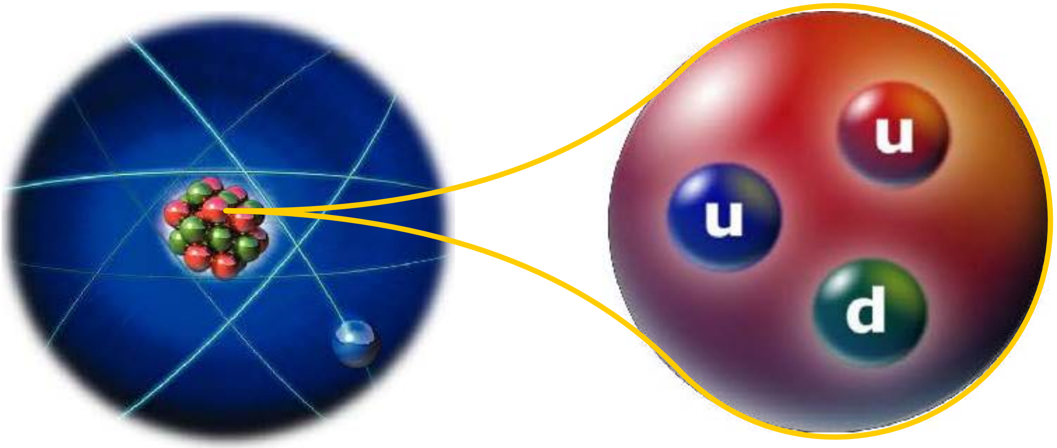
# Selected Topics in Nuclear Physics

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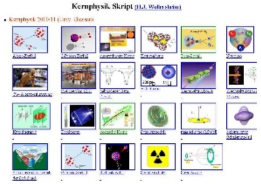
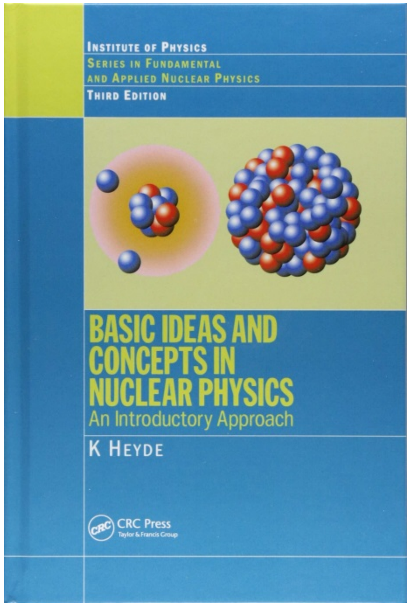
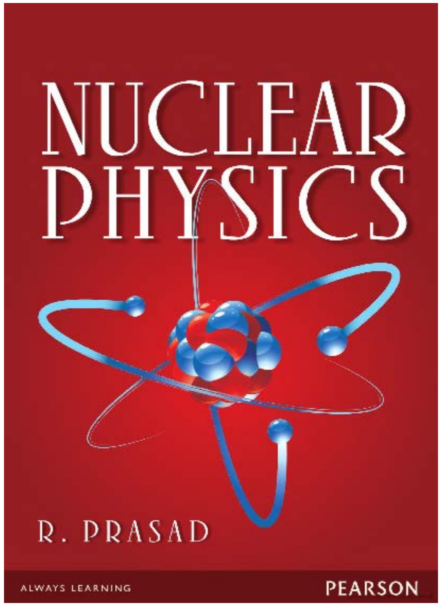
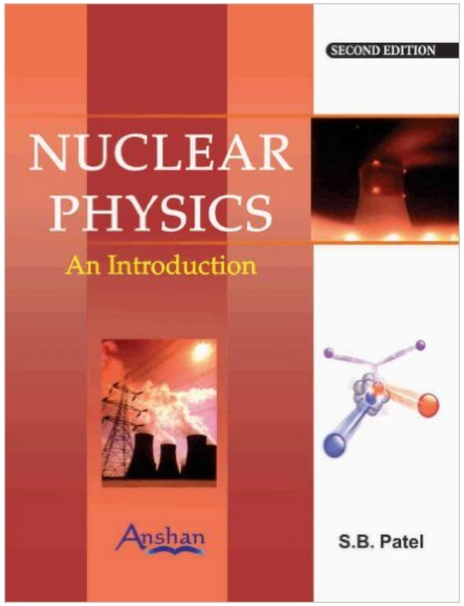
web-page: https://web-docs.gsi.de/~wolle/ and click on



# Literature

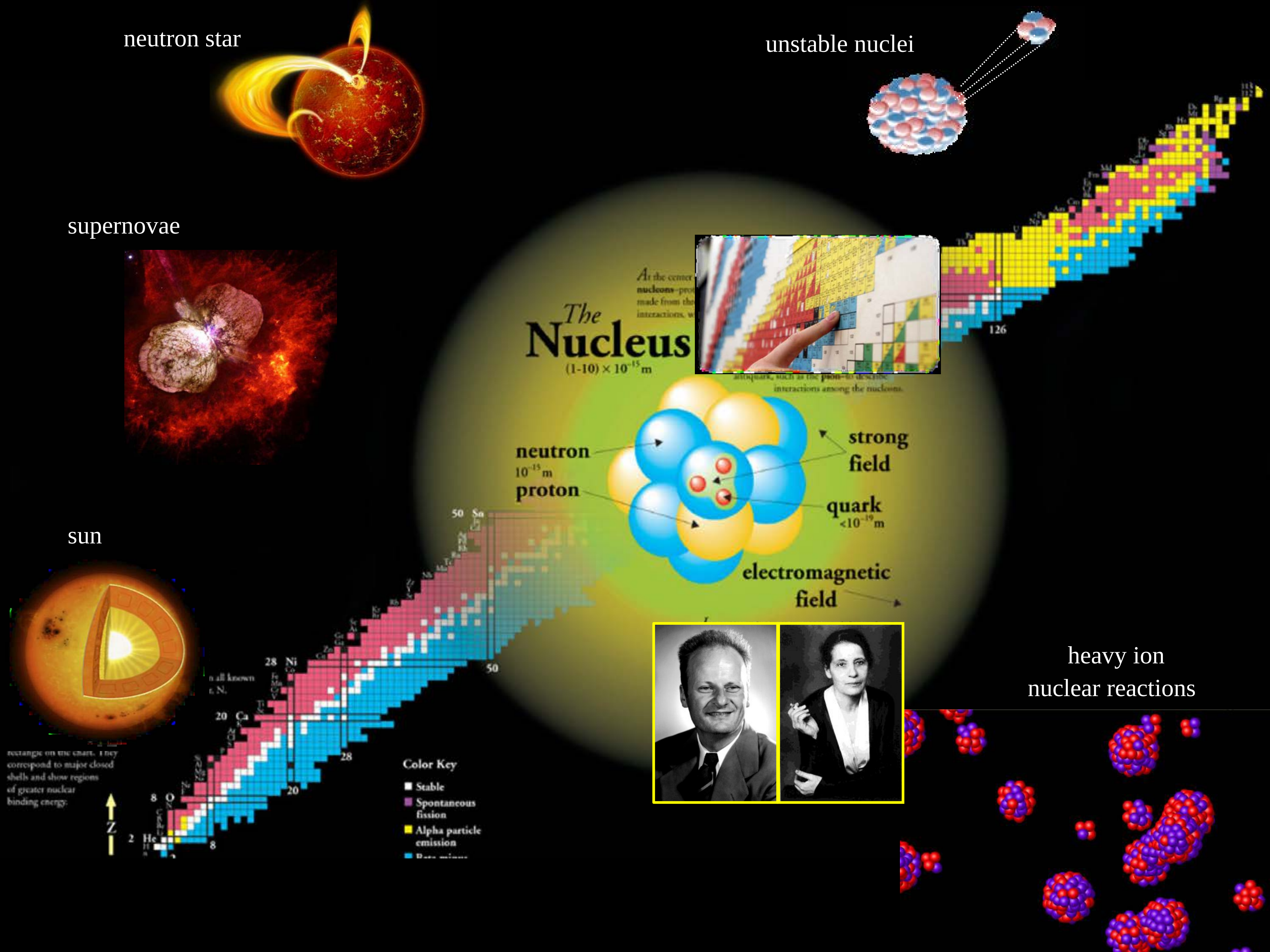



- ❖ Recommended Textbook
- ❖ Supplemental Textbook

www.bookzz.org


neutron star
unstable nuclei
supernovae
sun
heavy ion
nuclear reactions
The Nucleus
(1-10) × 10^-15 m
neutron
10^-15 m
proton
strong
field
quark
<10^-19 m
electromagnetic
field
Color Key
Stable
Spontaneous fission
Alpha particle emission
Z
126
50 Sn
28 Ni
20 Ca
8 O
2 He
50
28
20
8

Greek philosophers

4 building blocks

earth

air

water

fire

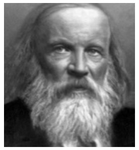
5th BC - Democritus

atomic hypothesis

18th – 19th century Lavoisier, Dalton, ...

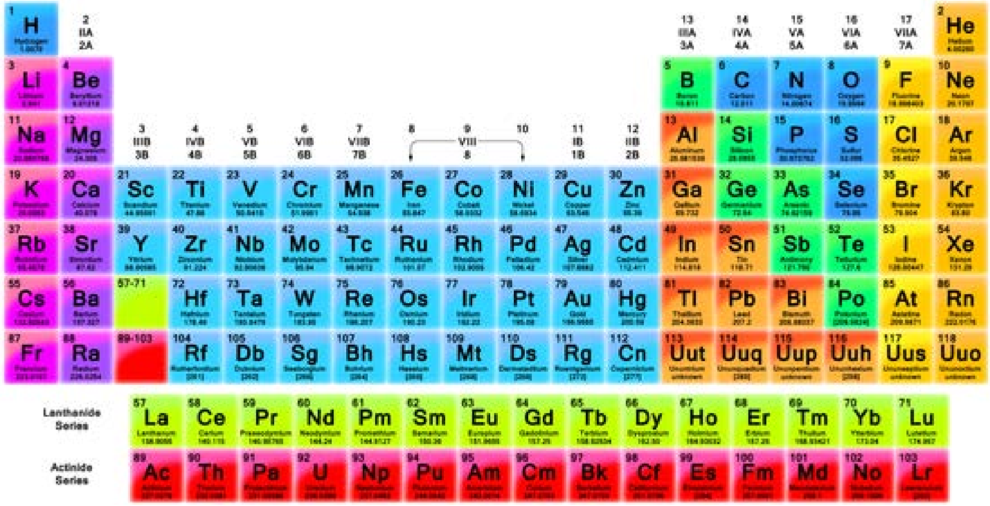
put atomic hypothesis on firm basis
distinction between compounds and pure elements

1896 Dmitri Mendeleev



92 building blocks
(chemical elements)

$_1H$, $_2He$, ... $_{92}U$



# Brief historical overview

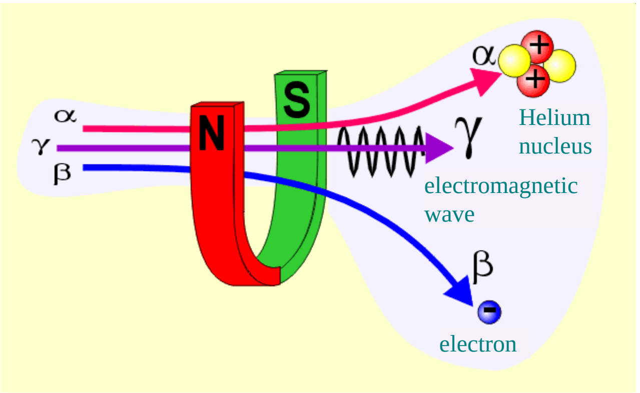
in search of the building blocks of the universe ...

## 1896 Henri Becquerel

discovers radioactivity

⇨ emission of radiation from atoms
3 types observed: α, β and γ

α and β deflected in opposite direction ⇨ opposite charges
α deflected less than β ⇨ α must have larger mass
γ not deflected ⇨ uncharged



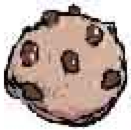

## ~1900 Ernest Rutherford

investigates new radiation

"... it was as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you"

α and β emissions change nature of element
α's charge = +2e     α's mass ~ 4H
β radiation = electrons
γ = electromagnetic radiation (photons)

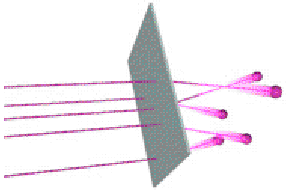
## 1911 Ernest Rutherford tests Thomson's model of the atom



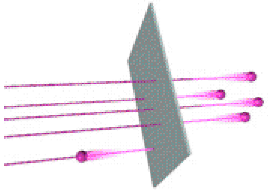
N electrons (-e·N) embedded in (+e·N) charge
uniformly distributed over atomic volume

"plum pudding model"

expected
α's ($_2$He) pushed a little to the side by charges of atom ($_{79}$Au)



observed
some α's deflected backwards to 180$^0$!!



# Brief historical overview

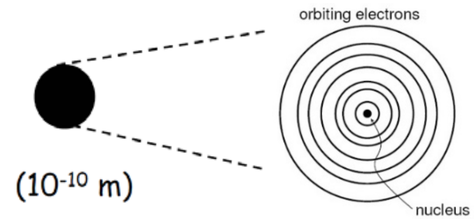
## in search of the building blocks of the universe

**1913 Niels Bohr**

planetary model of atom

all positive charges (and ~ all mass) concentrated in tiny region at the center

Atom = nucleus + electron



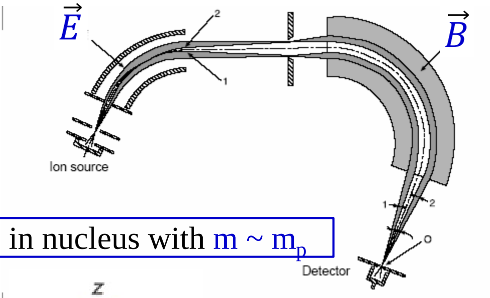

classical physics: electron should fall into the nucleus

**New mechanism is needed**

**1920 Francis William Aston** mass spectrograph

⇨ measures masses of atoms

| mass | charge |
|---|---|
| He ~ 4 H | He = 2 H |
| C ~ 12 H | C = 6 H |
| O ~ 16 H | O = 8 H |



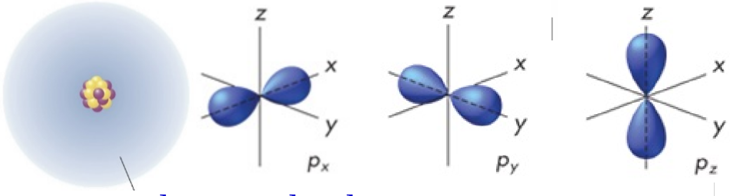

hypothesis of neutral particle in nucleus with $m \sim m_p$

**1925 Werner Heisenberg**

quantum mechanics

simplest atom = H

its nucleus = proton



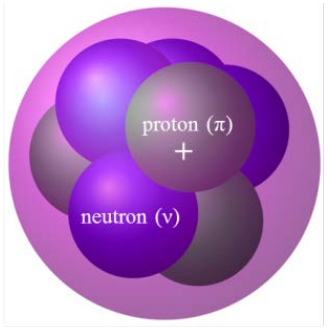

electron cloud

**1932 James Chadwick**

discovers the neutron

3 building blocks

electron + proton + neutron




~ $10^{-15}$ m = fm

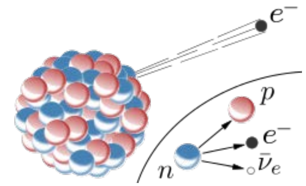
⇨ NUCLEAR PHYSICS

# Brief historical overview

in search of the building blocks of the universe

<u>1932</u> Enrico Fermi

developed the theory of β-decay

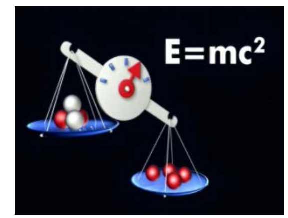


<u>1934</u> Irene Joliot-Curie & Frederic Joliot

artificial radioactivity $^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P^{*} + 1n$

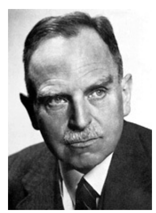
<u>1934</u> Hans Bethe

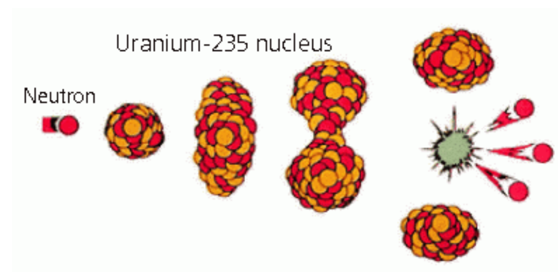
liquid drop model and mass formula




<u>1938</u> Otto Hahn, Lise Meitner & Fritz Strassmann

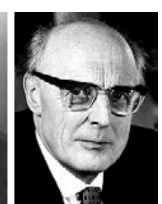
discover nuclear fission

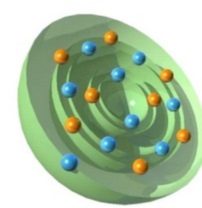





<u>1948</u> Maria Goeppert-Mayer & J. Hans D. Jensen

develop the nuclear shell model





# Brief historical overview

in search of the building blocks of the universe

1953 Aage Niels Bohr, Ben Roy Mottelson, Leo James Rainwater

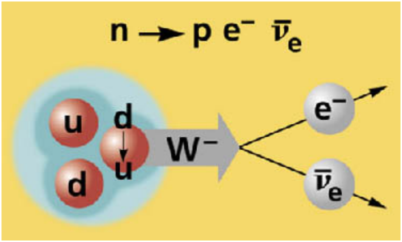
developed the collective nuclear model

1956 Frederick Reines & Clyde L. Cowan

discovery of the neutrino

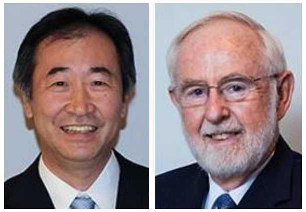
1983 Carlo Rubbia

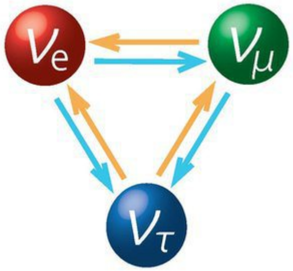
discovery of the W and Z Boson




1998 Takaaki Kajita & Arthur B. McDonald

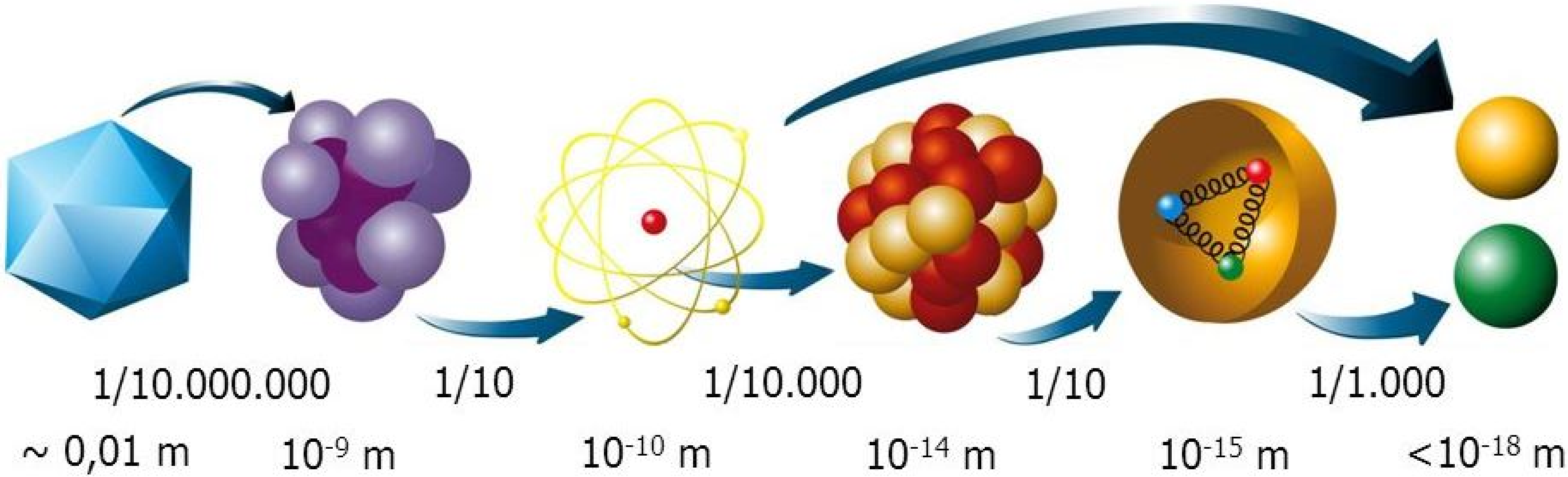
discovery of neutrino oscillations ⇨ neutrinos must have some mass





# So ... Where Do We Start?

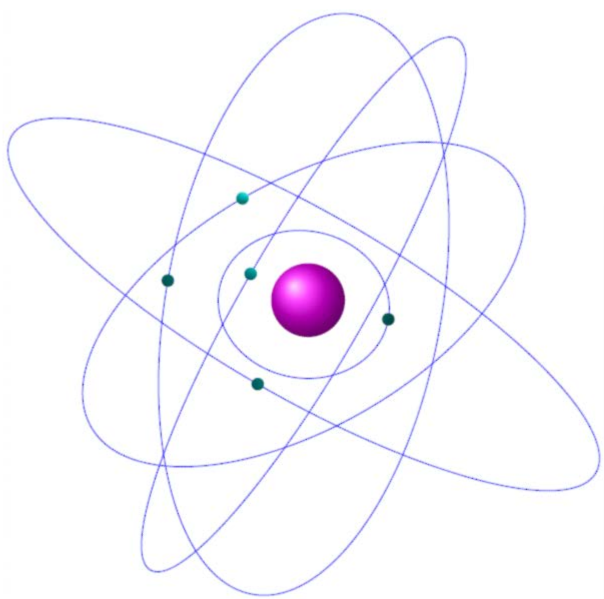
We need a point of reference to start discussing nuclear physics.




crystal molecule atom **nucleus** proton quark

# The atom

❖ atom is a neutral system

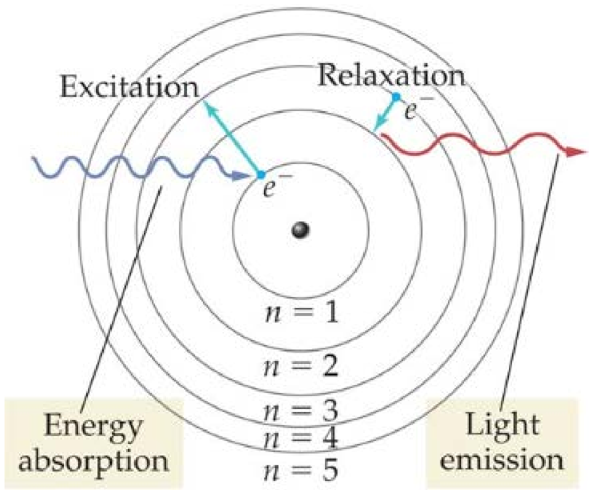


~ $10^{-10}$ m

atomic excitations

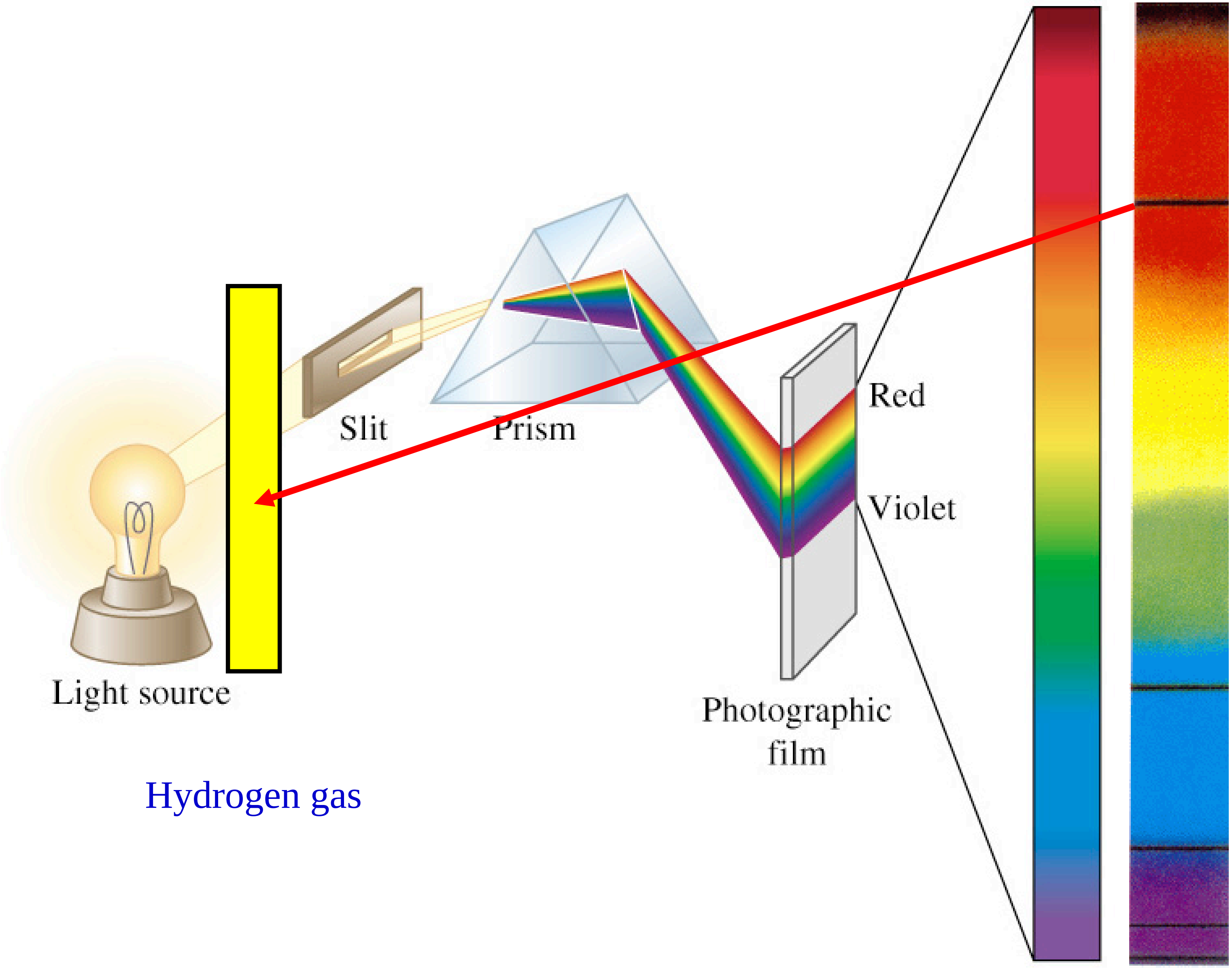
**~ 1-$10^{5}$ eV**

caused by transitions
between electronic states



# Bohr atomic model

absorption spectrum

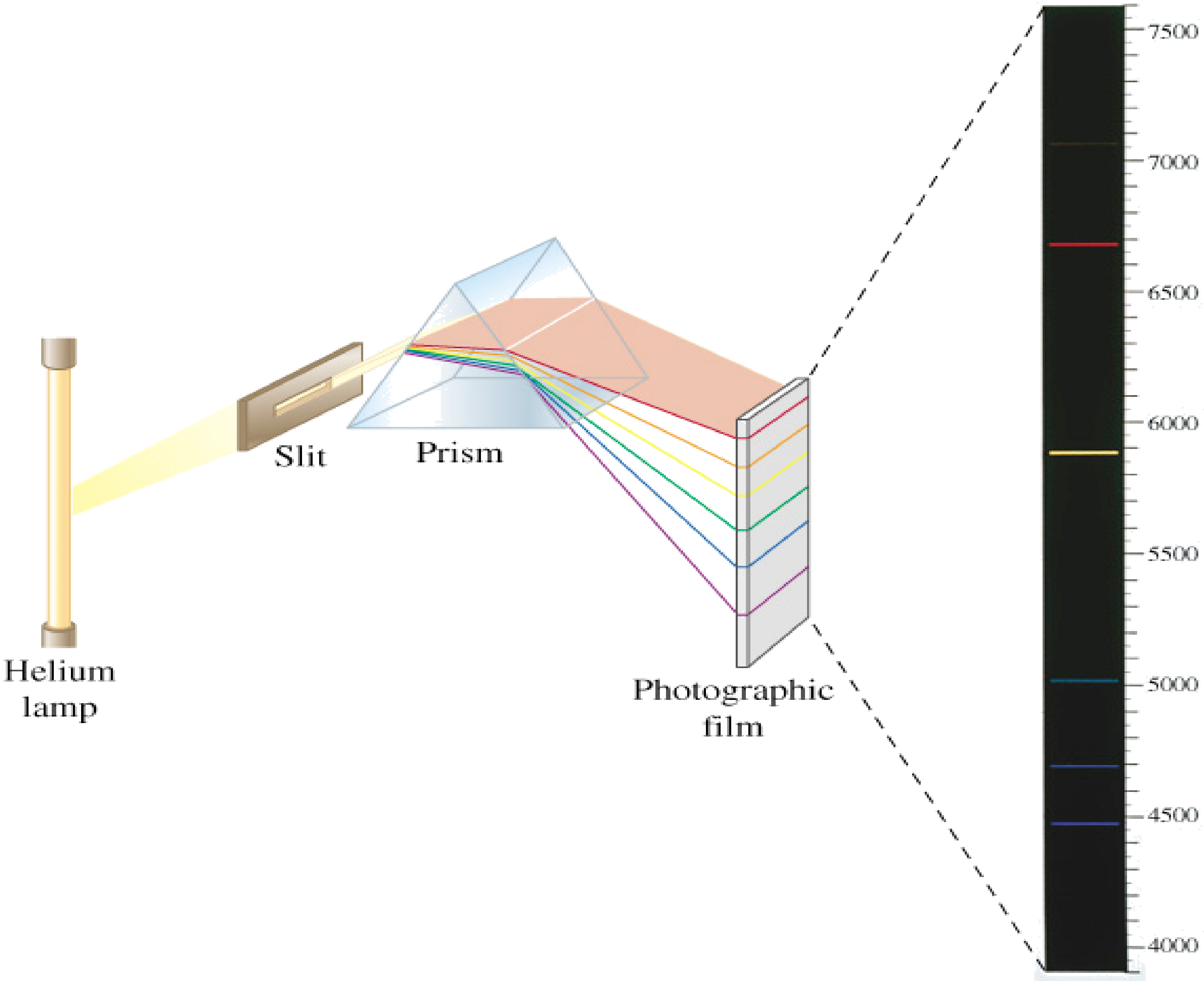



Hydrogen gas

Hydrogen

absorption spectrum

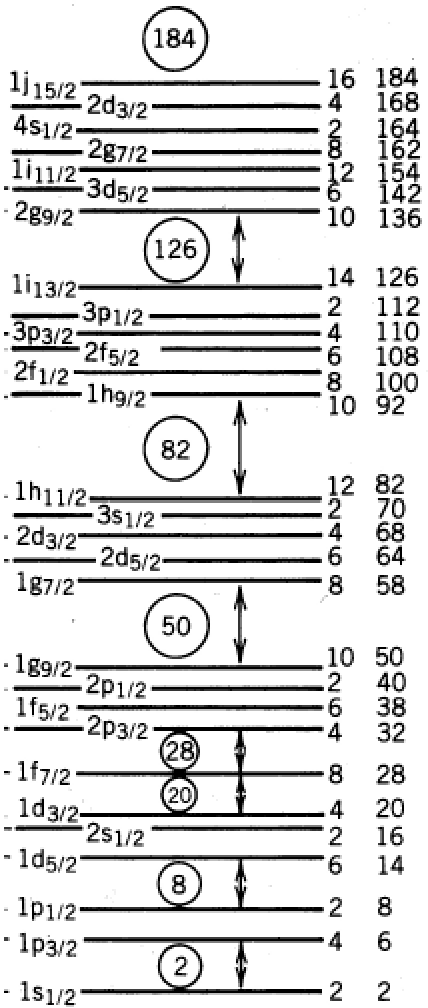
emission spectrum



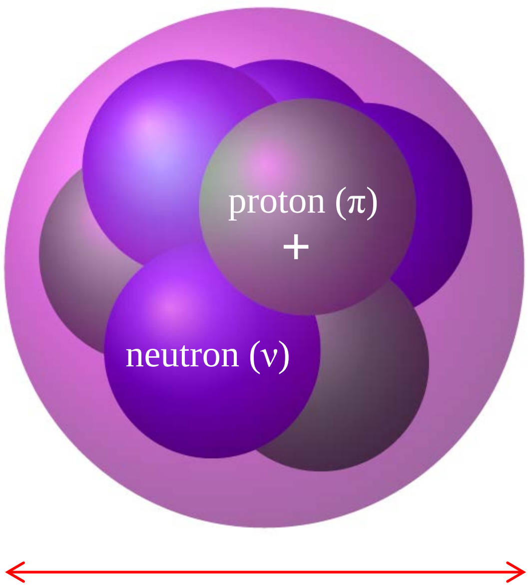

Helium

emission spectrum

# The atomic nucleus




nuclear shell model



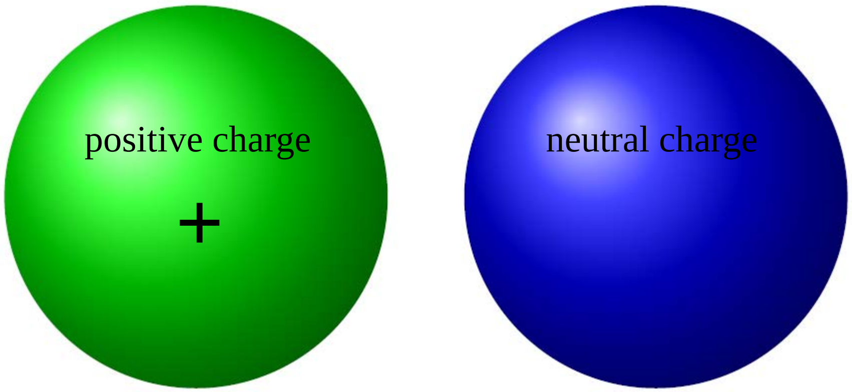

~ $10^{-15}$ m = fm

nuclear excitations

**~ $10^5$-$10^8$ eV**

caused by transitions between nuclear states

excitations can be caused by individual nucleons or as a collective motion of the nucleus

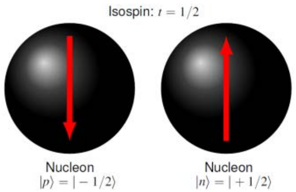



# proton neutron

protons and neutrons are very similar, they can be classified as the same object: **the nucleon**

Nucleons are quantum mechanical objects:

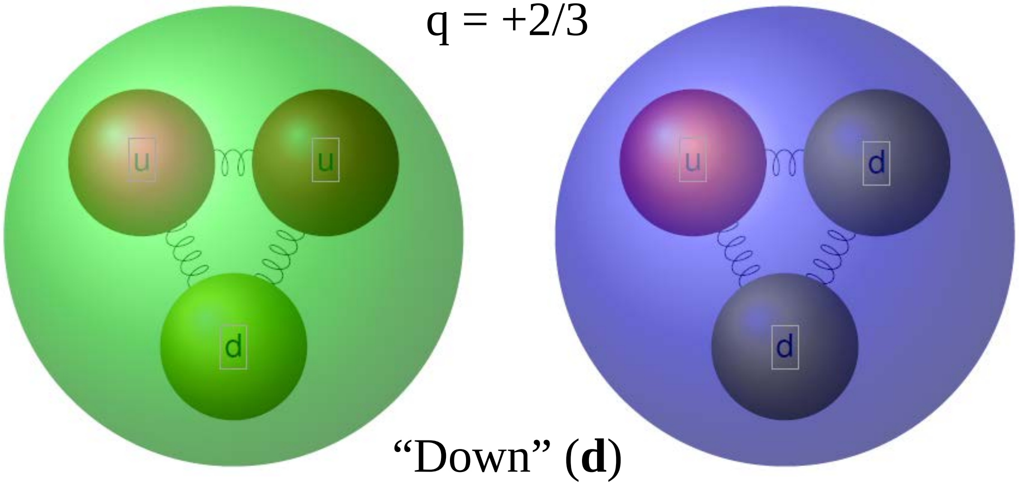
- They are spin ½ Fermions
- Radius: r ~ $1 \cdot 10^{-15}$ m, or 1 fm (fermi)
- Charge: p → + e
  n → 0
- Mass: p → 938.27 MeV/$c^2$
  n → 939.56 MeV/$c^2$
- Isospin: |p > = | -1/2 >
  |n > = | +1/2 >



# Structure of nucleons

particle excitations
**> $10^9$ eV**

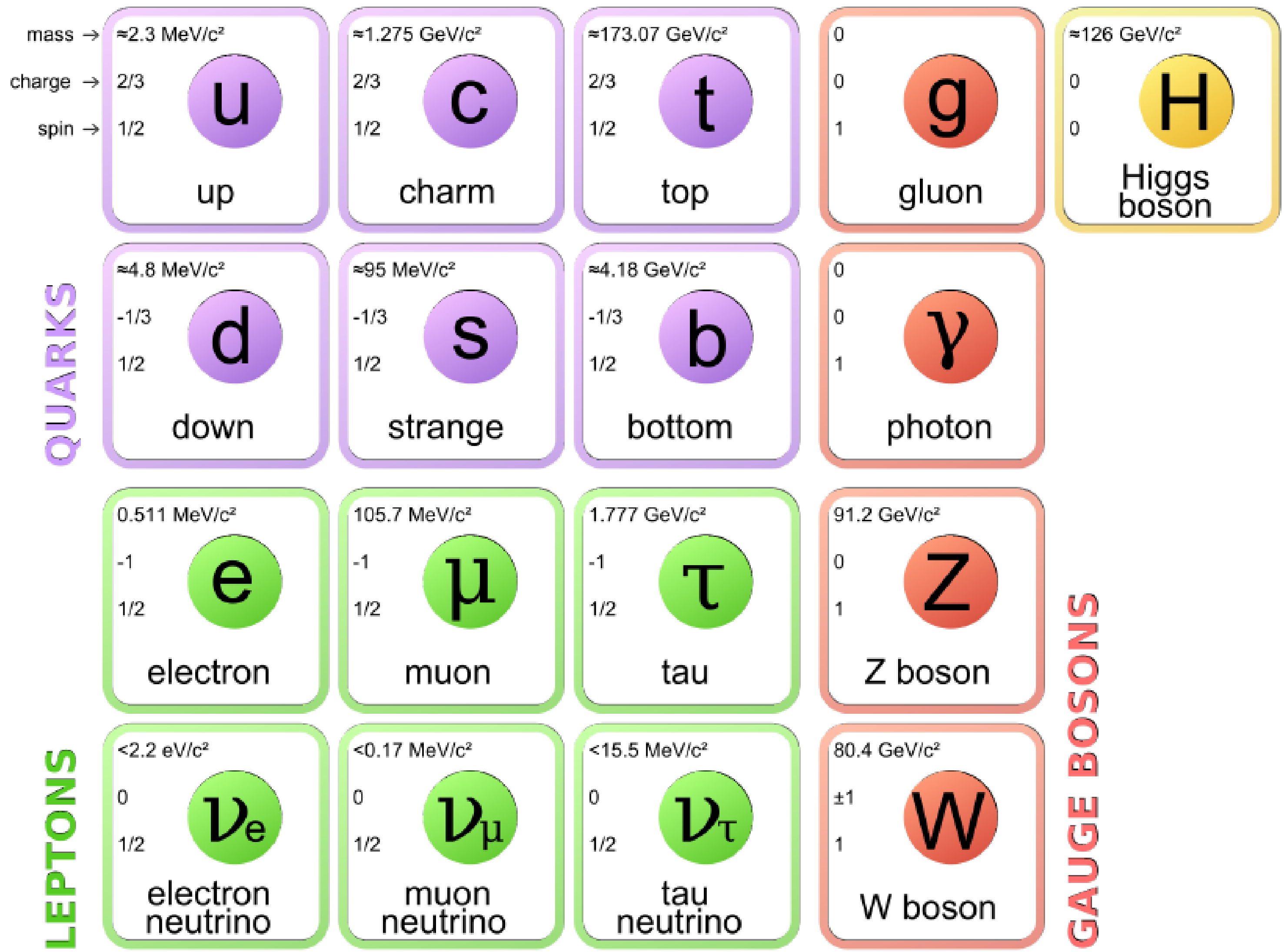
“Up” (**u**)
m = 2.4 MeV/$c^2$
q = +2/3



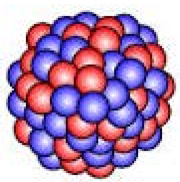

“Down” (**d**)
m = 4.8 MeV/$c^2$
q = -1/3

proton | neutron
---|---
**u, u, d** | **u, d, d**

# Elementary particles of the standard model



# Terminology



**A** – mass number gives the number of nucleons in the nucleus
**Z** – number of protons in the nucleus (atomic number)
**N** – number of neutrons in the nucleus

**A** = **Z** + **N**

In nuclear physics, nucleus is denoted as $^{A}_{Z}X$ , where X is the chemical element
e.g. $^{1}_{1}H$ - hydrogen, $^{12}_{6}C$ - carbon, $^{197}_{79}Au$ - gold.

Different combinations of Z and N (or Z and A) are called nuclides

- nuclides with the same mass number **A** are called *isobars* — $^{17}_{7}N, ^{17}_{8}O, ^{17}_{9}F$
- nuclides with the same atomic number **Z** are called *isotopes* — $^{12}_{6}C, ^{13}_{6}C, ^{14}_{6}C$
- nuclides with the same neutron number **N** are called *isotones* — $^{13}_{6}C, ^{14}_{7}N$
- nuclides with equal proton number and equal mass number, but different excited states are called *nuclear isomers* — $^{180}_{73}Ta, ^{180m}_{73}Ta$

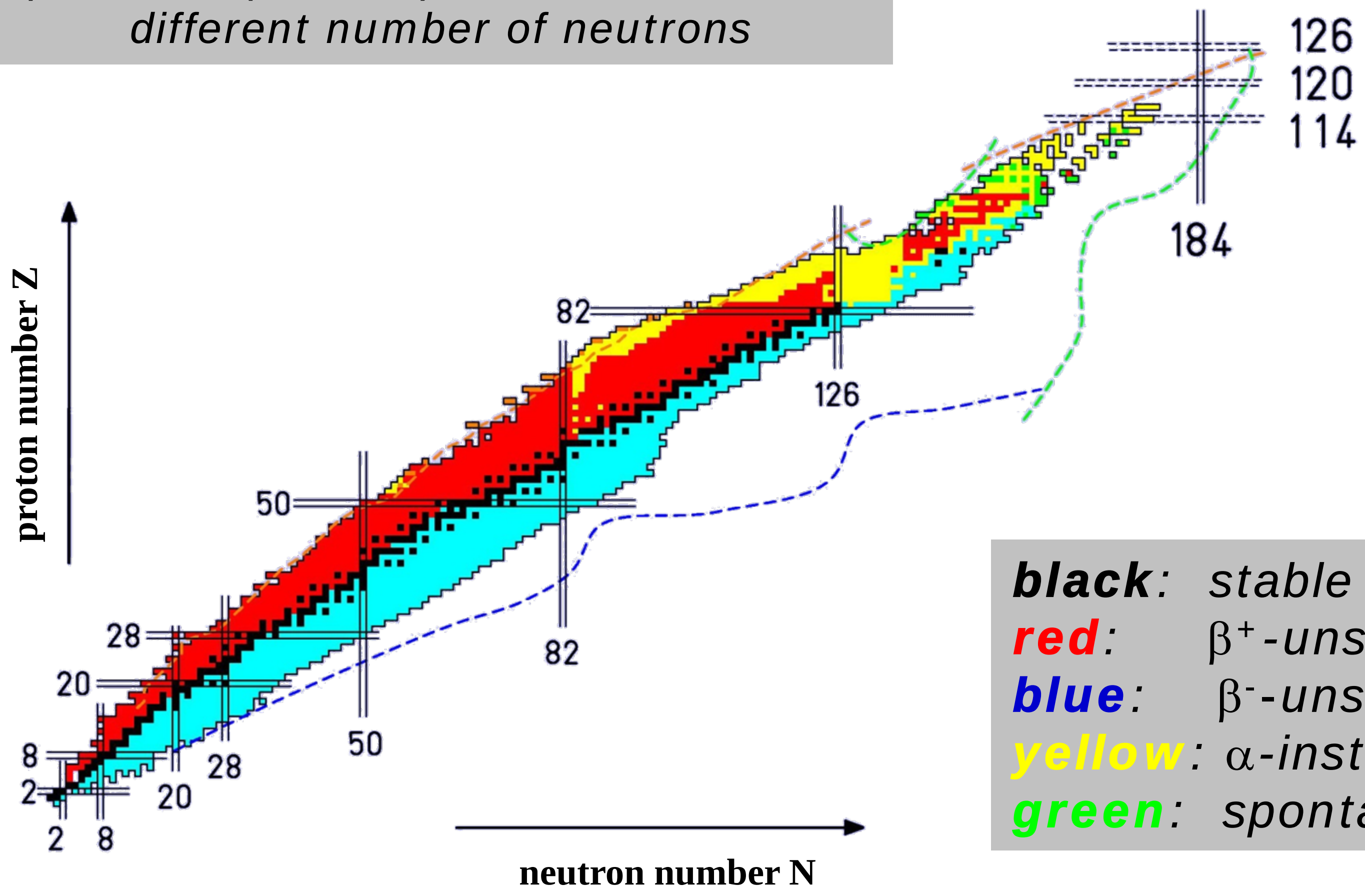
The most long-lived non-ground state nuclear isomer is tantalum-180m, which has a half-life in excess of 1000 trillion years

# The Chart of Nuclides
## - the “Playground” for Nuclear Physics

***chart of nuclides:***

*-representation of isotopes in the Z-N plane*

*-isotope: atom (nucleus) of an element with different number of neutrons*




***black**: stable isotope*
***red**: $\beta^+$-unstable isotope*
***blue**: $\beta^-$-unstable isotope*
***yellow**: $\alpha$-instable isotope*
***green**: spontaneous fission*

# The Chart of Nuclides
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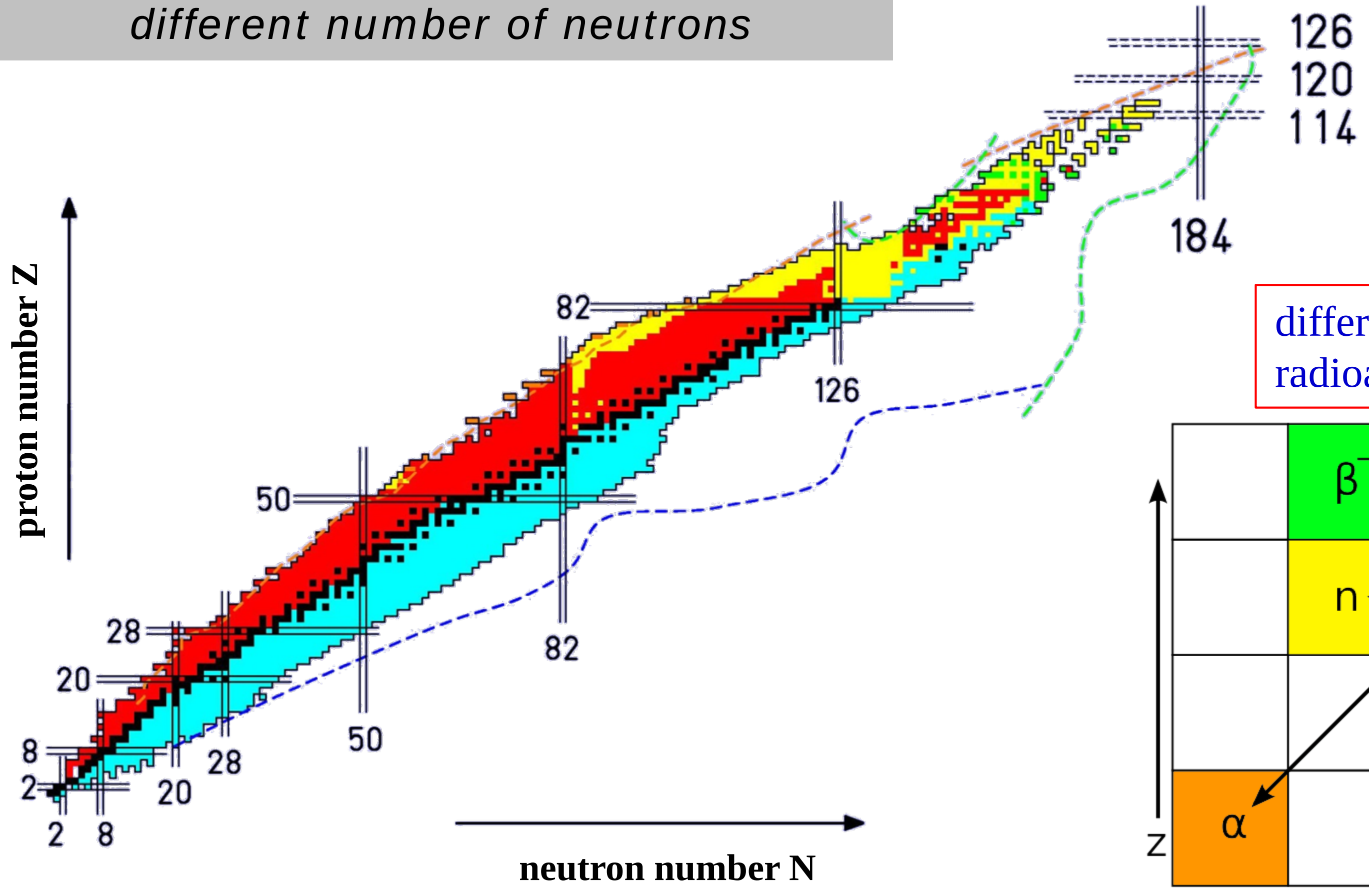
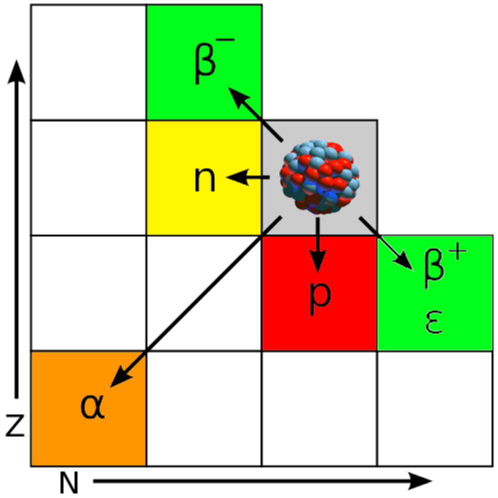



different modes of radioactive decay



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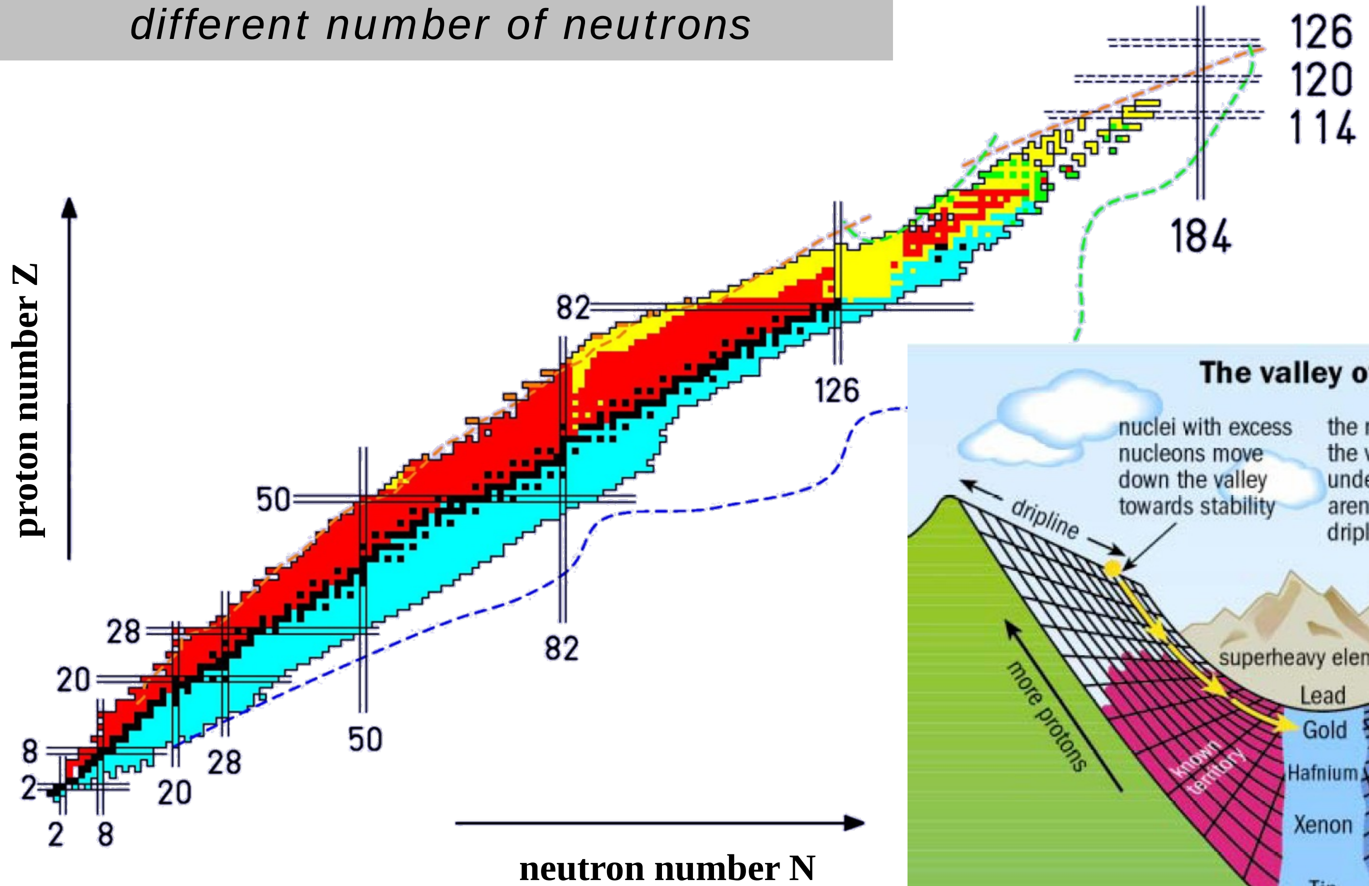
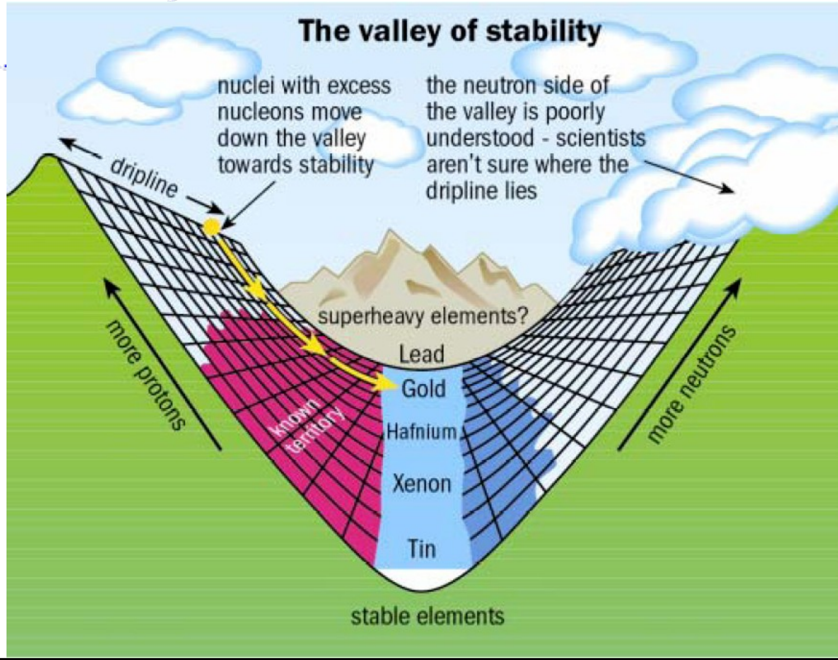
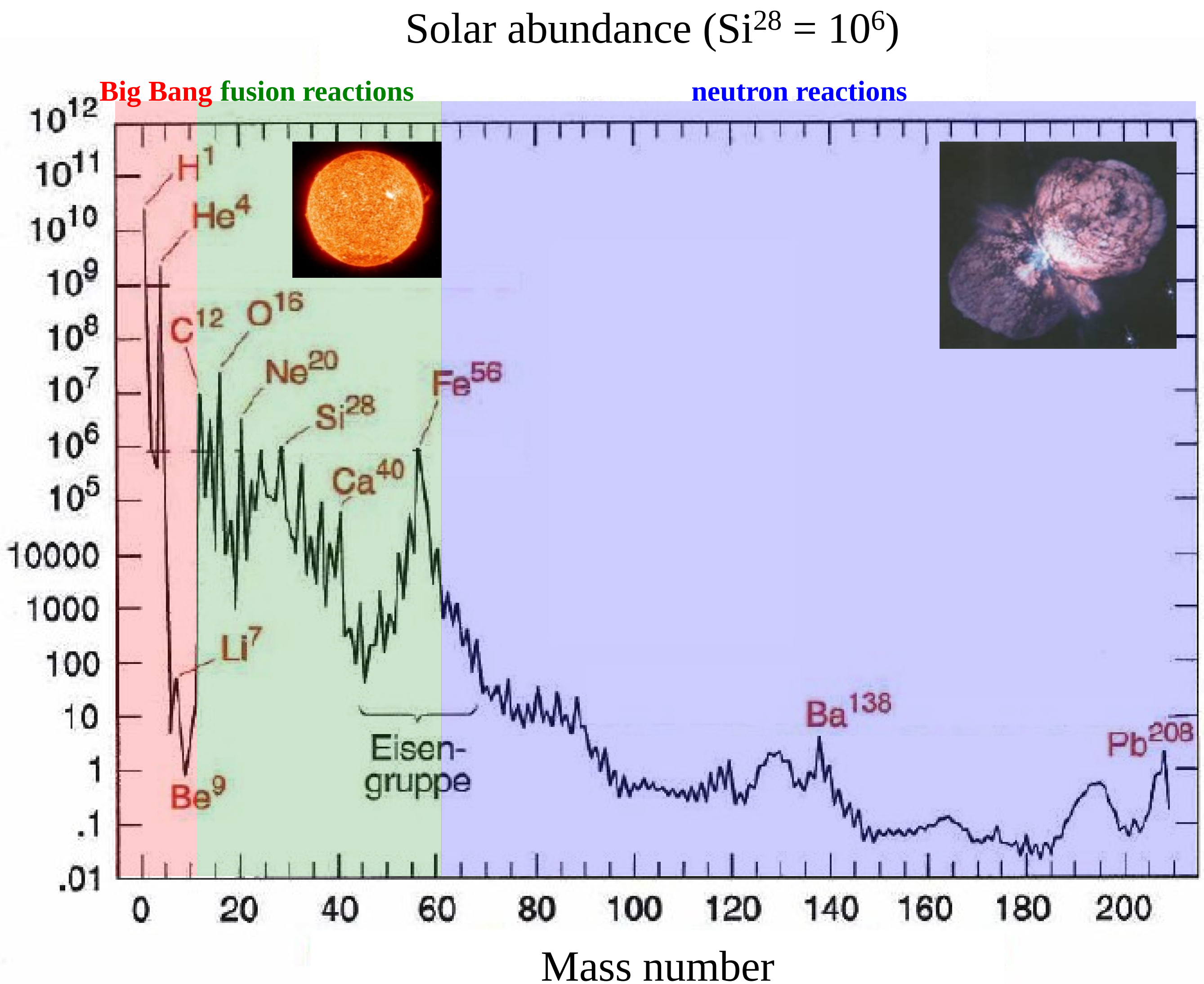


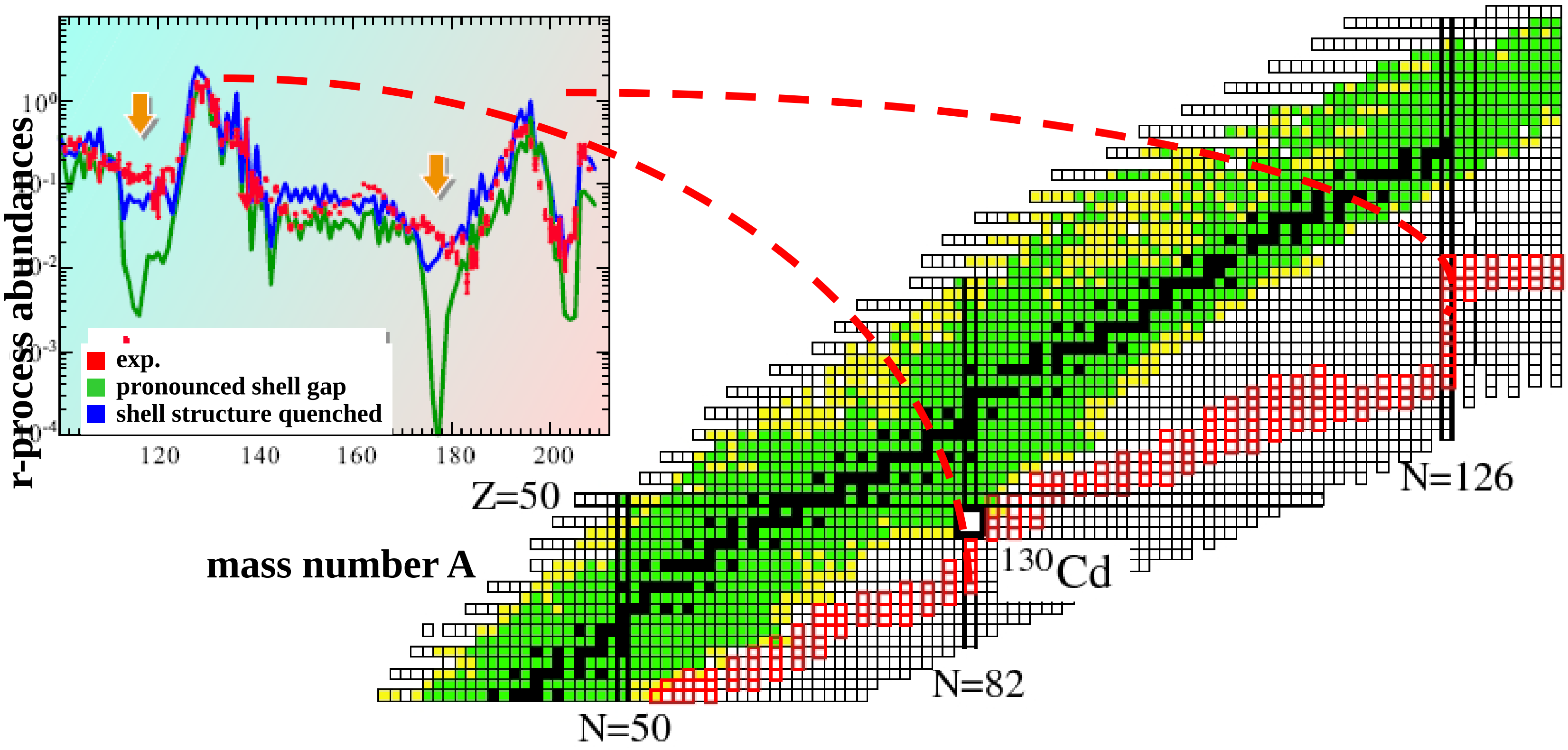





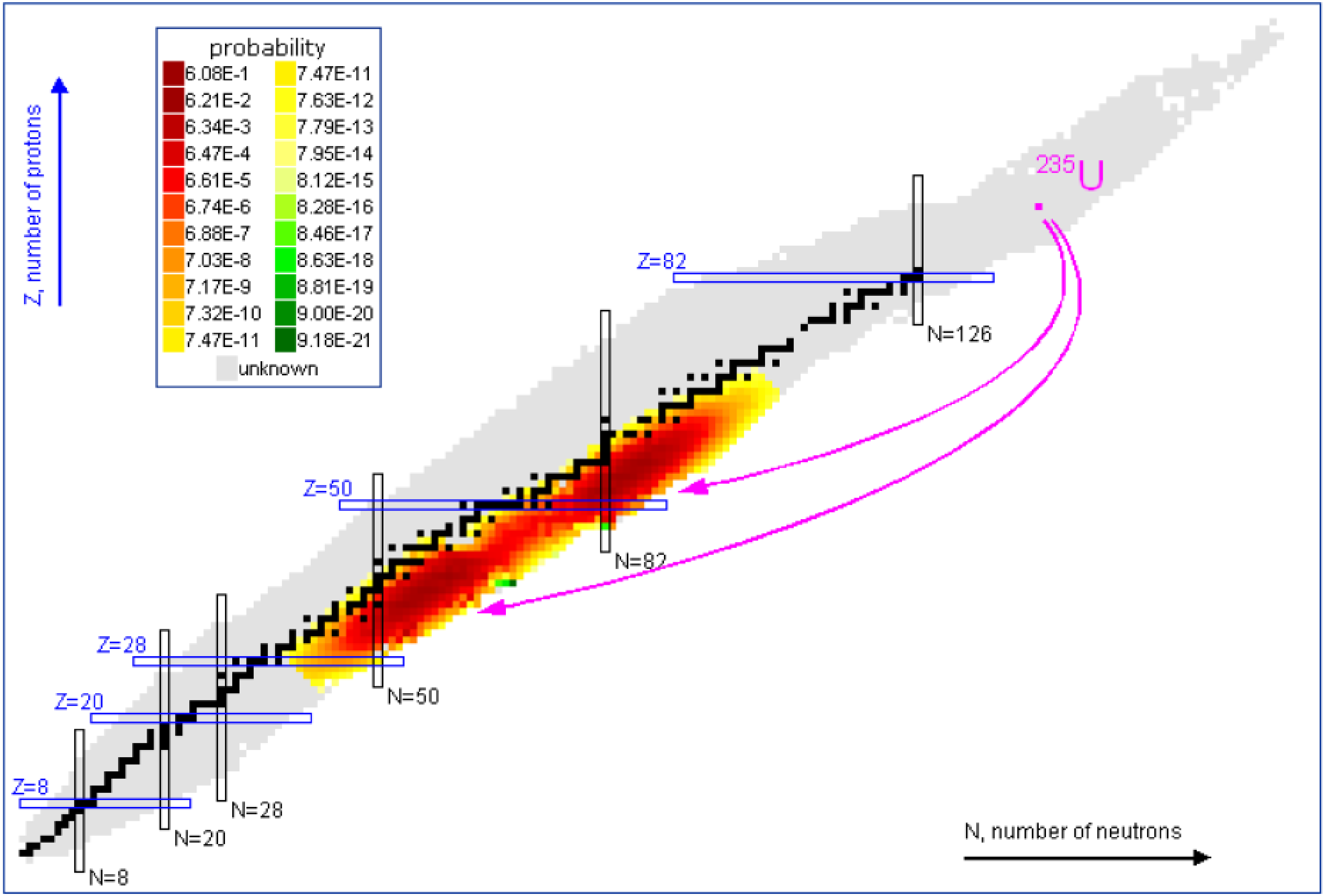

open questions:

- Why is Fe more common than Au ?
- Why do the heavy elements exist and how are they produced?
- Can we explain the solar abundances of the elements?

# Shell evolution, Nucleosynthesis (r-process)




**Assumption of N=82 and N=126 shell quenching leads to a considerable improvement in the global abundance fit in r-process calculations**

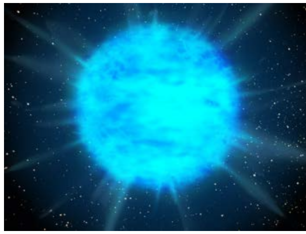

probability
6.08E-1
6.21E-2
6.34E-3
6.47E-4
6.61E-5
6.74E-6
6.88E-7
7.03E-8
7.17E-9
7.32E-10
7.47E-11
7.47E-11
7.63E-12
7.79E-13
7.95E-14
8.12E-15
8.28E-16
8.46E-17
8.63E-18
8.81E-19
9.00E-20
9.18E-21
unknown
Z, number of protons
N, number of neutrons
235U
Z=82
Z=50
Z=28
Z=20
Z=8
N=126
N=82
N=50
N=28
N=20
N=8

# Nuclear matter has exotic properties

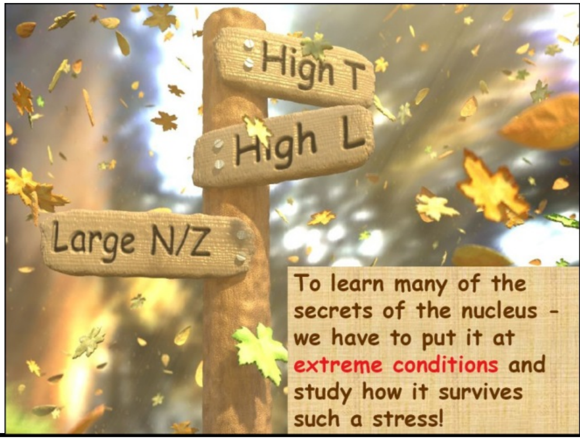
- Nuclear matter is extremely heavy  $2.3\cdot10^{17}$ kg/m$^3$

for comparison:
- sea water: $1.0\cdot10^3$ kg/m$^3$
- tin oxide: $1.6\cdot10^3$ kg/m$^3$
- steel: $1.1\cdot10^4$ kg/m$^3$
- lead: $2.5\cdot10^4$ kg/m$^3$
- core of the sun: $1.5\cdot10^5$ kg/m$^3$

- Although we know nuclear matter only in small portions inside atoms, it exists in nature also in big portions:
  - Neutron Stars have a diameter of typically 10 km



- Nuclear structure physics investigates the response of the nucleus as a function of:

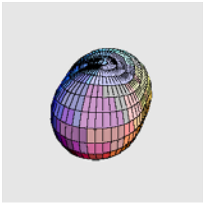



$$\rho = \frac{A m_p}{4/3\,\pi \cdot R^3} = \frac{m_p}{4/3\,\pi \cdot r_0^3} = \frac{1.66\cdot10^{-27}kg}{4/3\,\pi\cdot(1.2\cdot10^{-15}m)^3}$$

# Properties of stable nuclei

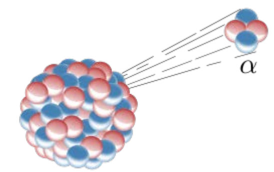
## Radius & shape

– size: nuclear radius ($R = 1.2 \cdot A^{1/3}$ fm)
– shape: spherical / deformed (prolate / oblate)



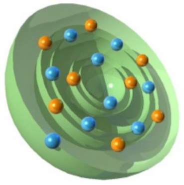
## Density & mass

– constant nuclear density ($\rho = 10^{17}$ kg/m$^3$)
– nuclear mass & valley of stability



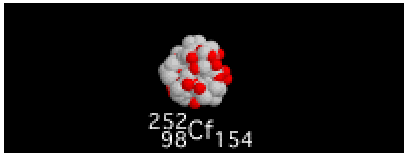

## Nuclear states

– quantum numbers spin S, parity P, magnetic moments
– shell structure: valence-nucleons, collective excitations



## Nuclear reactions

– binding energy: fusion & fission, nuclear astrophysics
– special reactions: exchange / transfer



# Long Standing Questions of Nuclear Structure Physics

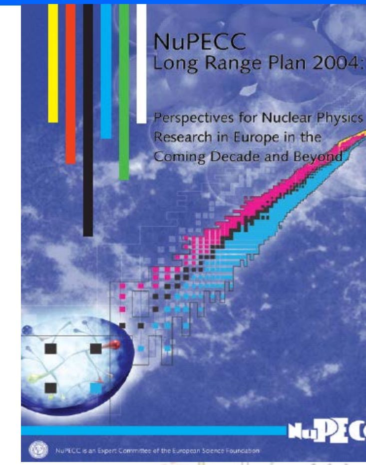
- What are the limits for existence of nuclei?
  - Where are the proton and neutron drip lines situated?
  - Where does the nuclear chart end?

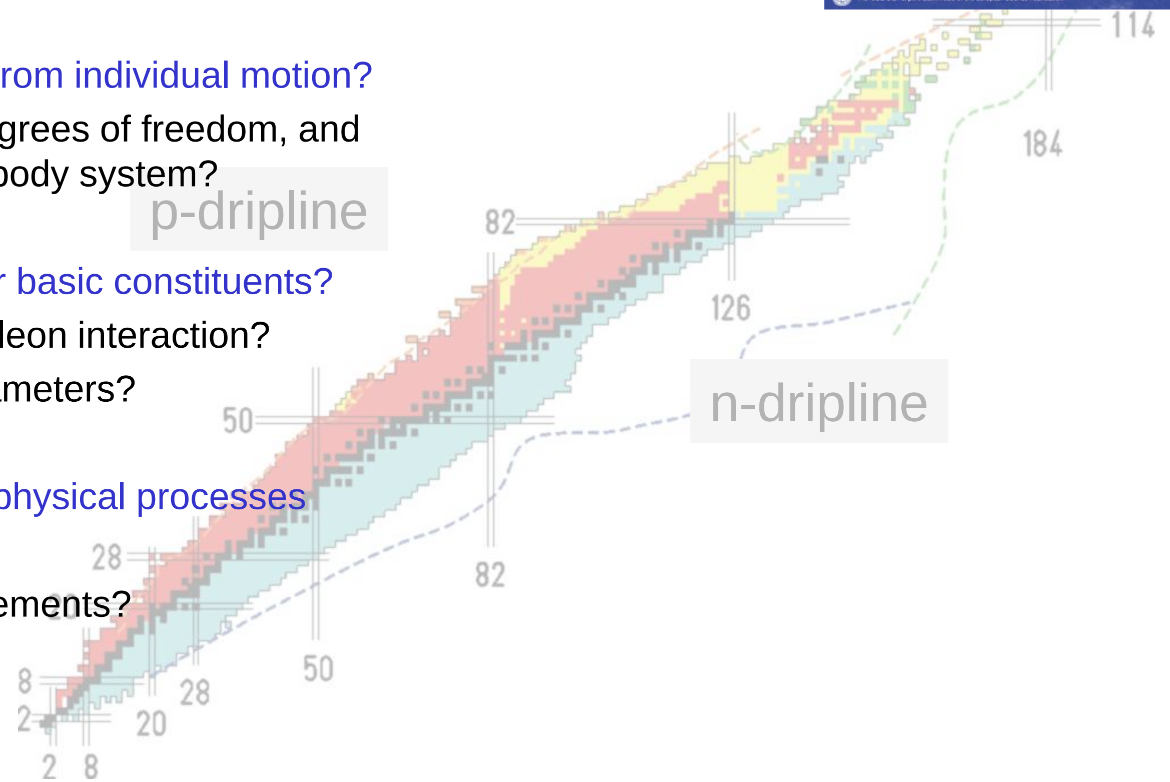
- How does the nuclear force depend on varying proton-to-neutron ratios?
  - What is the isospin dependence of the spin-orbit force?
  - How does shell structure change far away from stability?

- How to explain collective phenomena from individual motion?
  - What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?

- How are complex nuclei built from their basic constituents?
  - What is the effective nucleon-nucleon interaction?
  - How does QCD constrain its parameters?

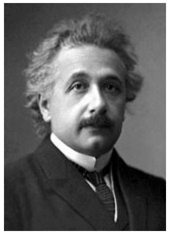
- Which are the nuclei relevant for astrophysical processes and what are their properties?
  - What is the origin of the heavy elements?



# Nuclear units and physical constants

## Nuclear units



Albert Einstein
1879-1955
Nobel price 1921

- length unit:
  Fermi = femtometer = fm = $10^{-15}$ [m]
- energy unit:
  MeV = $10^6$ eV = $10^6 \cdot 1.602 \cdot 10^{-19}$ CV = $1.602 \cdot 10^{-13}$ [J]
- mass unit:
  1 u = 1/12·m[$^{12}$C] = 931.49432 MeV/$c^2$ = $1.66054 \cdot 10^{-27}$ [kg]
- time unit:
  [s] or [fm/c] ≈ $3 \cdot 10^{-24}$ [s]

$$E = m \cdot c^2$$

## Constant of nature relevant to nuclear physics

- speed of light in vacuum, c = $2.99792458 \cdot 10^8$ [m/s]
- Planck's constant / 2π = ħ = $6.58211889 \cdot 10^{-22}$ [MeV s] = 1.054·10-34 [J s]
- ħc = 197.3269602 [MeV fm]
- fine structure constant (dimensionless), $\alpha = e^2/(\hbar c)$ = 1/137.0359976
  → $e^2 = \alpha \cdot \hbar c$ = 1.4399643929 [MeV fm]
- elementary charge, e = $1.602 \cdot 10^{-19}$ [C] or e = 1.1999851636 $\left[\sqrt{MeV\ fm}\right]$
- rest energy of proton, $m_p c^2$ = 938.27231 [MeV]
- rest energy of neutron, $m_n c^2$ = 939.56563 [MeV]
- rest energy of electron, $m_e c^2$ = 0.51099906 [MeV]
- Avogadro's number, $N_A$ = $6.0221367 \cdot 10^{23}$ /mol

- E – p relationship: $E^2 = p^2c^2 + {m_0}^2c^4$
- Kinetic energy: $T = E - m_0c^2 = m_0c^2(\gamma - 1)$