1/3

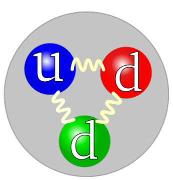
THE FIRST GENERATION

ESSENTIALLY ALL AN ATOMIC OR NUCLEAR PHYSICIST NEEDS

The quark[illegible] [illegible]nbedded in the proton and [illegible] [illegible]eutron, which are simply [illegible] [illegible]west energy bound states of a [illegible]ystem of three quarks.



Proton (uud)



Neutron (udd)

Matter : 3 generations

Nature turns out to be quite not so simple. There are actually 3 generation (or families) of fundamental fermions :

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			
Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2			
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

- Each generation e.g. (μ^-,ν_μ,c,s) is a replica of (e^-,ν_e,u,d)
- The main difference is the mass of the particles: The first generation is the lightest and the third the heaviest
- Consequence of relativity and quantum mechanics (Dirac equation) is that for each particle there exists an antiparticle which has identical mass, spin but opposite sign of interaction (e.g. electric charge)

Leptons

Particle which do not interact via the strong interaction

- Spin ½ fermions
- 6 distinct "flavours"
- 3 charged leptons : e^-, μ^-, τ^-
  μ and τ unstable
- 3 neutral leptons : ν_e, ν_μ, ν_τ
  ν are stables and (almost) massless.
- Antimatter partners : $e^+, \bar{\nu}_e$,…
- Charged leptons only experience the electromagnetic and weak forces
- Neutrinos only experience the weak force

Leptons spin = 1/2			
Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	−1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	−1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	−1

Quarks

Quarks experience ALL the forces (electromagnetic, strong, weak)

- Spin ½ fermions
- 6 distinct "flavours"
- Quarks come in 3 colors :
  Red, Green, Blue
- Quarks are confined within HADRONS
  e.g p=(uud) $\pi^+=(u\bar{d})$
- Antimatter partners : antiquarks $\bar{u}$,$\bar{d}$…
- COLOR is just a label for the charge of the strong interaction. Unlike the electric charge of an electron (-e), the strong charge comes in three orthogonal colors RGB.

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

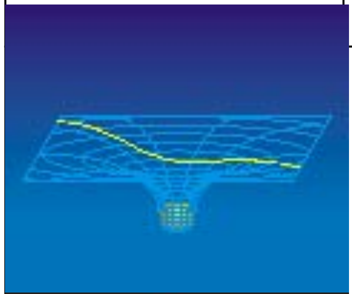
Forces

- Quantum field theory: As well as the matter particles, the electromagnetic field should be quantized (second quantization). Forces arise due to exchange of virtual field quanta (gauge bosons = photon for EM).
- This process violates energy/momentum conservation, but this is OK for sufficiently short times owing to the uncertainty principle. The exchanged particle is called virtual

  $$\Delta E\,\Delta t \sim \hbar \Longrightarrow \text{Range } R \sim c\Delta t \sim \hbar c/\Delta E$$

  i.e. larger energy transfer (larger force) ⇒smaller range

- Coulomb's law is the resultant of all virtual exchanges

	Interaction	Fermions	Bosons	Range	Charge	Relative intensity
	**Gravitation** Gravity, ocean tide, planets tralectories	All massive particles	graviton (?)	infinite	mass	10^{-39}
	**Electromagnetic** Almost all current life phenomenons	Charged leptons and quarks	photon	infinite	Electric charge	10^{-2}
	**Strong** Atomic nuclei cohesion	quarks	gluon	10^{-15} m	Color charge	1
	**Weak** Beta radioactivity, Sun	leptons and quarks	W^+, W^-, Z° bosons	10^{-18} m	Weak charge	10^{-7}

Gauge Bosons

Gauge Bosons mediate the fundamental forces

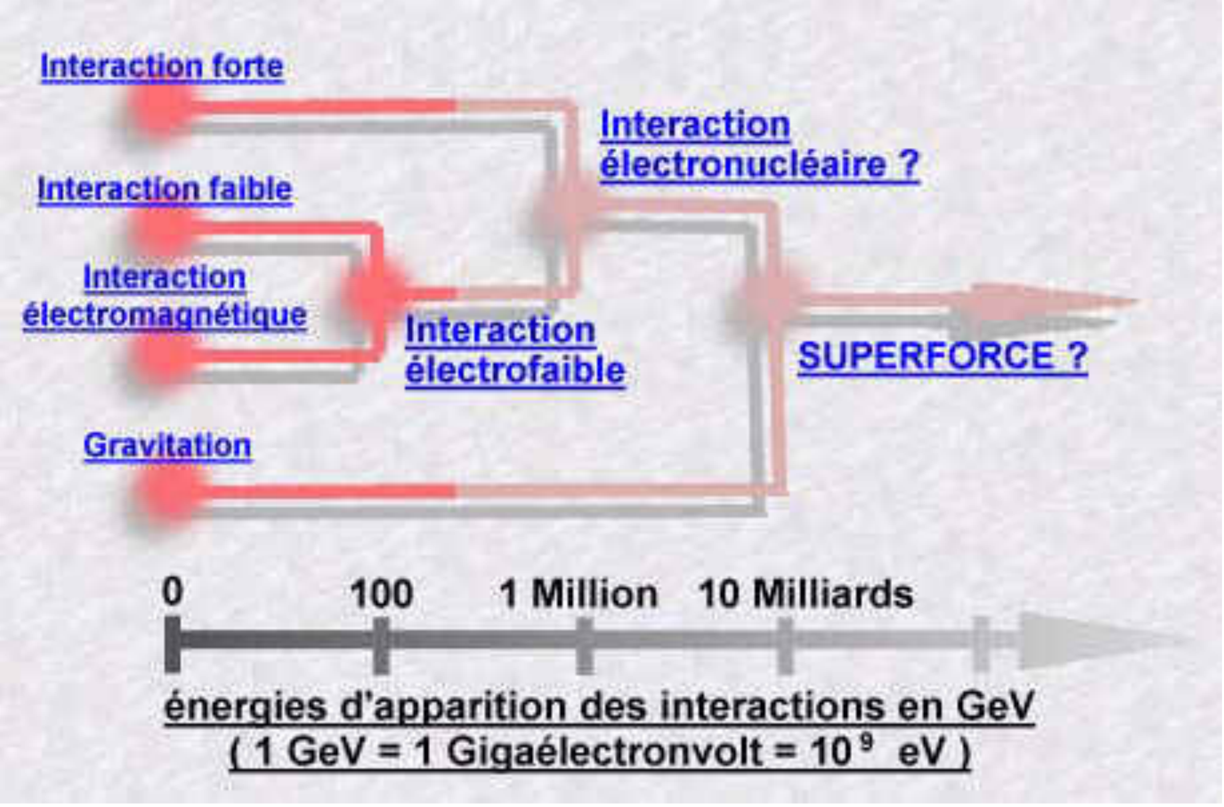
- Spin 1 particles (vector bosons)
- Interact in a similar way with all fermions generations

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Forces


Interaction forte
Interaction faible
Interaction électromagnétique
Interaction électrofaible
Interaction électronucléaire ?
Gravitation
SUPERFORCE ?
0
100
1 Million
10 Milliards
énergies d'apparition des interactions en GeV
(1 GeV = 1 Gigaélectronvolt = 10 9 eV)

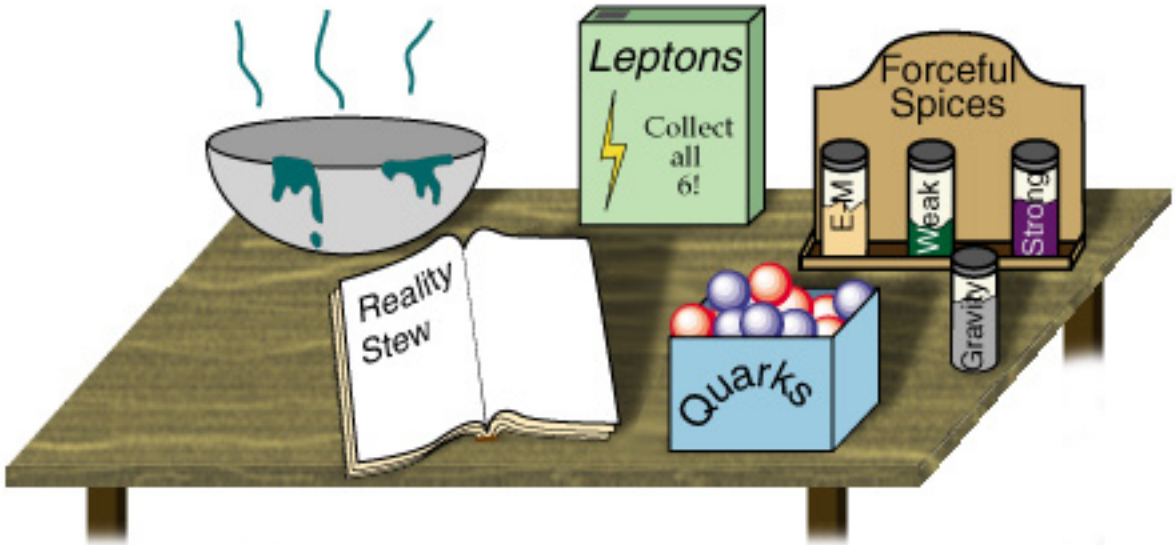
Range of Forces

The maximum range of a force is inversely related to the mass of the exchanged boson

$$\Delta E\,\Delta t \sim \hbar \text{ and } E = mc^2$$
$$\implies mc^2 \sim \hbar/\Delta t$$
$$\implies R \sim c\,\Delta t \sim \hbar/mc$$

Force	Range (m)
Strong Strong (Nuclear)	∞ 10^{-15}
Electromagnetic	∞
Weak	10^{-18}
Gravity	∞

Due to quark confinement, nucleons start to experience the strong interaction at ~2fm



STANDARD MODEL OF PARTICLE PHYSICS

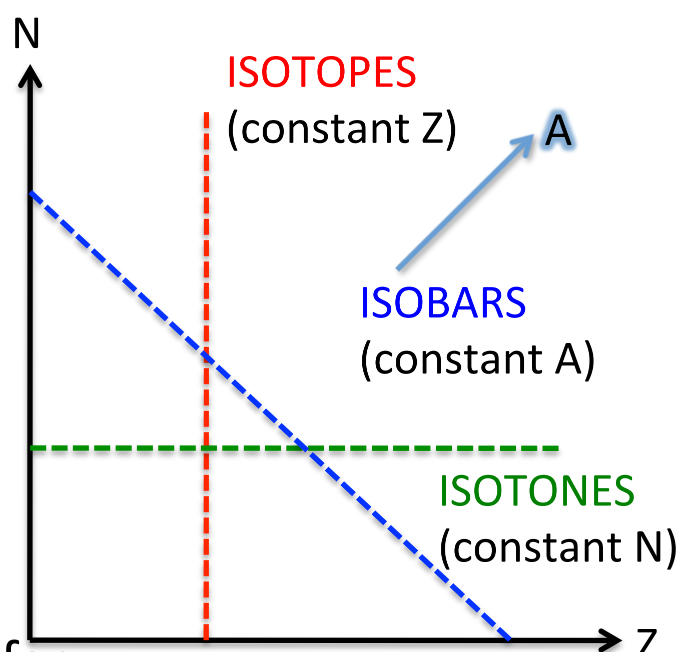
Hadrons

- Single free quarks are never observed, but are always confined in bound states called hadrons.
- Macroscopically hadrons behave as almost point-like composite particles.
- Hadrons are of two types:
  - MESONS ($\bar{q}q$)
    bound states of a quark and an antiquark
    all have integer spin (0,1,2,…) ⇒Bosons
    e.g : $\pi^+ = (u\bar{d})$ and $K^- = (d\bar{s})$
  - BARYONS (qqq)
    bound states of 3 quarks
    all have half-integer spin (1/2,3/2,…) ⇒Fermions
    e.g : $p = (uud)$ and $n = (udd)$
  - ANTIBARYONS ($\overline{qqq}$) e.g. $\bar{p} = (\bar{u}\bar{u}\bar{d})$

Nuclei

- A nucleus is a bound state of Z protons and N neutrons.
- p and n are generically referred to as "NUCLEONs"
- A (mass number) = Z (atomic number) + N (neutron number)
- A "NUCLEIDE" is a specific nucleus characterized by Z,N
  notation : ${}^{A}_{Z}\mathrm{X}$

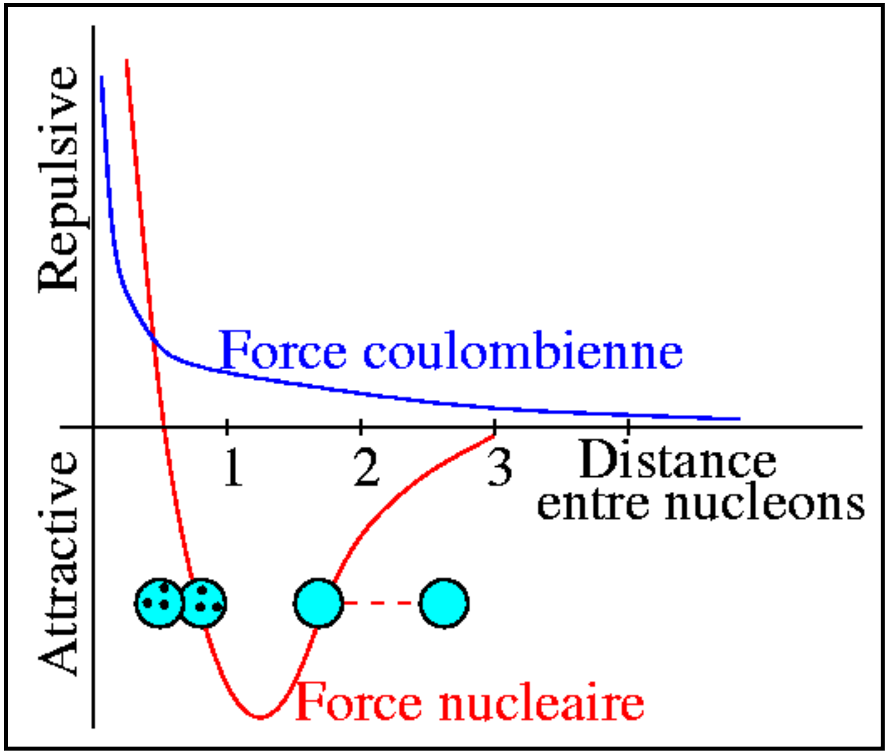
$$
\begin{aligned}
&{}^{1}_{1}\mathrm{H}\ \mathrm{or}\ \mathrm{p}\ :\ Z=1,\ N=0,\ A=1\\
&{}^{2}_{1}\mathrm{H}\ \mathrm{or}\ \mathrm{d}\ :\ Z=1,\ N=1,\ A=2\\
&{}^{4}_{2}\mathrm{H}\ \mathrm{or}\ \alpha\ :\ Z=2,\ N=2,\ A=4\\
&{}^{208}_{82}\mathrm{Pb}\ \ :\ Z=82,\ N=126,\ A=208
\end{aligned}
$$



- In principle, antinuclei and antiatoms can be made from antiprotons, antineutrons and positrons. Experimentally challenging ~300 antihydrogen atoms made and trapped so far

Strong nuclear force

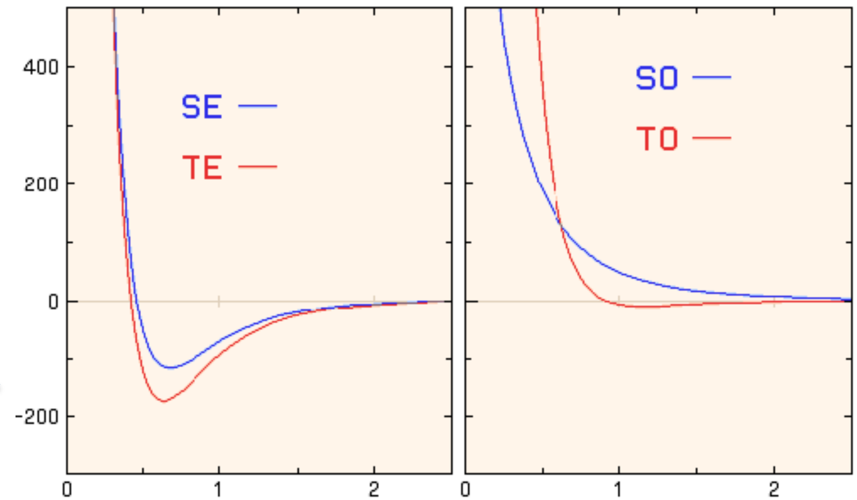
- ✓ The force between nucleons is called the "strong nuclear force"
- ✓ Relationship between the "strong nuclear force" and the "strong color force" is similar to that in QED between Coulomb potential and van der Waals force.
- ✓ The Nuclear Force is not calculable in detail at the quark level and can only be deduced empirically from nuclear data.
- ✓ Some properties:
  - ❖ "Hard core" at very small distance
  - ❖ Very Strong at small distance (max at 1.3 fm)
  - ❖ Charge independence (same force between protons and neutrons)
  - ❖ Spin dependant
  - ❖ Non central component
  - ❖ If necessary, Three body interactions



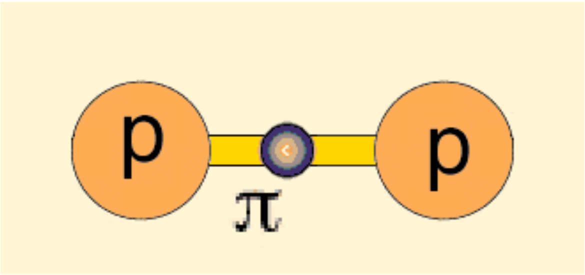
Nucleon-nucleon interaction

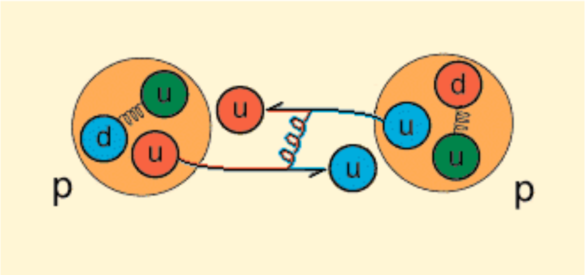
- Spin dependence
  (very qualitatively)
  - *Explains why pp and nn bound states do not exist while d=pn is bound*

Radial dependence of the nucleon-nucleon potential energy. Horizontal axis is in fm, vertical axis is in MeV.



- Quark-model description of the nuclear force:
  → pion exchange





The periodic table

- Only three elements are formed in the Big Bang (H, He, Li)
- All other elements are formed in stars
- Natural Elements : from H (Z=1) to Pu (Z=94)
- Periodic tables classifies elements according to their chemical properties.

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

* Lanthanoids	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinoids	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Atomic number colors show state at standard temperature and pressure (0 °C and 1 atm)

Solids **Liquids** **Gases** **Unknown**

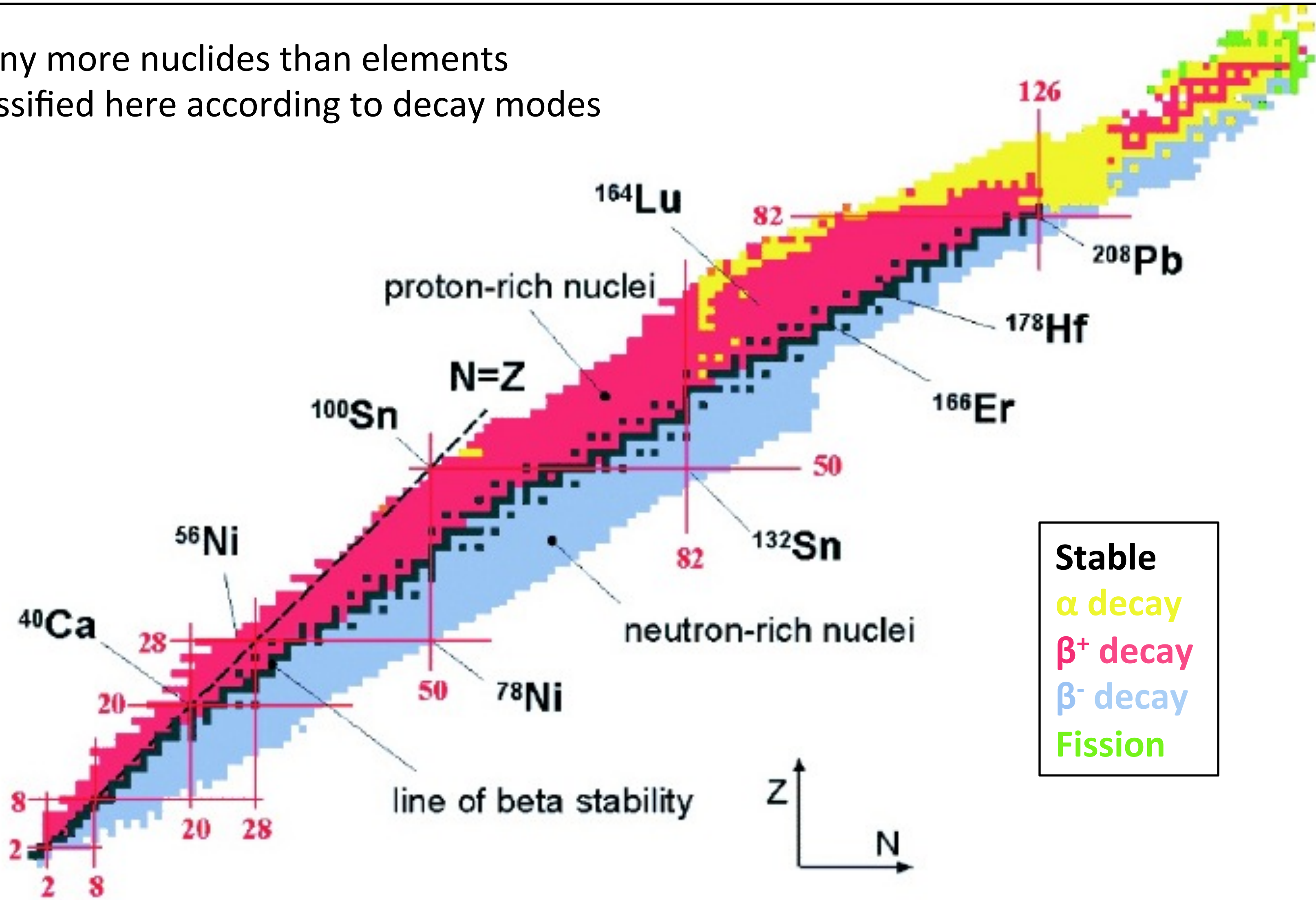
Borders show natural occurrence

Primordial | From decay | Synthetic | Undiscovered

Metals						Metalloids	Nonmetals			Unknown
Alkali metals	Alkaline earth metals	Inner transition elements		Transition elements	Other metals		Other nonmetals	Halogens	Noble gases	
		Lanthanides	Actinides							

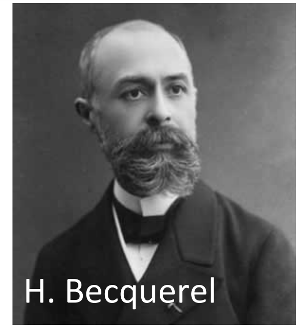
Chart of the nuclides

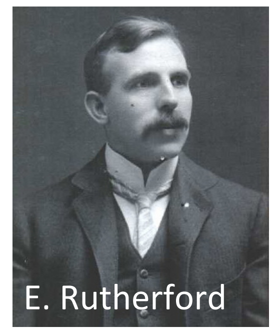
Many more nuclides than elements
Classified here according to decay modes

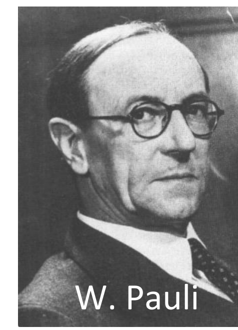


Historic

- 1895 : discovery of X-rays by Röntgen
- 1896 : discovery of the radioactivity of Uranium by Becquerel
- 1897 : discovery of electron by J. J. Thomson
- 1898 : discovery of the Radium by P. and M. Curie
- 1911 : discovery of the atomic Nucleus by E. Rutherford
- 1919 : discovery of the proton by E. Rutherford
- 1930 : discovery of the neutron by J. Chadwick
- 1930 : hypothesis of the neutrino by W. Pauli (discover in 1956 by F. Reines and C. Cowan)
- 1934 : discovery of artificial radioactivity by I. and F. Joliot-Curie







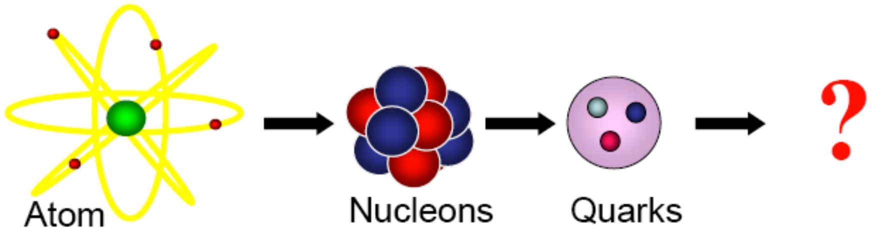

I.Curie and F. Joliot

Nuclear physics = 11 Nobel prices
Particle physics = 20 Nobel prices

Why study Nuclear physics ?

Nuclear processes play a fundamental role in the physical world:

- Origin of the Universe
- Creation of chemical elements
- Energy of stars
- Constituents of matter



Nuclear processes also have many practical applications

- Uses of radioactivity in research, health and industry
  NMR, radioactive dating, Radiotherapy,…
- Various tools for the study of materials
- Nuclear Power

Some properties of the nucleus

- Radioactivity
  - Decay modes
  - Decay rates
  - Allowed/forbidden decays
- Static properties
  - Mass
  - Spin
  - Parity
  - Magnetic moments
- Dynamic properties
  - Excited states
- Particle scattering
  - Nuclear size and shape

Useful relations

$\hbar c = 197\, MeV.fm \simeq 200\, MeV.fm$

$\alpha = e^2/(4\pi\epsilon_0 \hbar c) = 1/137$