Radioactivity
lecture 1

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in this lecture:

- Radioactive decay definition
- History of discovery
- Mass of atoms and nuclei, Conditions of decay, Stability valley of the nuclei
- Types of radioactive decay
- Energy and probability of decay
- Exponential decay law, Mean lifetime, Half-life and specific activity

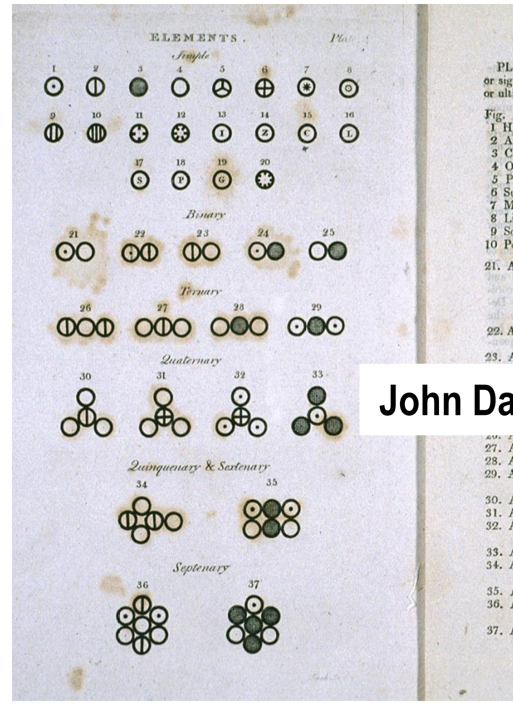
Radioactive decay
definition

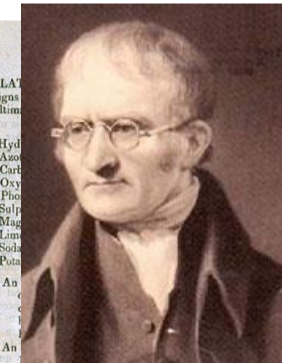
Radioactive decay is spontaneous change of the composition (charge Z, the mass number A) or of the internal structure of unstable atomic nuclei by the emission of particle(s) and / or nuclear fragment(s)

Atom

The idea that matter is consists of discrete units (atoms) is a very old one (ancient India and Greece)

- In the beginning of the XIX century J. Dalton used the concept of atoms to explain why elements always react in ratios of small whole numbers



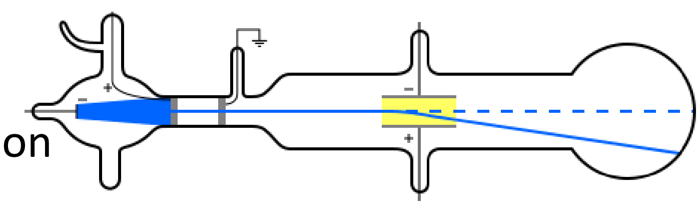


John Dalton (1766 –1844)

- In 1827, botanist Robert Brown observed chaotic motion of particles in water ("Brownian motion“)

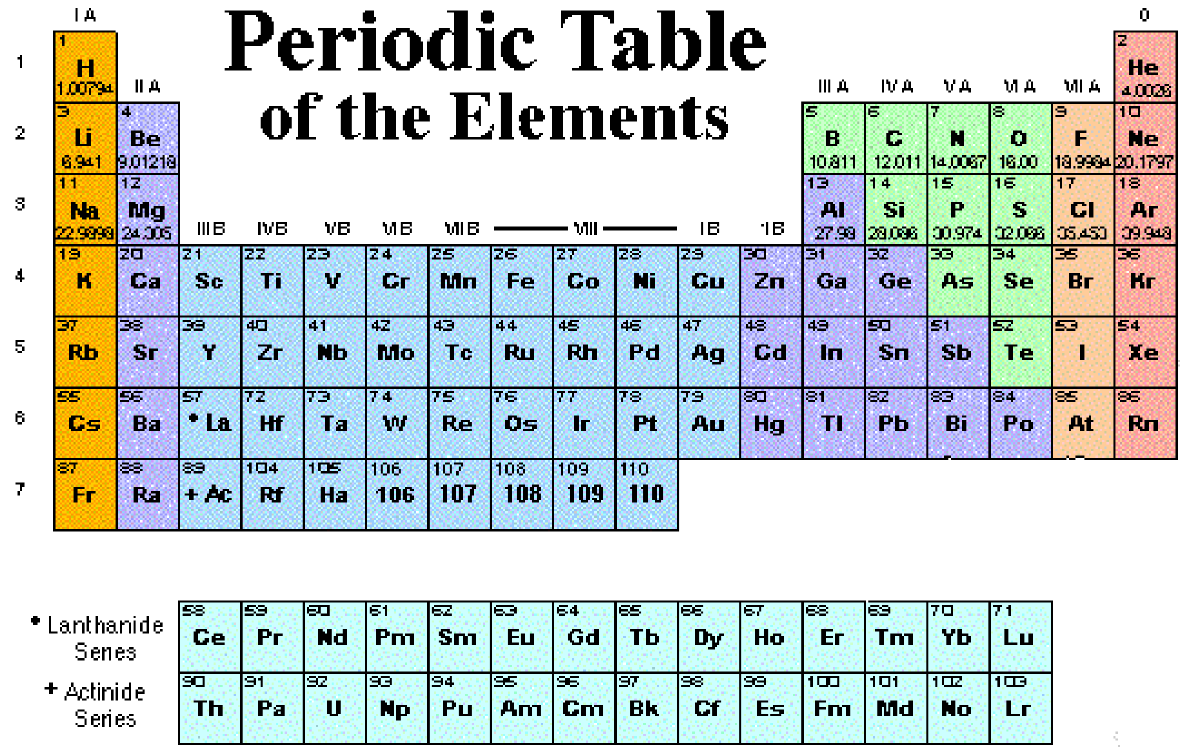
Robert Brown (1773 –1858)

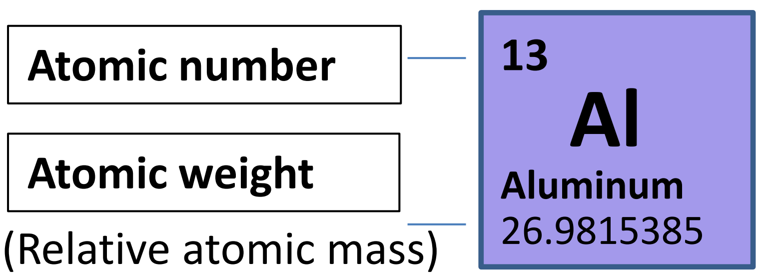
- 1897: discovery of electron, the first subatomic particle, by J.J.Thomson



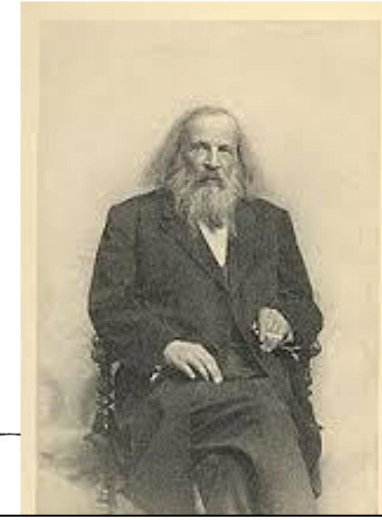
- 1913: first evidence for multiple isotopes of a stable elements

Sir Joseph John Thomson (1856 –1940)

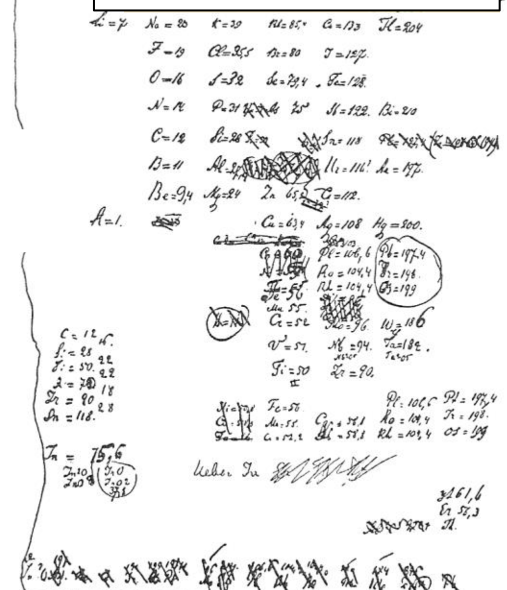




Draft of periodic table by Mendeleev, 1869



Dmitri Mendeleev
1834 –1907



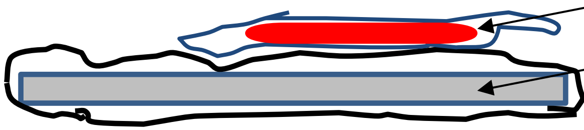
Without giving a presentation on the structure of the atom, the periodic law, however, surely leads straight to the problem

Radioactive decay
discovery

Becquerel has been studied the phenomenon of phosphorescence (long time irradiation of light by some materials after excitation by higher energy irradiation, e.g., by ultraviolet present in the solar light)

In 1896 Becquerel has found that all uranium salts fogged photographic plate being covered with opaque paper. Becquerel also discovered ionization of air by the irradiation of uranium.

Antoine Henri Becquerel
(1852 –1908) in the lab



Uranium salt

Photographic plate covered by opaque paper

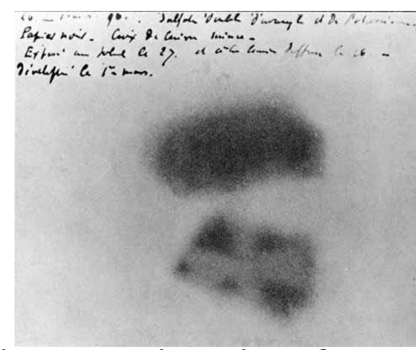


Image of photographic plate fogged by exposure to radiation from uranium salt

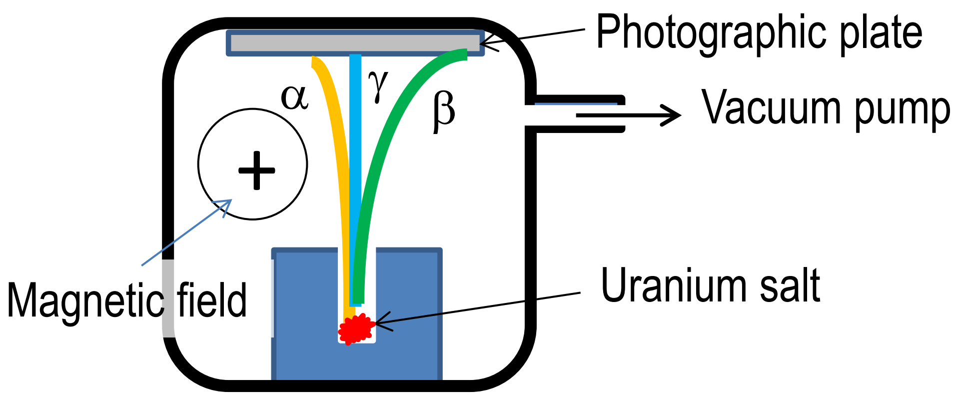
He decided that uranium atoms spontaneously irradiate penetrating rays.

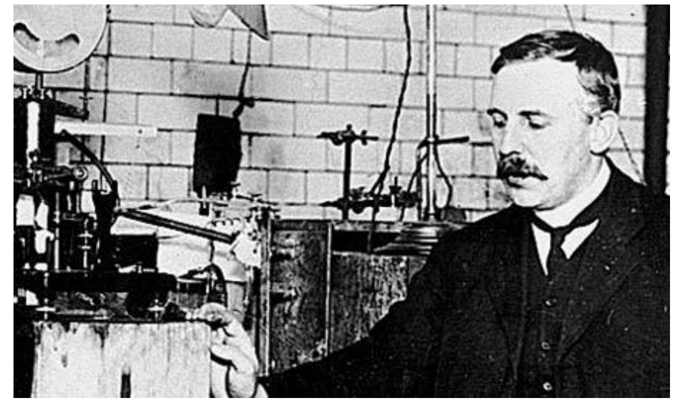
In 1897-1898 **Pierre and Marie Curie** studied many other elements and found similar effect for thorium

Radioactive decay

further study

E. Rutherford observed that uranium irradiated three different types of particles (with different behavior in magnetic field)

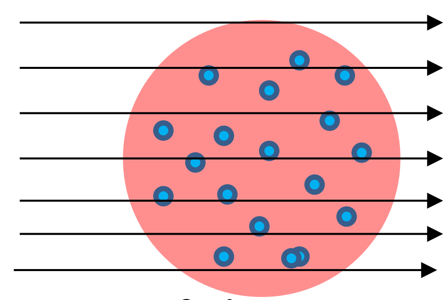




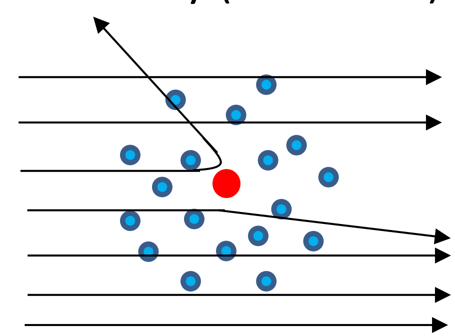
Ernest Rutherford (1871 – 1937) in the lab

E. Rutherford then discovered radioactive gas produced by thorium (**“emanation”**), and found that a sample of this gas took the same time for half the sample to decay (**"half-life“**)

In 1910, investigations into the scattering of alpha rays and the nature of the inner structure of the atom which caused such scattering led to the postulation of the concept of the "nucleus"



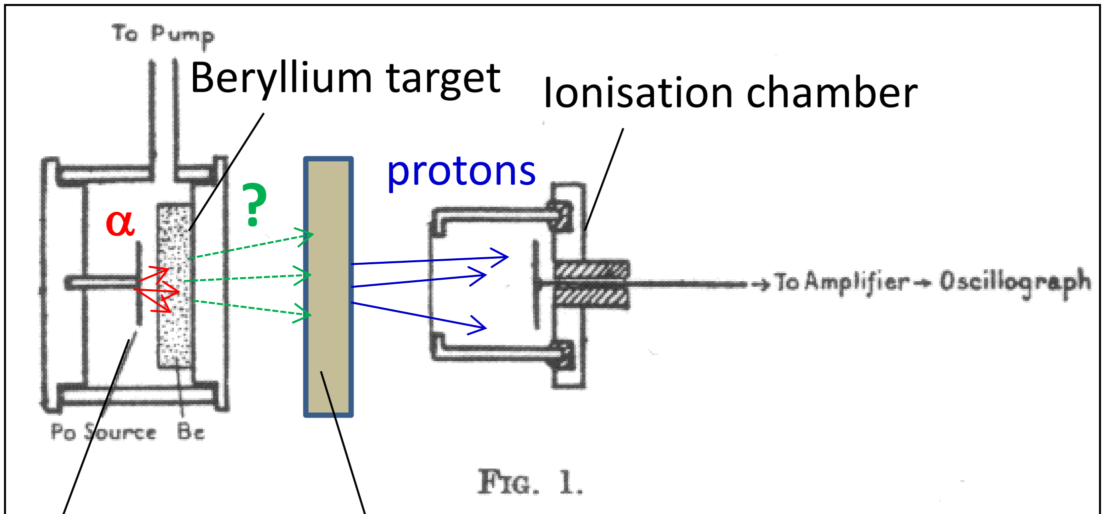
Atom of Thomson



Rutherford

Discovery of neutron

Discovery of **neutron** by **Sir James Chadwick** in 1932



Polonium source

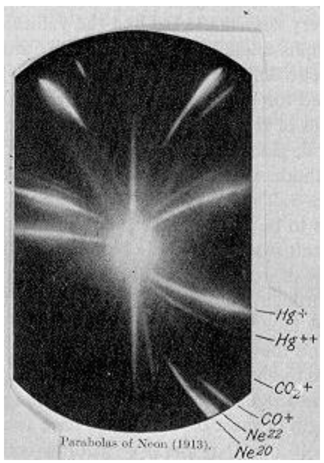
Paraffin wax

Sir James Chadwick
(1891 –1974)

Nuclei consist of protons and neutrons (nucleons)

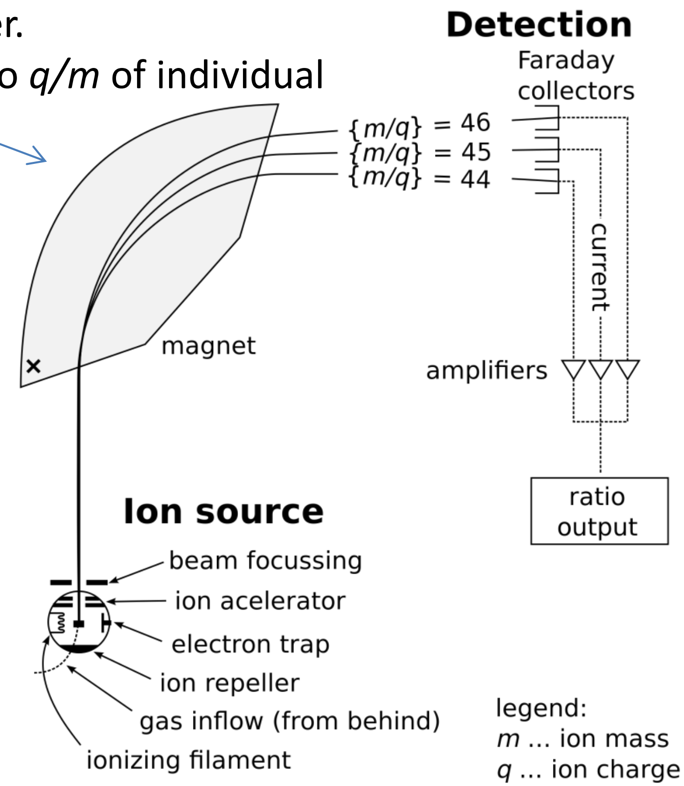
Measurement of atomic masses
mass spectrometry

Discovery of neon isotopes by Thomson using mass-spectrograph



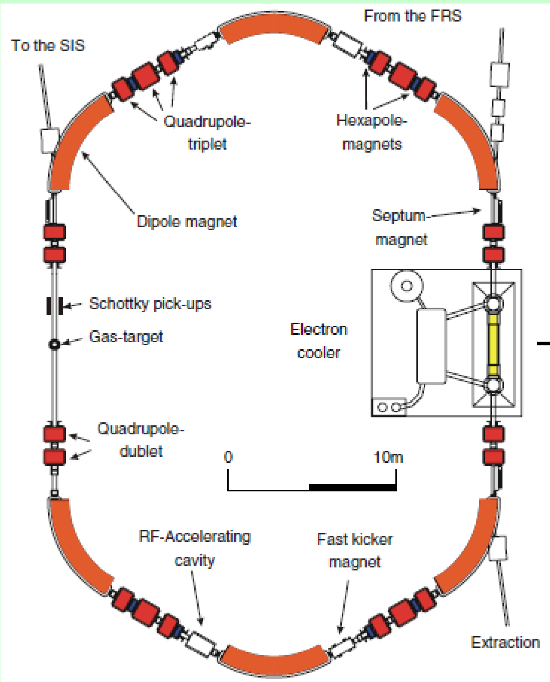
1897: J. J. Thomson demonstrated the existence of the electron as an electrically charged particle, and measured the ratio of its mass to its charge

Scheme of “standard” mass-spectrometer.
Measurement of the charge-to-mass ratio *q/m* of individual atomic or molecular ions

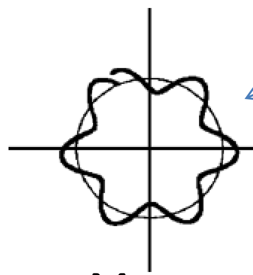


Measurement of atomic masses

mass spectrometry: current status



Schematic view of the experimental storage ring at GSI-Darmstadt



the Betatron oscillation superposed on the ideal trajectory

Mass measurements on stable atoms now reach a relative uncertainty of about 10^{-11} [1]

Atomic mass values [2]

Precise atomic mass values are very important, e.g., for the neutrino mass measurements using beta and electron capture, search for neutrinoless double beta decay

[1] Klaus Blaum, High-accuracy mass spectrometry with stored ions, Physics Reports 425 (2006) 1
[2] M. Wang et al., The AME2012 atomic mass evaluation, Chinese Phys. C 36 (2012) 1603

Measurement of atomic masses
reactions

Kinematic of reaction is used in case of very short living nuclei, e.g. of neutron-rich nuclei

Production of neutron-rich nuclei by the fragmentation of a ^{76}Ge beam [1]

The observed fragments include 15 new isotopes that are the most neutron-rich nuclides of the elements chlorine to manganese (^{50}Cl, ^{53}Ar, ^{55,56}K, ^{57,5}8Ca, ^{59,60,61}Sc, ^{62,63}Ti, ^{65,66}V, ^{68}Cr, ^{70}Mn).

The mass of a neutron (m_n) cannot be directly determined by mass spectrometry due to lack of electric charge. However, it can be determined as difference

$$m_n = m_d - m_p + B_d - E_{rd}$$

since the mass of proton (m_p) and deuteron (m_d) can be measured by mass spectrometry, while the binding energy of deuterium (B_d) can be directly measured by measuring the energy of the single 782.2 keV gamma photon emitted when neutrons are captured by protons, taking into account the small recoil kinetic energy (E_{rd}) of the deuteron (about 0.06% of the total energy).

[1] O.B. Tarasov et al., Evidence for a Change in the Nuclear Mass Surface with the Discovery of the Most Neutron-Rich Nuclei with 17 Z 25, PRL 102 (209) 142501

Mass of nuclei

The mass of a nucleus with Z proton and N neutrons in a neutral-atom state is:

$$\text{Mass}(Z,N) = Z \times \text{Mass (hydrogen atom)} + N \times \text{Mass(free neutron)} - \Delta E(Z,N)$$

where $\Delta E(Z,N)$ is the Binding Energy, that is, the energy needed to dissociate the nucleus into free nucleons.

The unified atomic mass unit (symbol: **u**) is defined so that 1 u is equal to the mass of an unbound neutral atom of ^{12}C divided by 12.

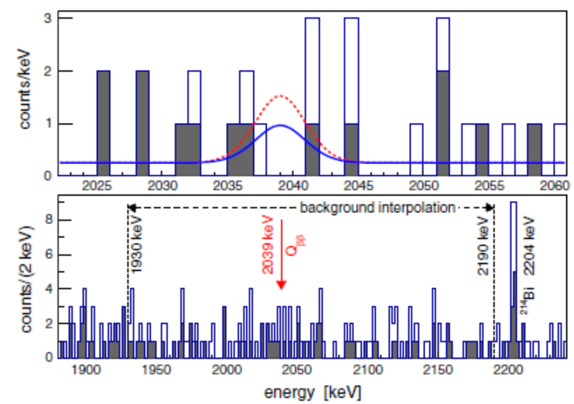
$$1\ u = M(^{12}C)/12 = \text{atomic mass unit}$$
$$1\ u = 1\,660\,538.921 \pm 0.073\ 10^{-33}\ \text{kg}$$
$$1\ u = 931\,494.061 \pm 0.021\ \text{keV}$$

Mass difference

In many cases we need to know the mass difference between two nuclei rather than absolute masses.

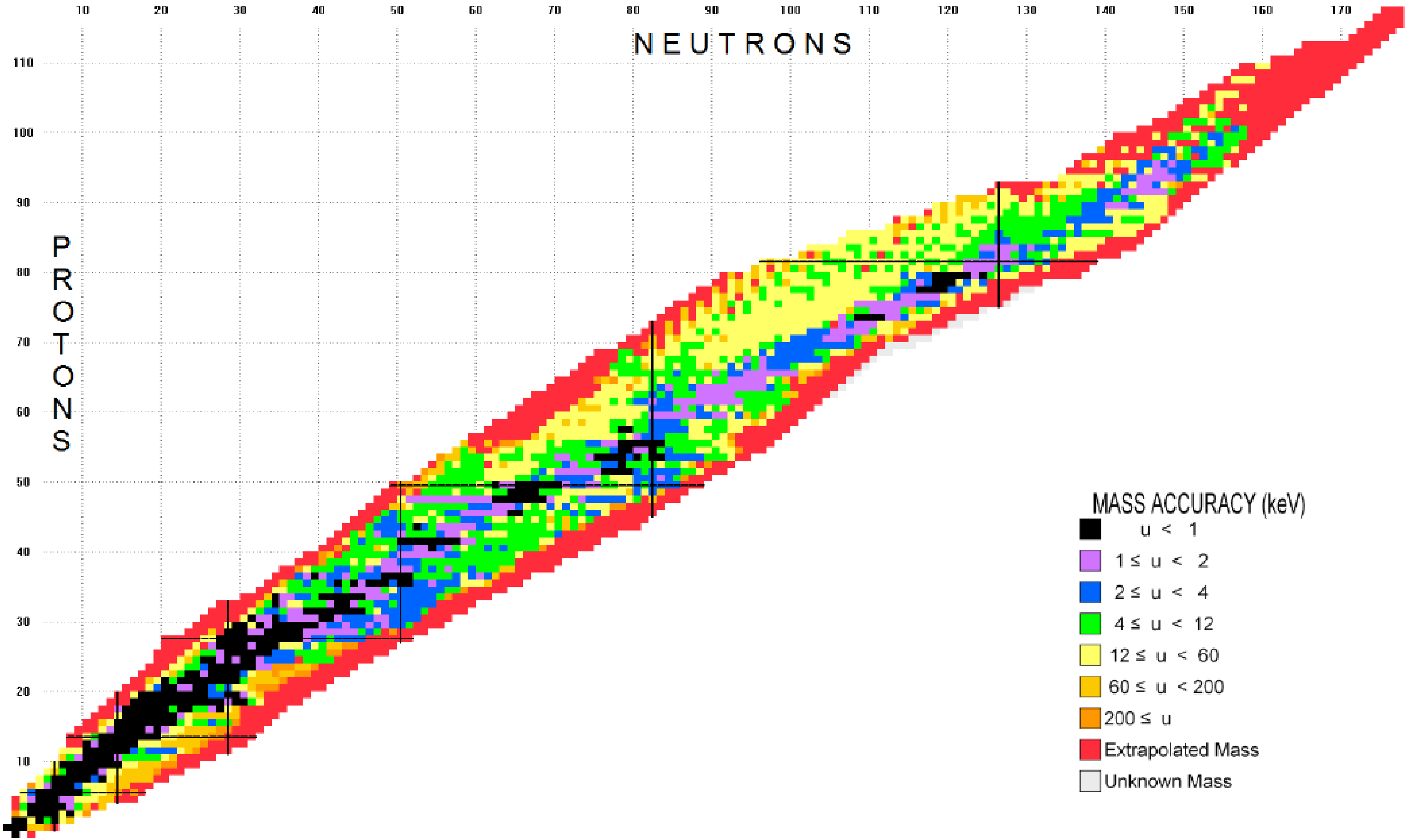
Example: we need as much as possible precise $Q_{2\beta}$ value to search for neutrinoless double beta decay:

Double beta decay	$Q_{2\beta}$ (keV)	
	1995	2015
$^{76}Ge \rightarrow {}^{76}Se$	2038.7(0.5)	2039.061(7)
$^{100}Mo \rightarrow {}^{100}Ru$	3034(6)	3034.40(17)
$^{116}Cd \rightarrow {}^{116}Sn$	2804(4)	2813.50(13)
$^{130}Te \rightarrow {}^{130}Sn$	2528.1 (2.1)	2526.97(23)
$^{150}Nd \rightarrow {}^{150}Sm$	3367.5(2.2)	3371.38(20)



[1] M. Agostini et al., Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment, Phys. Rev. Lett. 111 (2013) 122503

Accuracy of atomic masses [1]



[1] G. Audi et al., The NUBASE2012 evaluation of nuclear properties, Chinese Phys. C 36 (2012) 1157

Binding energy

Mass of nucleus ≠ mass of the nucleons (protons + neutrons) due to the negative binding energy (typical value: $E_b \approx 8$ MeV / nucleon):

$$E = \sum_i E_i - \Delta E$$

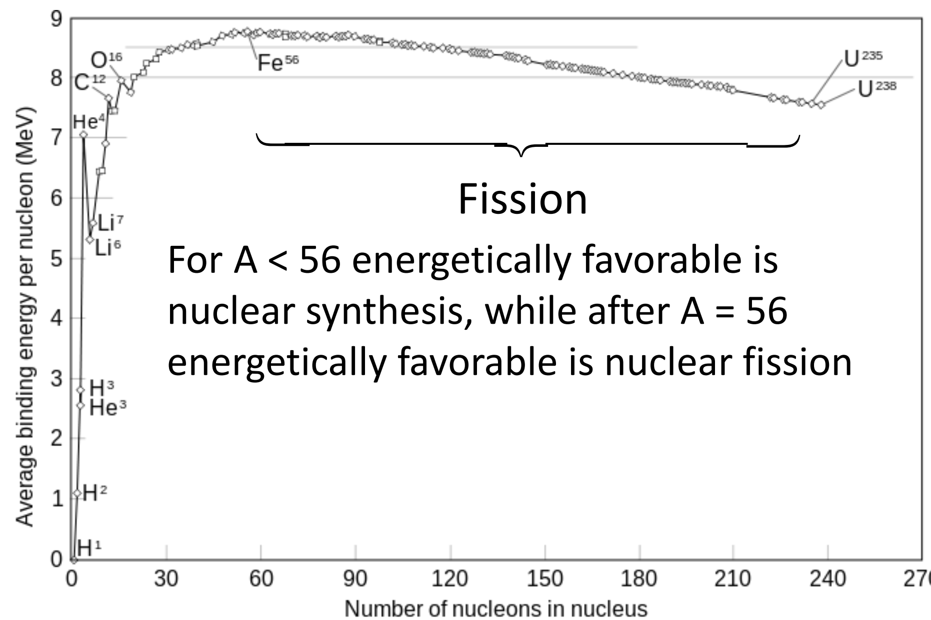
where E – energy of the whole nuclei, E_i – energy of protons and neutrons, ΔE is **binding energy**.

According to the Einstein's relativity theory energy is proportional to the mass:

$$E = Mc^2,$$

where E is energy, M – mass, c - light speed.

Synthesis



Fission

For A < 56 energetically favorable is nuclear synthesis, while after A = 56 energetically favorable is nuclear fission

Mass excess (Δ)
The mass excess Δ(Z,N) is defined as: Δ(Z,N)=(Mass(Z,N) (u) - A) × u
where Mass(Z,N) (u) is mass in atomic mass units and u = Mass(^{12}C)/12, A is atomic number

Principle of minimum energy

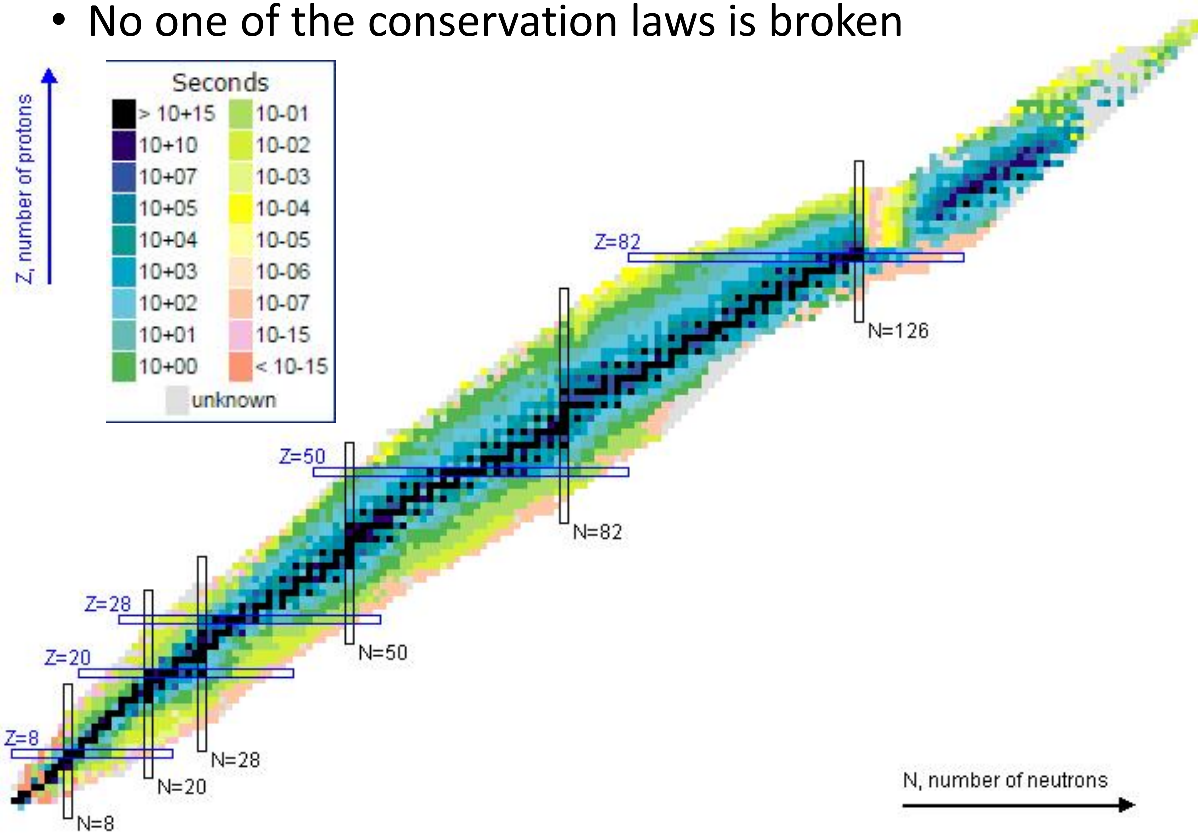
Any physical system tends to a state with the lowest potential energy

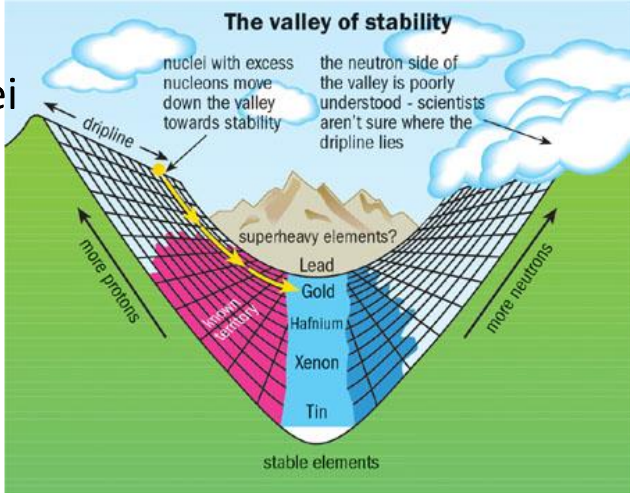
The principle is an empirical finding that has been accepted as an axiom of thermodynamic theory

Stability valley of the nuclei

The conditions for radioactive decay:

- Energy of the mother nuclei > Energy of the daughter nuclei
- No one of the conservation laws is broken





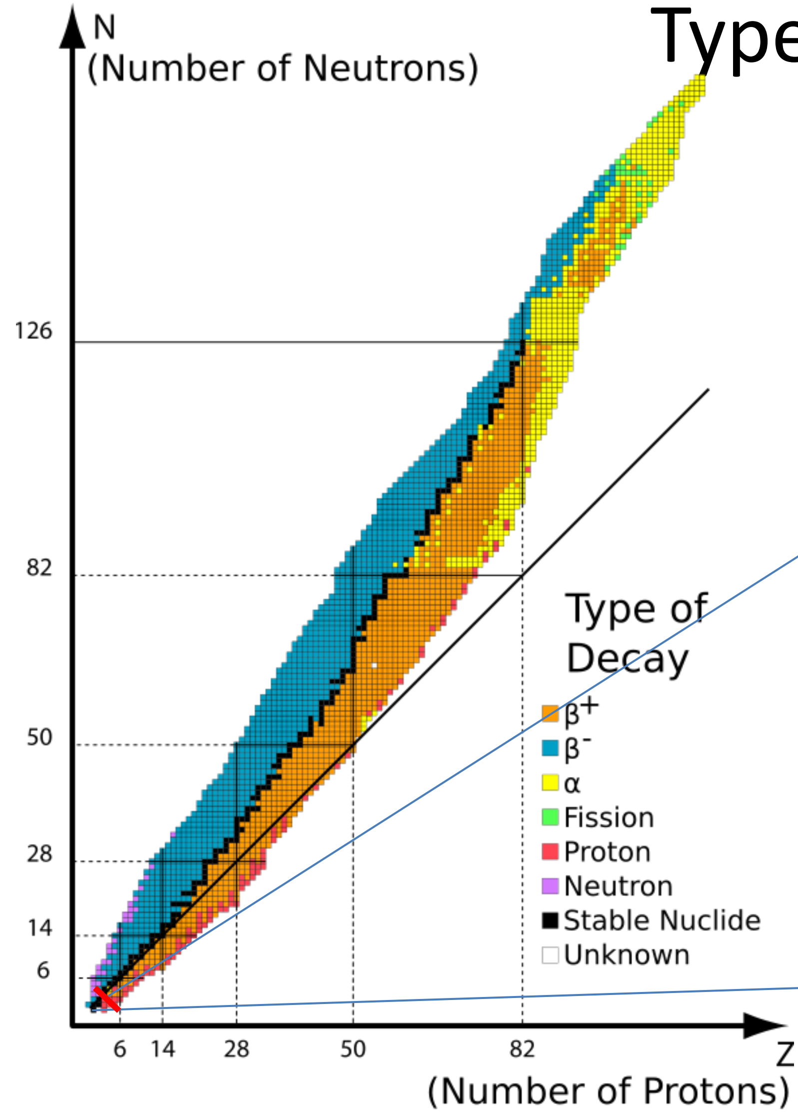
Conservation laws:

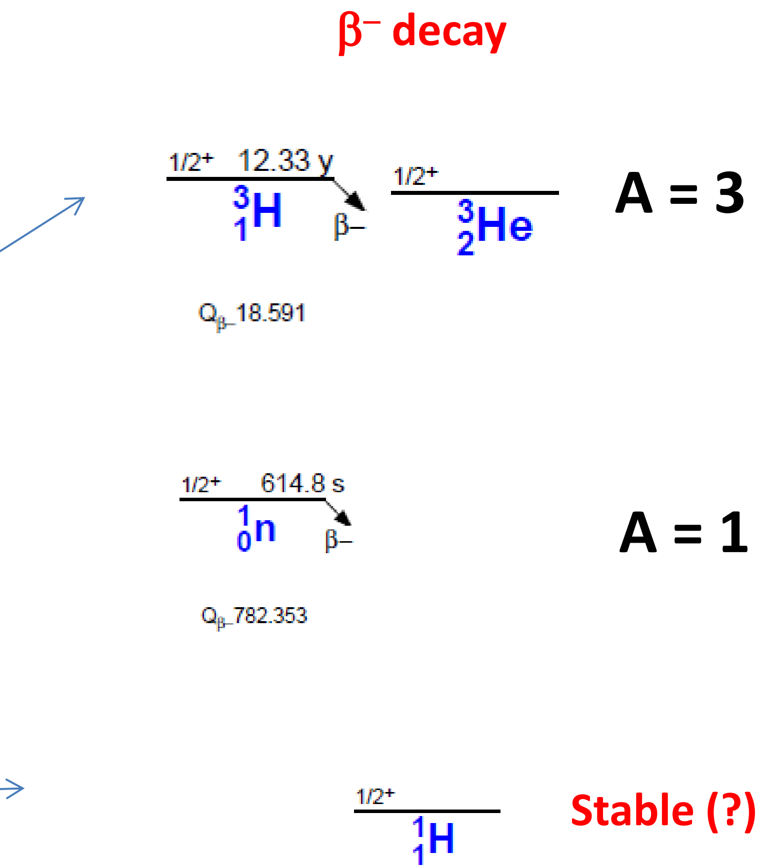
- Electric charge
- Pauli principle
- Baryon number (?)
- Lepton number (?)
- Angular momentum
- Parity

Behavior of particles and nuclei is described by quantum mechanics

[1] http://www.nndc.bnl.gov/chart/ (National Nuclear Data Center, BNL) Chart of Nuclides

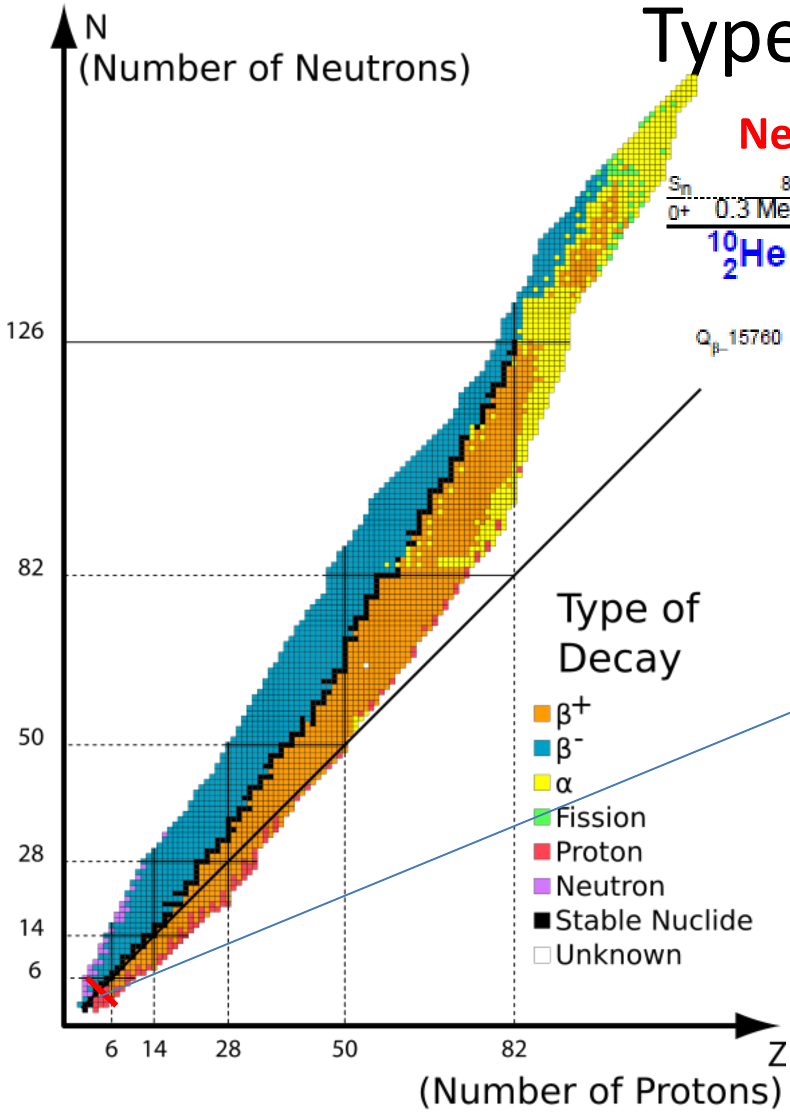
Types of radioactive decay



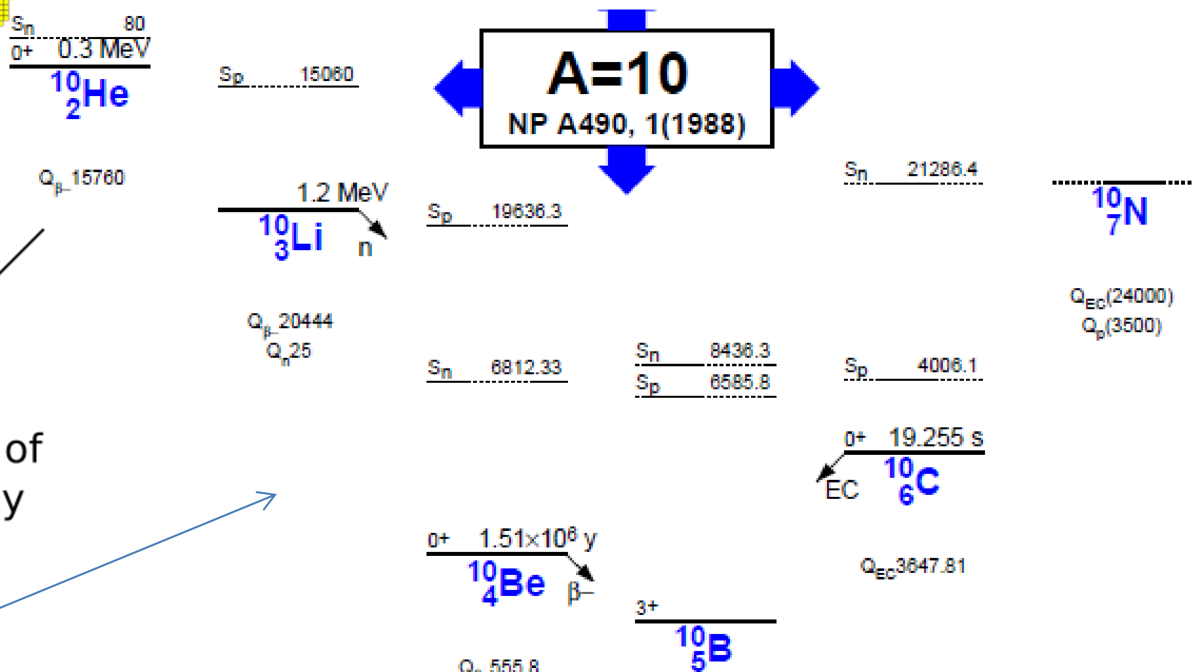


[1] R.B. Firestone, C.M. Baglin, S.Y.F. Chu, Table of Isotopes CD-ROM, Eighth Edition: 1998 Update, Lawrence Berkeley National Laboratory, University of California

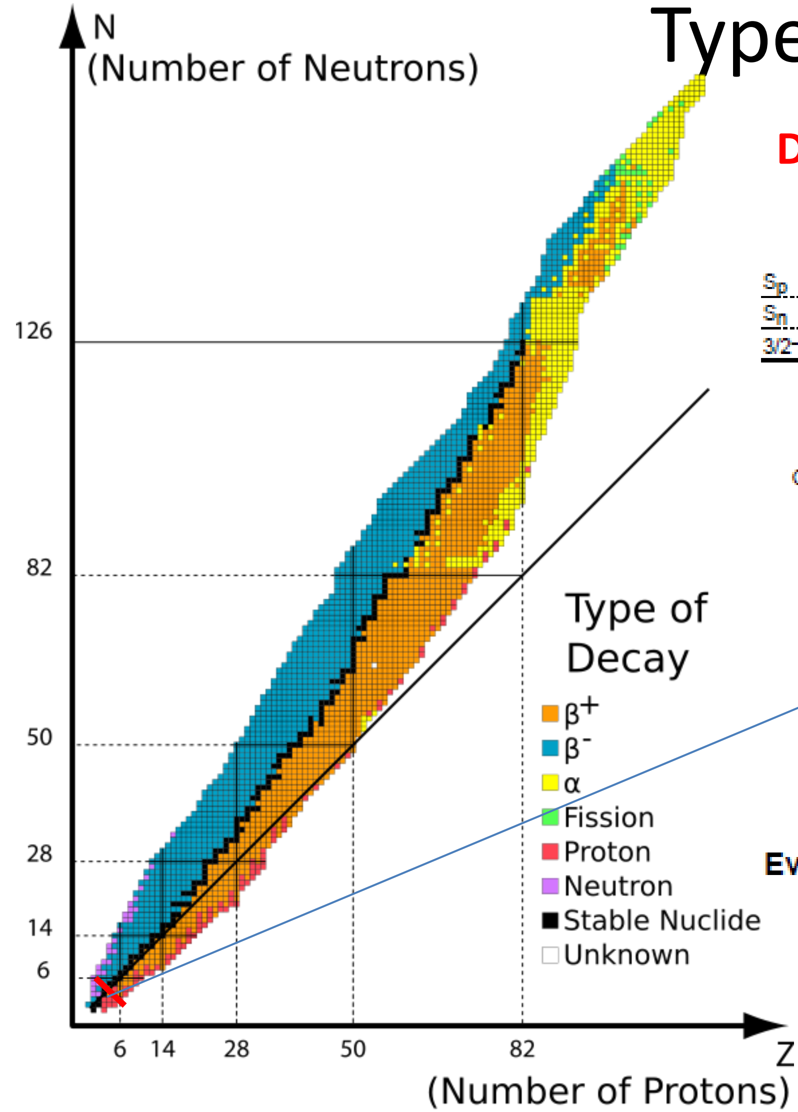
Types of radioactive decay



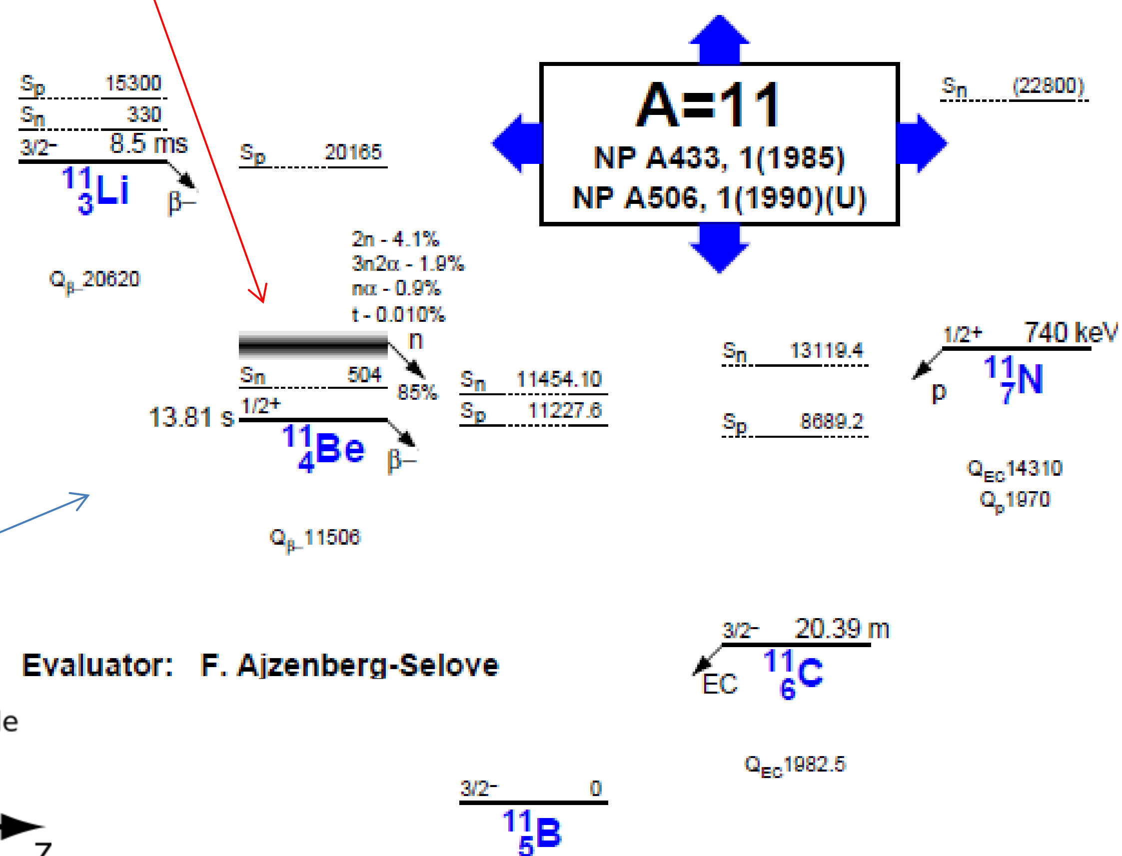
Neutron decay (n)



Types of radioactive decay

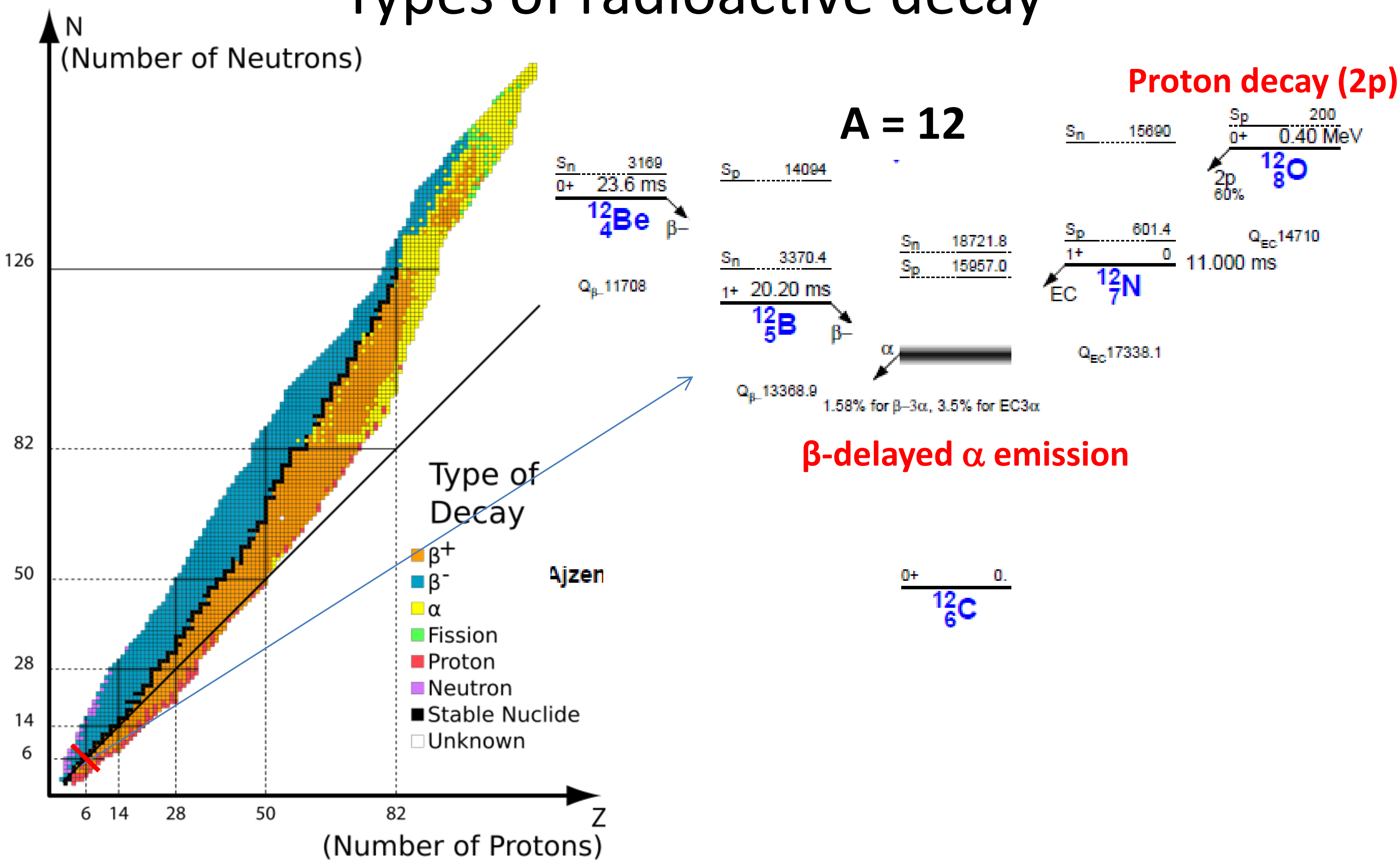


Delayed triton and deuteron emission

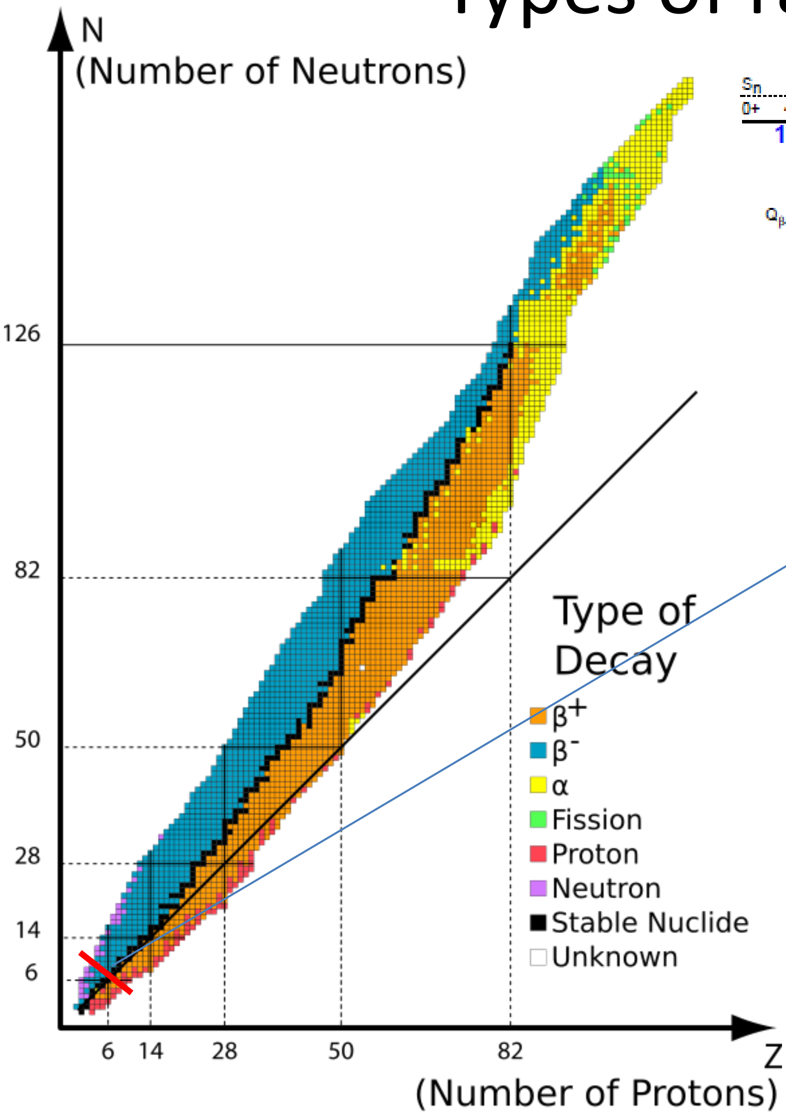


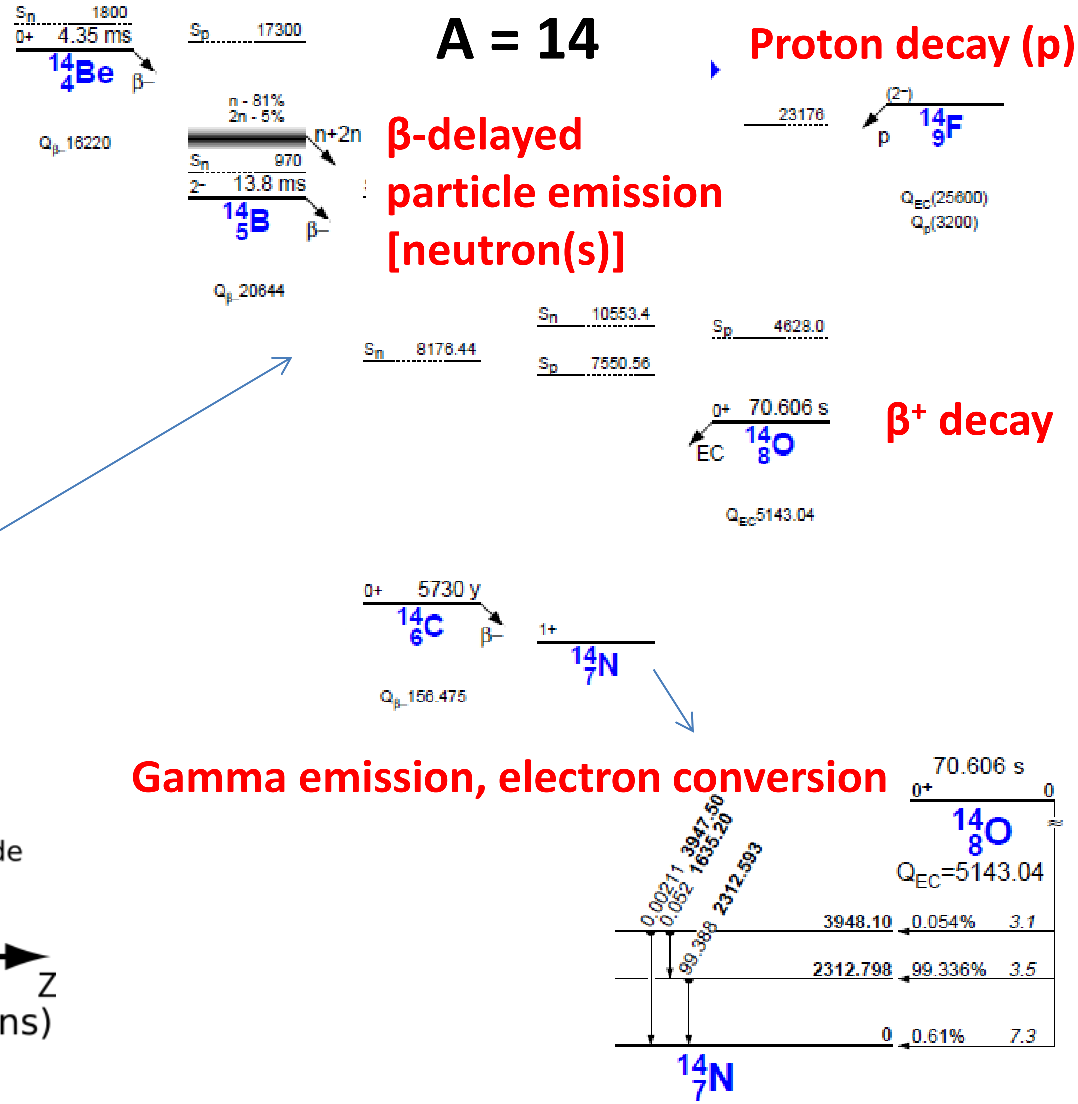
R. Raabe et al., β-Delayed Deuteron Emission from Li11: Decay of the Halo, PRL 101 (2008) 212501

Types of radioactive decay

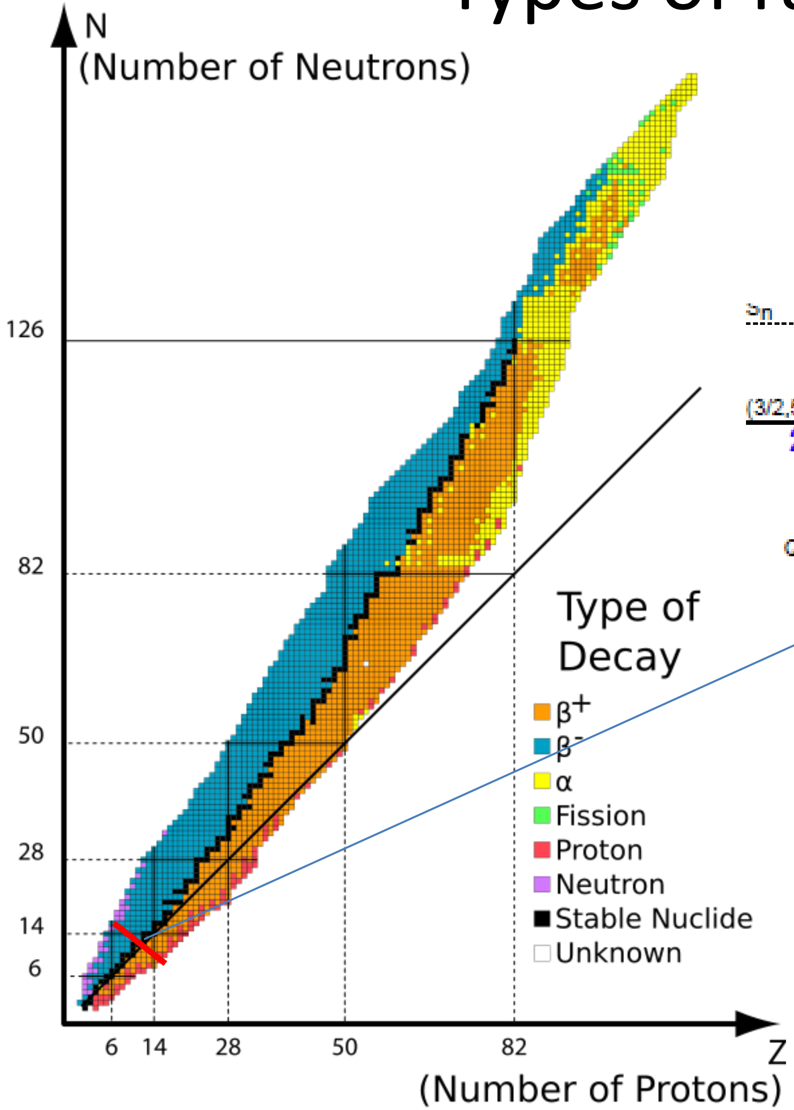


Types of radioactive decay



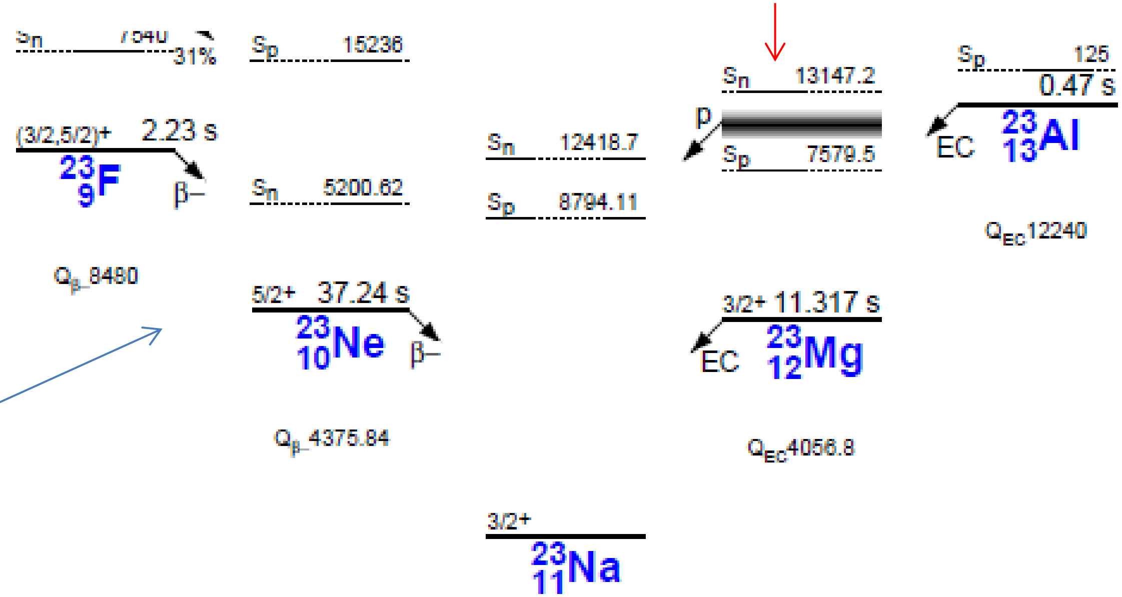


Types of radioactive decay

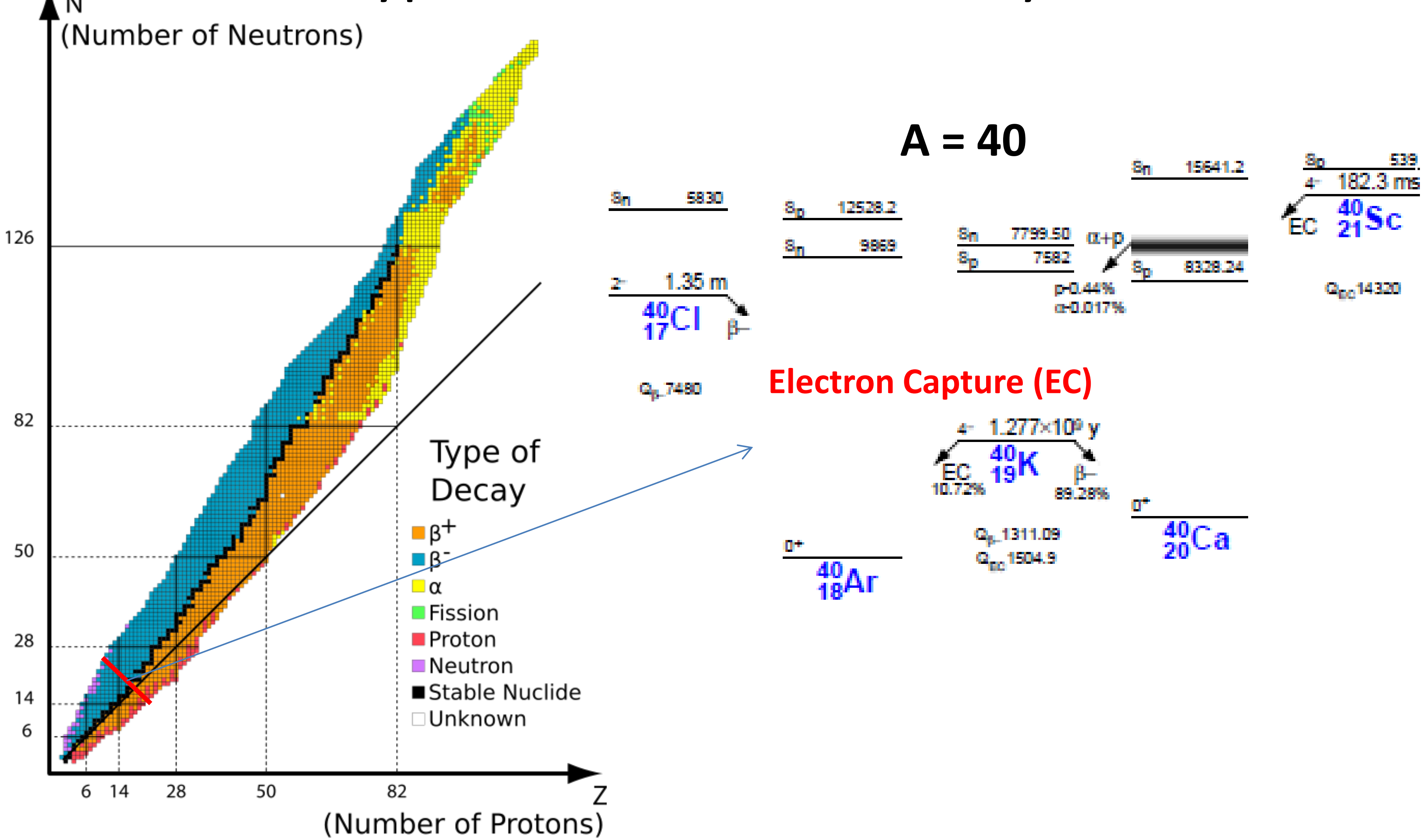


A = 14

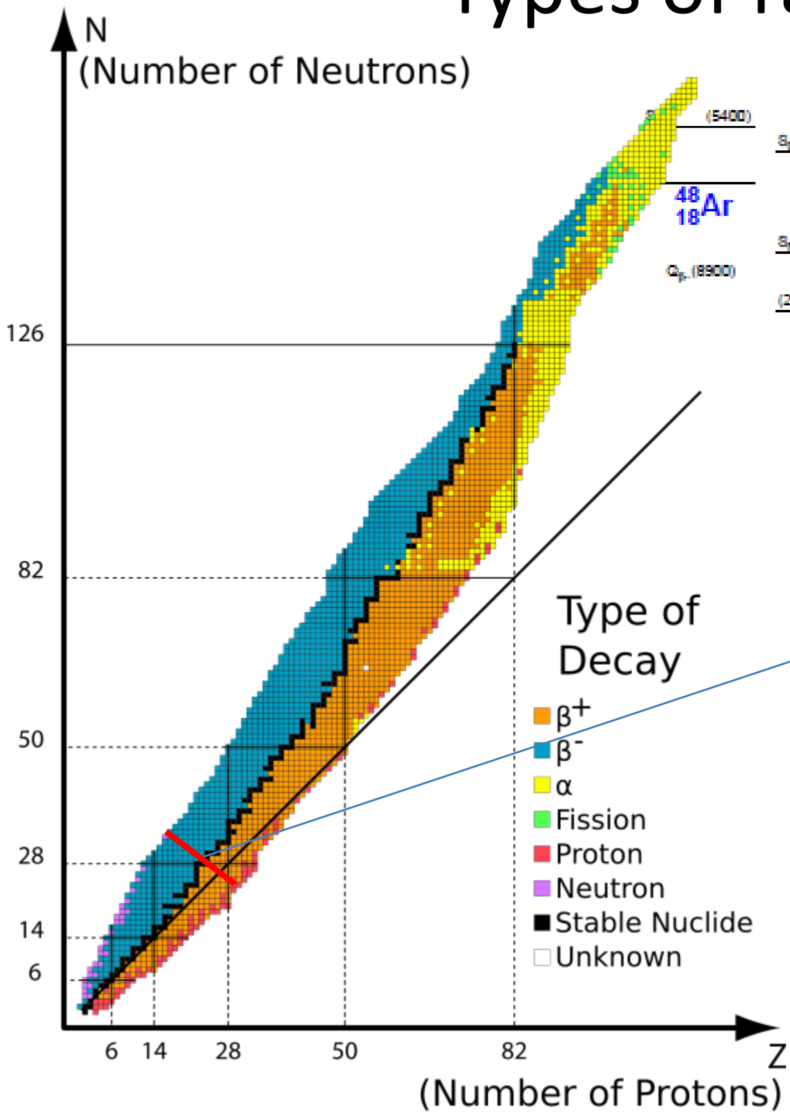
β-delayed particle emission (proton)



Types of radioactive decay

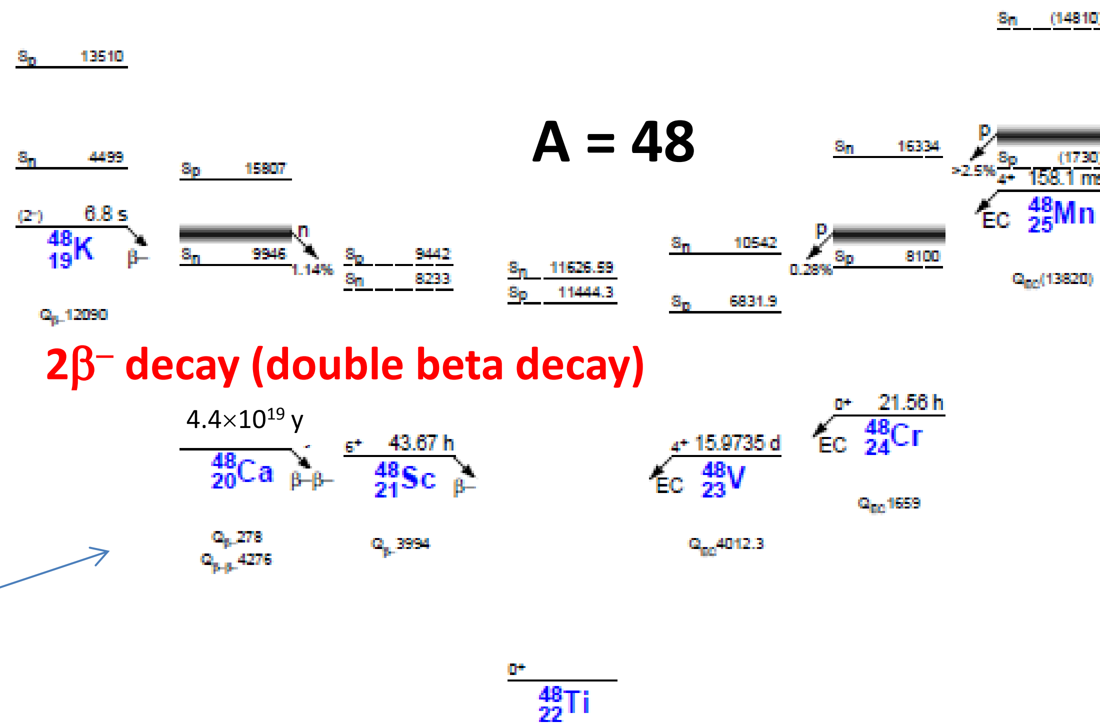


Types of radioactive decay

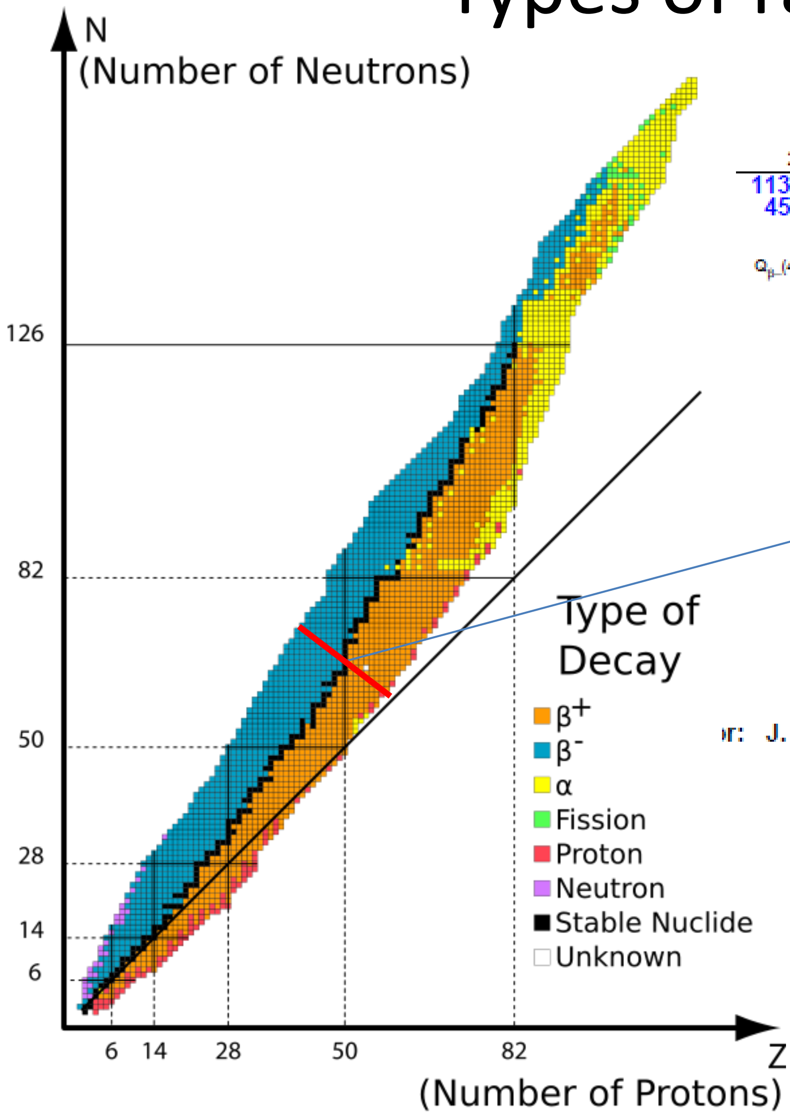


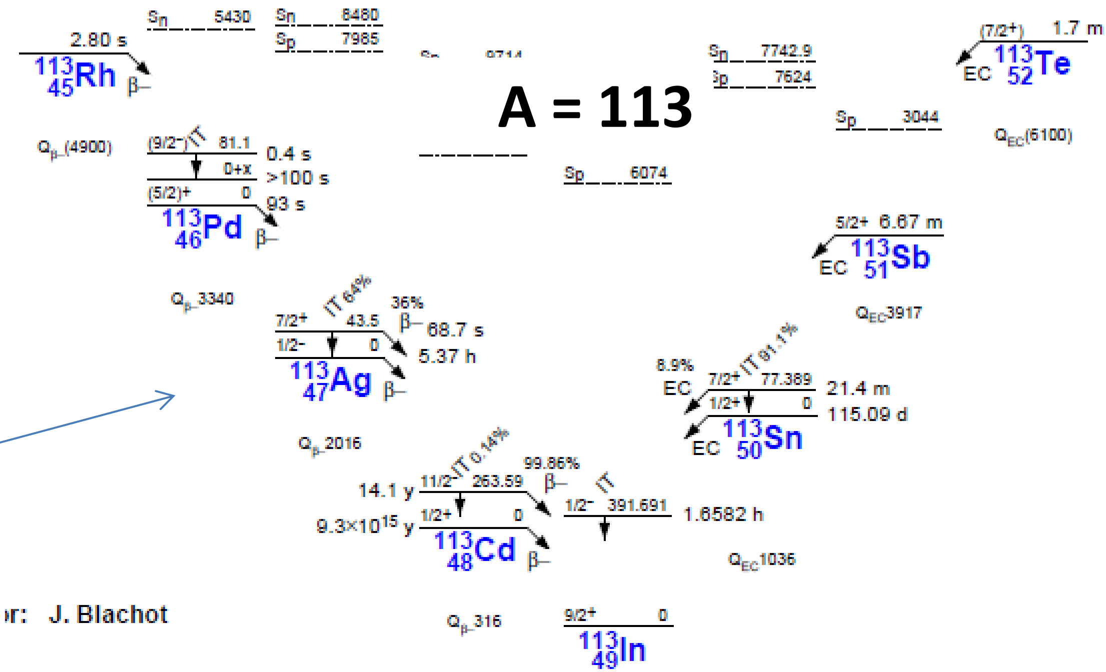
A = 48

2β⁻ decay (double beta decay)



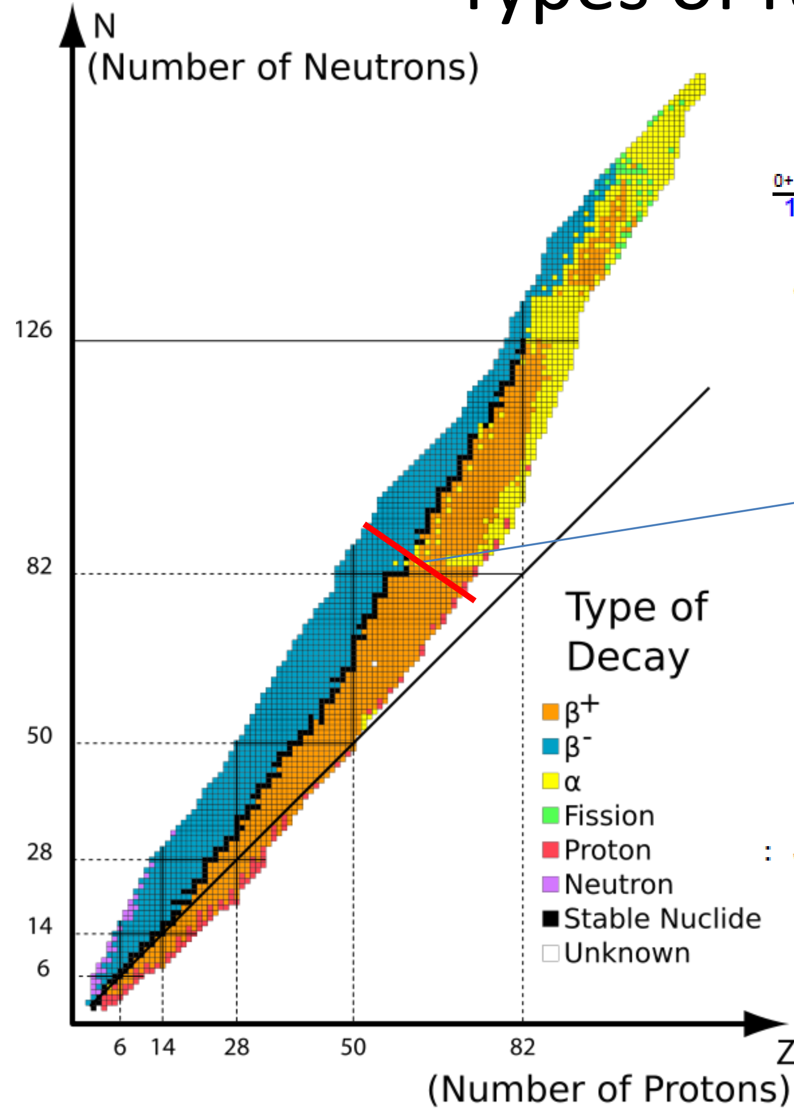
Types of radioactive decay

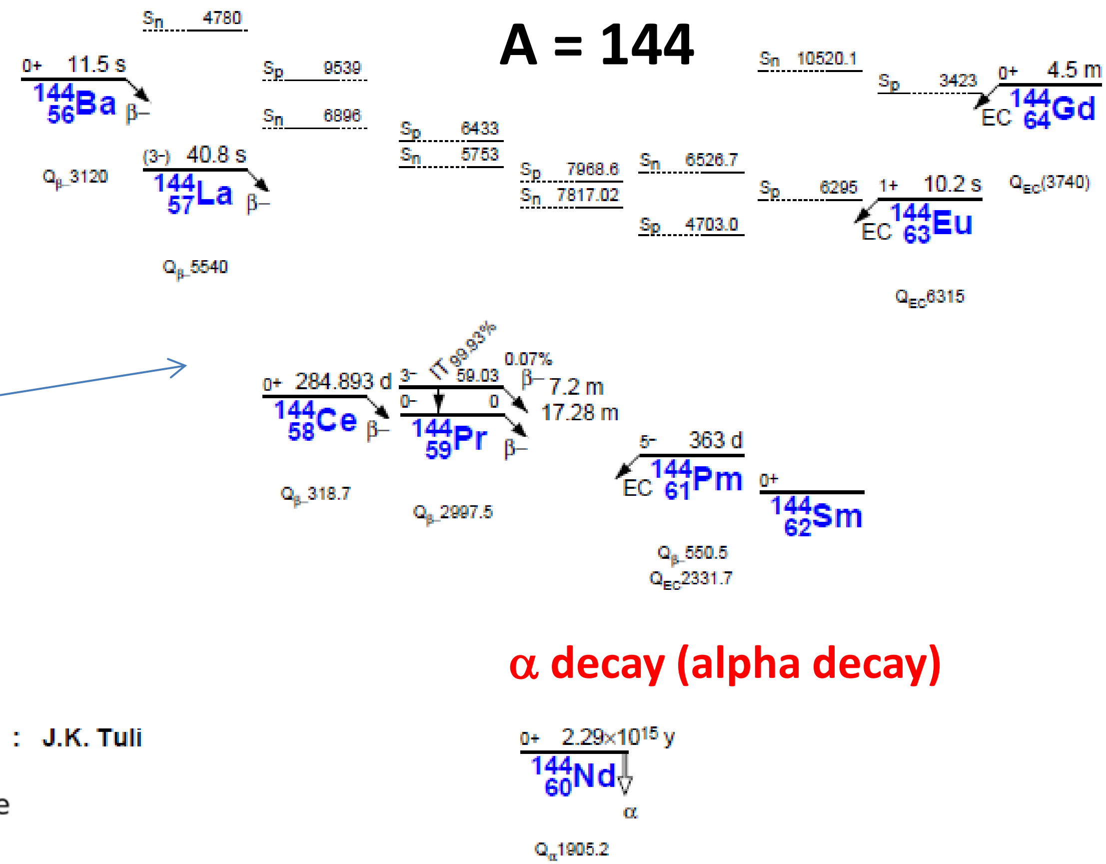




Isomeric transition (IT)
(gamma emission, electrons)

Types of radioactive decay

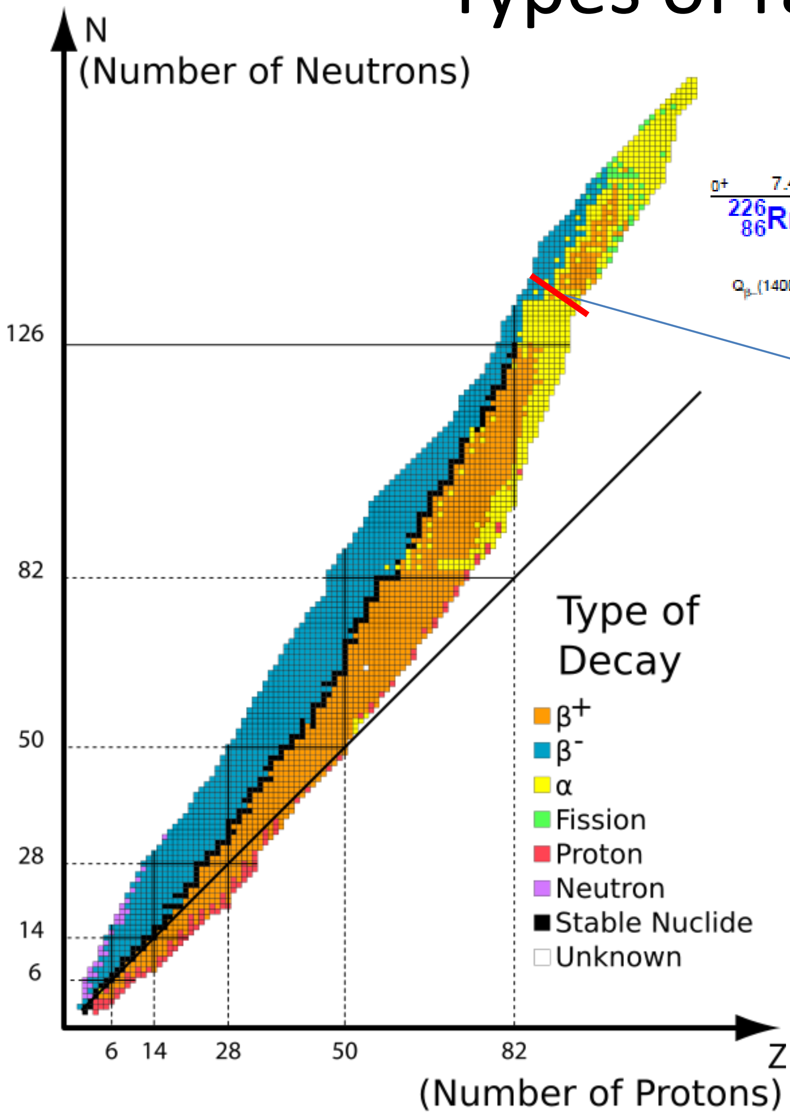


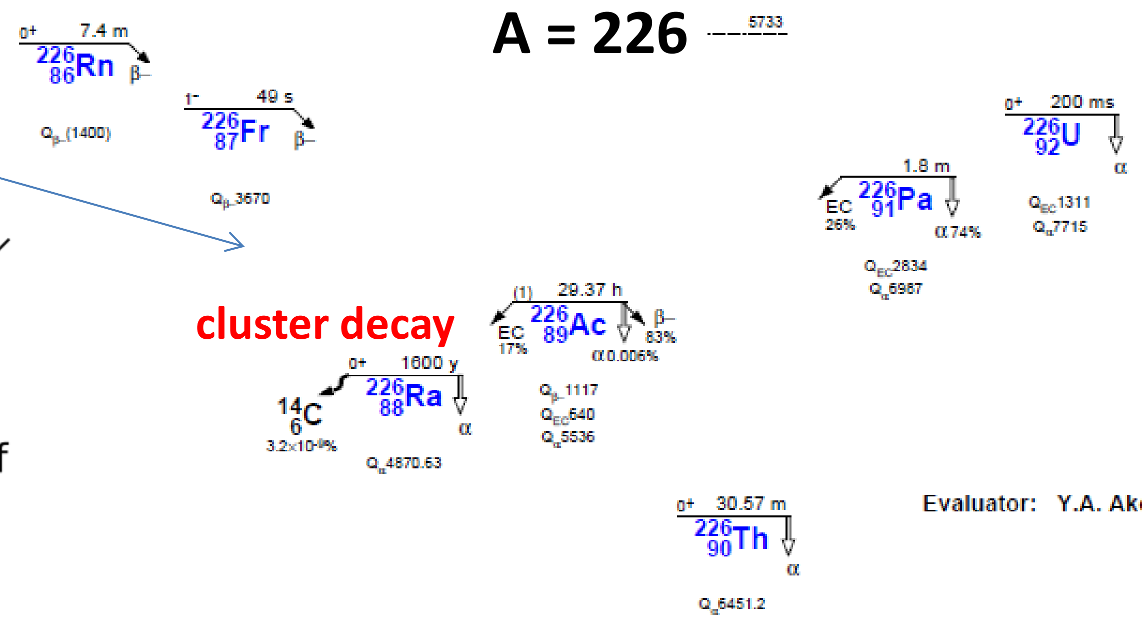


α decay (alpha decay)

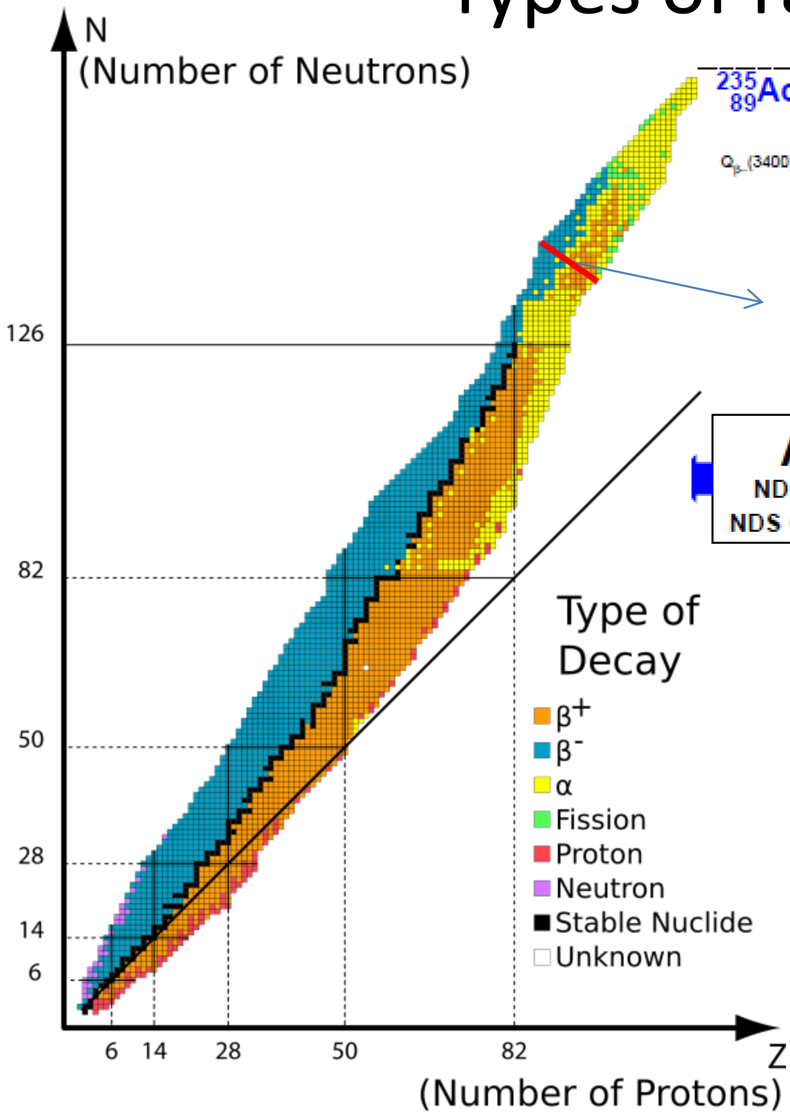
: J.K. Tuli

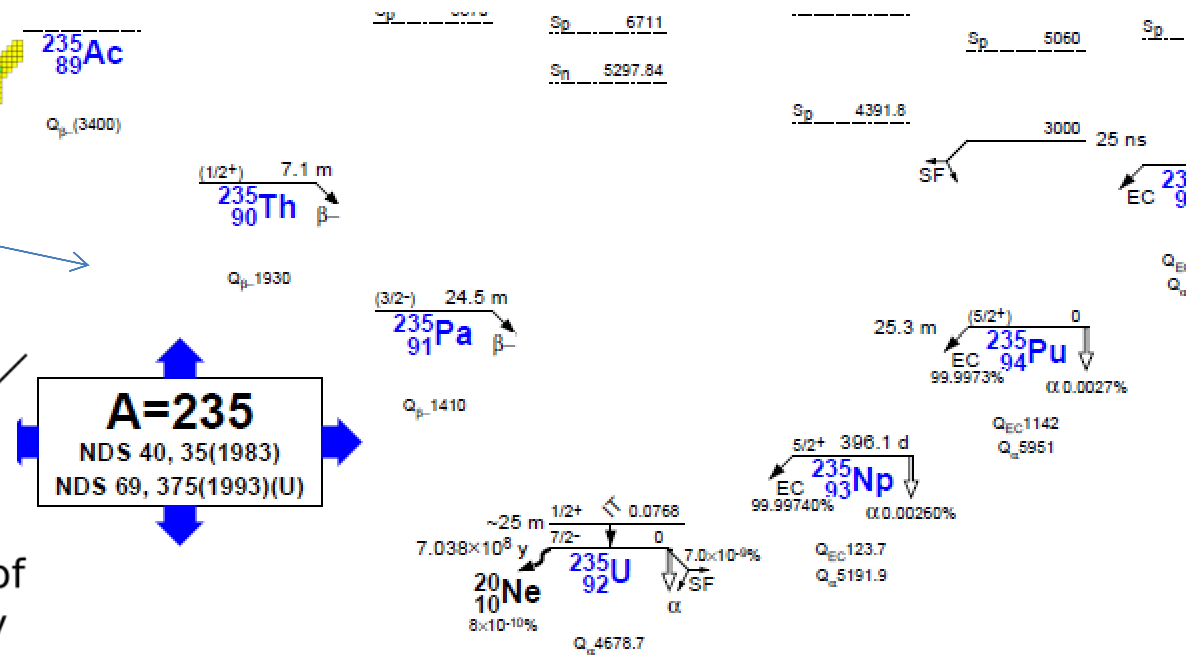
Types of radioactive decay





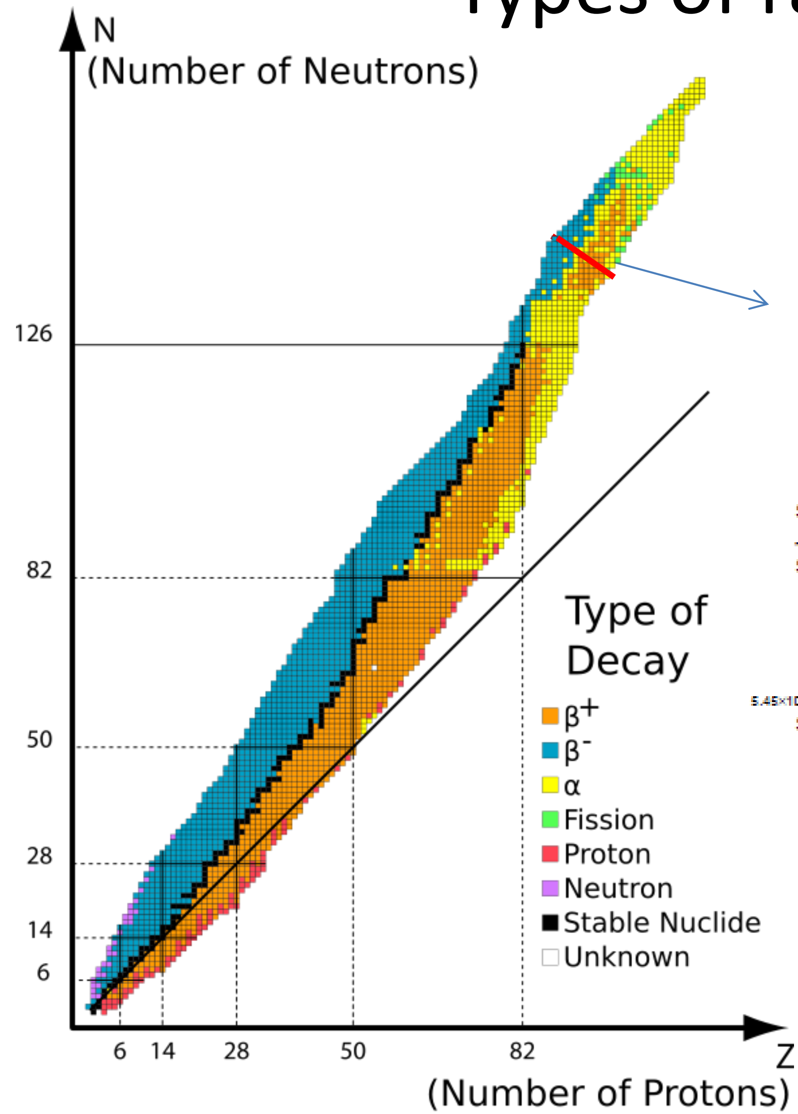
Types of radioactive decay



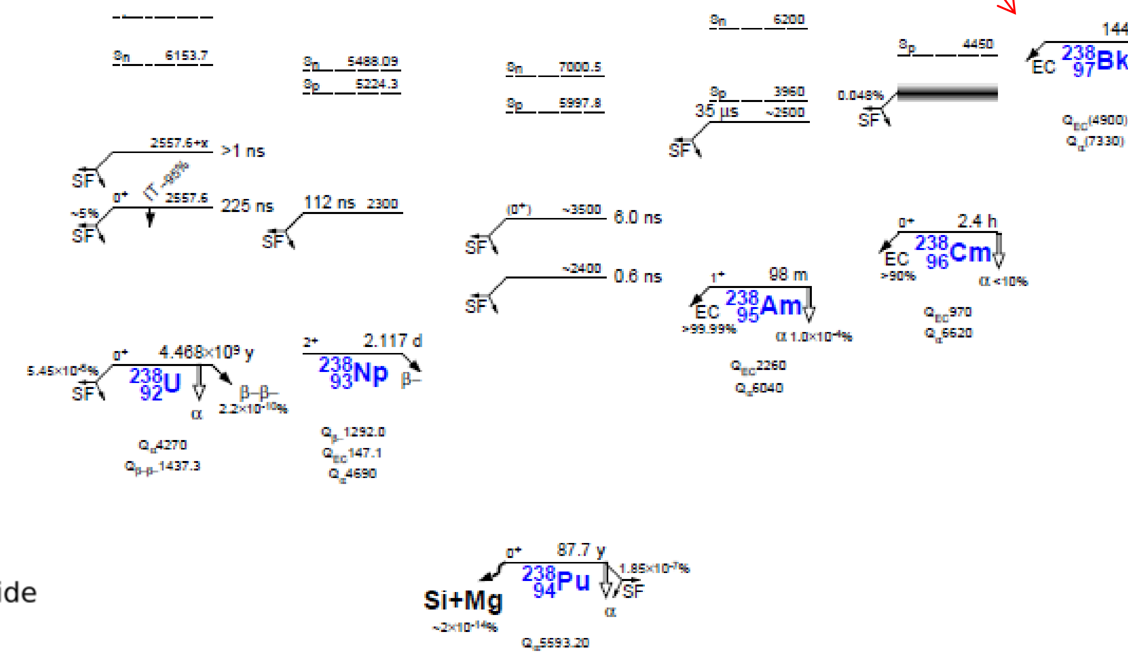


Spontaneous fission

Types of radioactive decay



β-delayed particle emission (fission)



Types of radioactive decay

summary

- Gamma emission, electron conversion
- β^- decay
- β^+ decay
- Electron Capture (EC)
- β-delayed particle emission
- Neutron decay
- Double β decay
- Proton decay
- Alpha decay
- Cluster decay
- Spontaneous Fission (SF)

$\beta^- n$	β^- delayed neutron emission
$\beta^- 2n$	β^- delayed 2-neutron emission
$\beta^+ p$	β^+ delayed proton emission
$\beta^+ 2p$	β^+ delayed 2-proton emission
$\beta^- \alpha$	β^- delayed α emission
$\beta^+ \alpha$	β^+ delayed α emission
$\beta^- d$	β^- delayed deuteron emission
$\beta^- t$	β^- delayed triton emission
β+SF	β+ delayed fission
β^- SF	β^- delayed fission

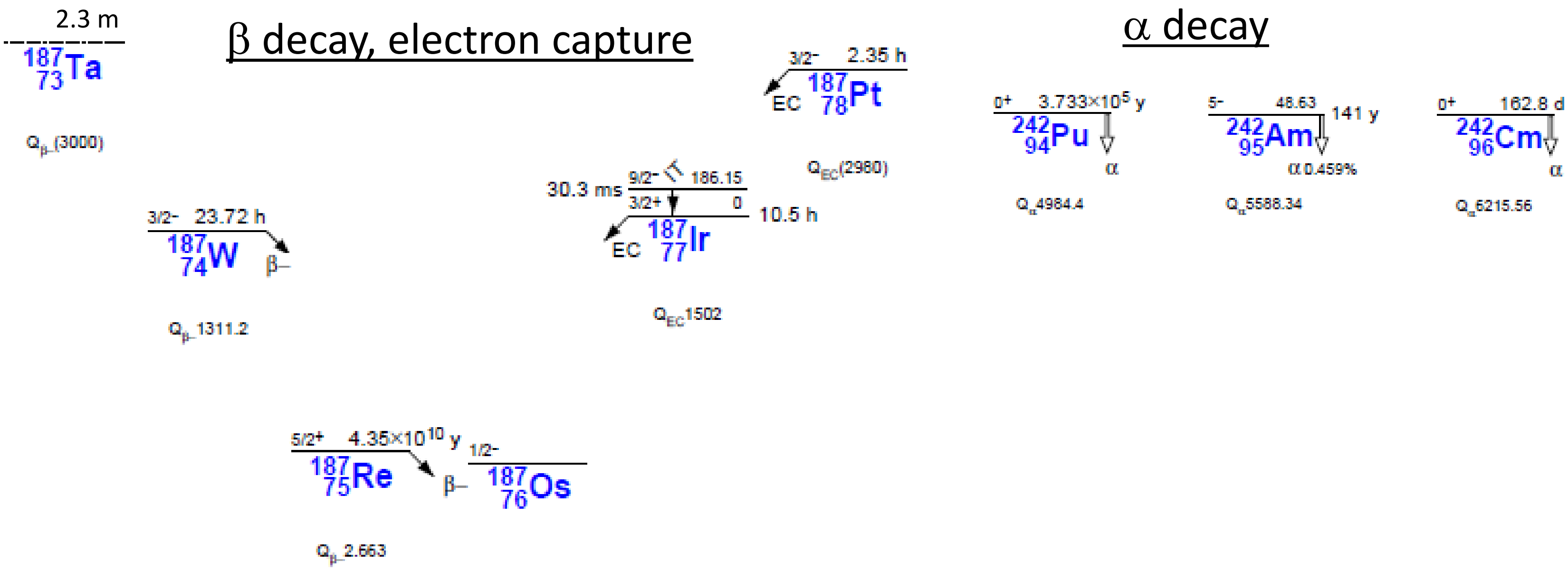
$2\beta^-$	double β^- decay
EC/EC	double electron capture
ECβ^+	electron capture with β^+ emission
$2\beta^+$	double β^+ decay

Energy and probability of decay

Probability of decay depends on energy of decay:

β decay, electron capture

α decay



Exponential decay law

decay constant, mean lifetime, half-life

Since radioactive decay is spontaneous, change ΔN of the nuclei number N during the time interval Δt depends only on the number of nuclei N at time t and is proportional to the time interval Δt:

$$-\Delta N = \lambda N \Delta t \ ,$$

where λ is the decay constant. By integrating the equation, assume that $N = N_0$ at $t = 0$:

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

The equation can be written in another form: $N \doteq N_0 e^{-\frac{t}{\tau}}$,

where τ is the mean lifetime (the time at which the number of nuclei is reduced to 1/e ≈ 0.36788 times its initial value)

The half-life $T_{1/2}$ is the time at which the number of nuclei is reduced to 1/2 times its initial value:

$$N = N_0 e^{-t\frac{\ln 2}{T_{1/2}}}$$

The three parameters λ, τ and $T_{1/2}$ are related in the following way:

$$T_{1/2} = \frac{\ln 2}{\lambda} = \tau \cdot \ln 2$$

In a sample of a radionuclide , the number of atoms in the original state follows exponential decay as long as the remaining number of atoms is large

Units of radioactivity, specific activity

The SI derived unit of radioactivity is becquerel (symbol Bq, named after Henri Becquerel who discovered radioactivity), defined as the activity in which one nucleus decays per second:

$$1 \text{ Bq} = 1 \text{ s}^{-1}$$

The specific activity is a number of decays in some amount of per second:

$$1 \text{ Bq / kg} = 10^3 \text{ mBq/kg} = 10^6 \ \mu\text{Bq/kg} = ...$$

Some time people still use **curie** (**Ci,** named after Pierre Curie and Marie Curie, who contribute a lot for radioactivity study), an older unit based on the activity of 1 gram of ^{226}Ra. 1 Ci = 3.7×10^{10} Bq = 37 GBq