Banana Equivalent Dose

Bananas are a natural source of radioactive isotopes.

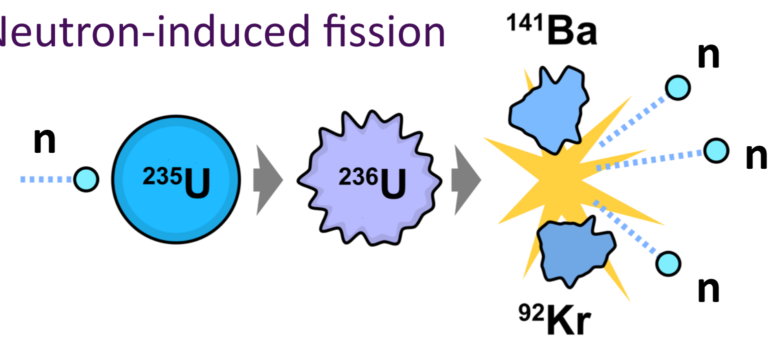
Eating one banana = 1 BED = 0.1 μSv = 0.01 mrem

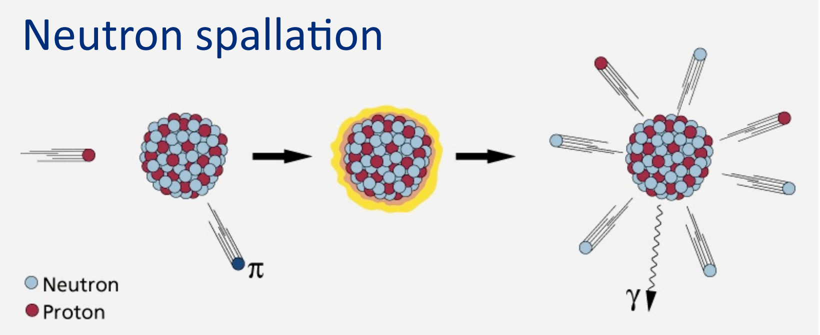
Number of bananas	Equivalent exposure
100,000,000	Fatal dose (death within 2 weeks)
20,000,000	Typical targeted dose used in radiotherapy (one session)
70,000	Chest CT scan
20,000	Mammogram (single exposure)
200 - 1000	Chest X-ray
700	Living in a stone, brick or concrete building for one year
400	Flight from London to New York
100	Average daily background dose
50	Dental X-ray
1 - 100	Yearly dose from living near a nuclear power station

Neutron radiation

- Neutrons are components of atomic nucleus, zero electric charge, $m_n \approx m_p$
- Sources of neutron radiation:
  - interaction of cosmic radiation with the atmosphere
  - neutron emission during fission (e.g. in nuclear reactors)
  - particle accelerators (spallation sources, e.g. ISIS, SNS)
- Interaction with matter:
  - neutron capture (n is captured by a nucleus and α or γ is emitted)
  - elastic scattering (recoiling nuclei collide and produce charge or scintillation light that can be detected)

Neutron-induced fission





Hydrogen-rich materials make the best neutron shielding: e.g. water, polyethylene, paraffin wax, concrete

Neutron RBE

RBE figures set by the International Commission on Radiological Protection (ICRP):

ICRP Publication 92 (2003)

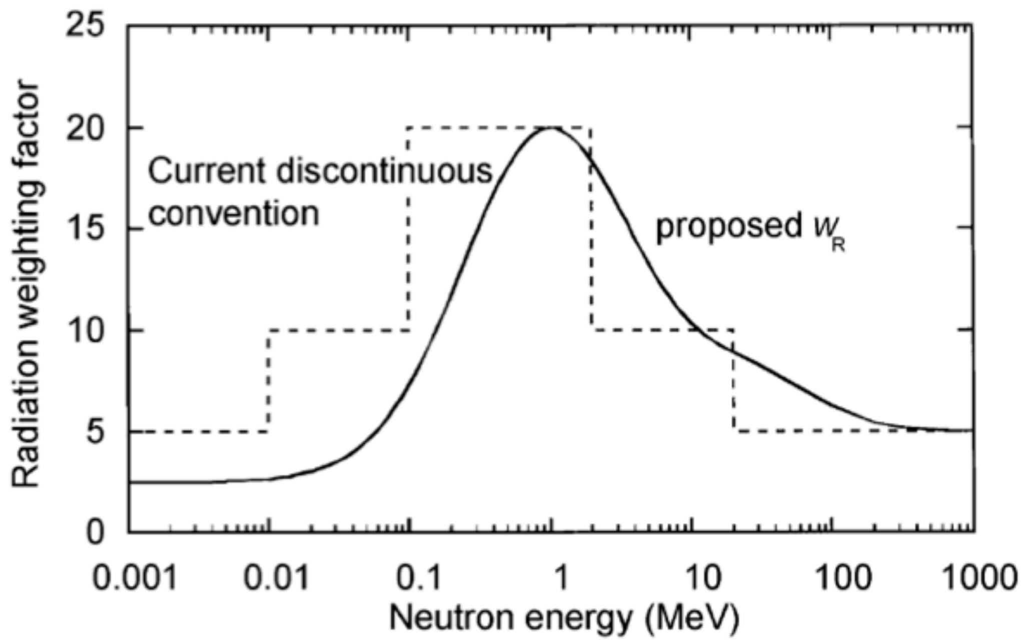


Fig. 1. The radiation weighting factor w_R for neutrons introduced in *Publication 60* (ICRP, 1991) as a discontinuous function of the neutron energy (- - -) and the proposed modification (—).

Radiation definitions and facts

- **Definitions:**
  - **Radiation** - energy traveling in the form of particles or waves, for example: microwaves, radio waves, light, medical X-rays, alpha, beta, gamma radiation
  - **Radioactivity** - a natural process through which unstable atoms of an element radiate excess energy in the form of particles or waves
  - **Radioactive material** - material that emits radiation
  - **Radioactive contamination** - radioactive material in unwanted places
- **Important facts:**
  - Radiation is commonplace
  - A person exposed to radiation does not become contaminated, except for neutron radiation which *can* induce radioactivity
  - Contamination is the result of direct contact with removable radioactive material
  - The distinction between harmful and safe depends on *quantity*. This is true about everything from paracetamol to arsenic
  - Dose is important

Nuclear and Particle Physics
Part 2: Nuclei

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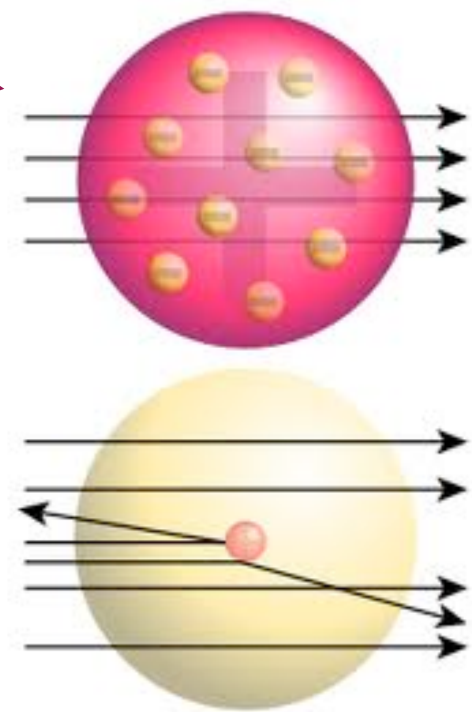
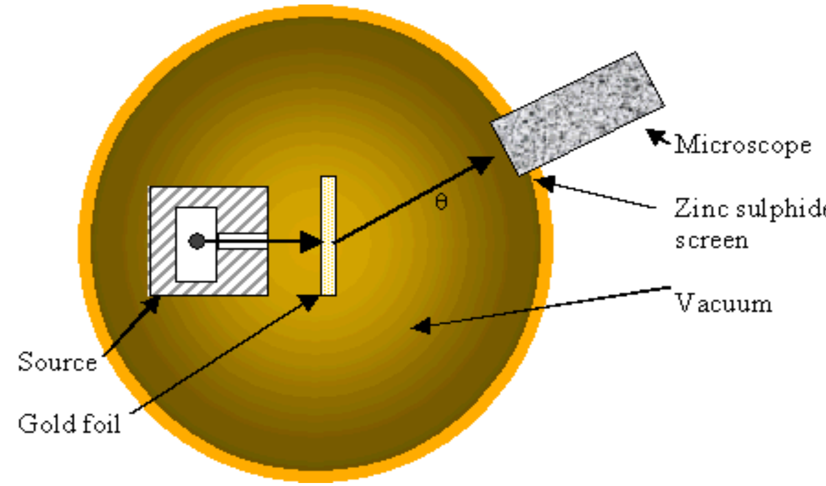
The discovery of the nucleus: Rutherford Scattering

- The Thomson model of the atom (the *plum pudding* model) assumed that electrons were embedded in a positive charge with an atomic size ~10^{-10}m
- Firing α-particles at Au foil Geiger and Marsden (1909) were expecting to see the alphas passing through and undergoing only a small amount of scattering.
- However, they observed an amazing result: some of the alphas were scattered by very large angles up to almost 180^o

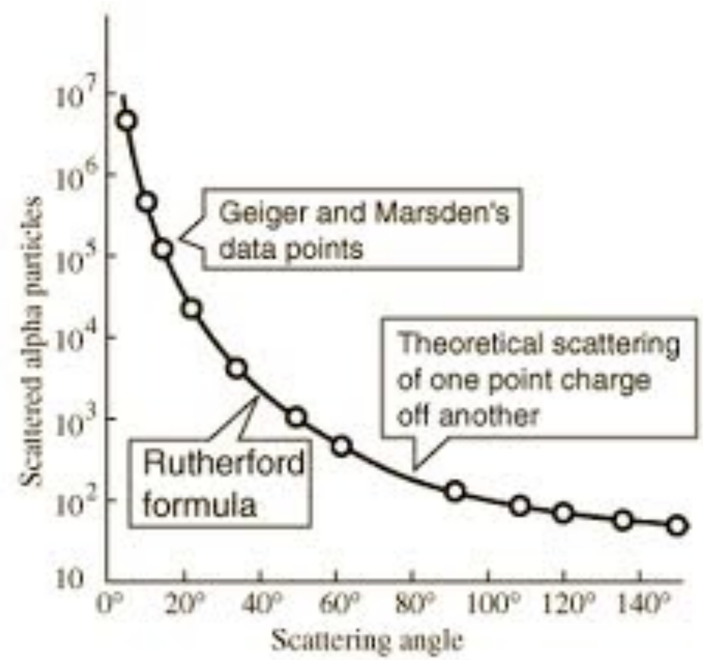


Rutherford Scattering

- Rutherford interpreted these results as the scattering of the alpha particle from a very small dense core of positive charge in the centre of the atom: the nucleus



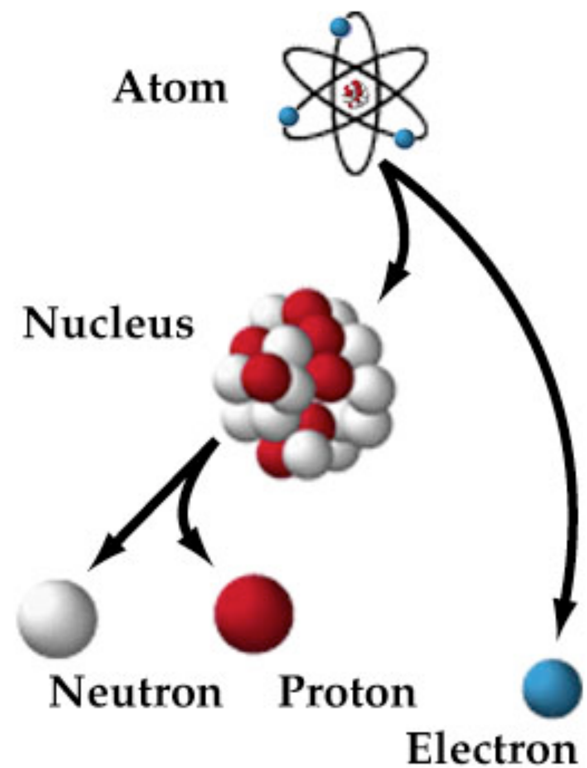
Ernest Rutherford:
"it was quite the most incredible event that ever happened to me in my life. It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it had come back and hit you"



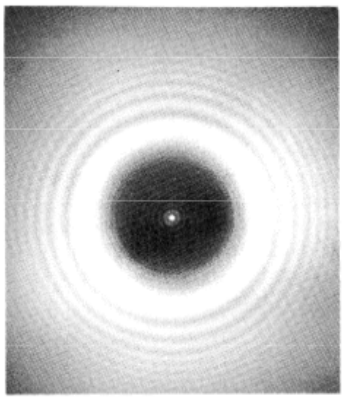
- This was the basis for the Bohr model of the atom
- Chadwick later discovered the neutron

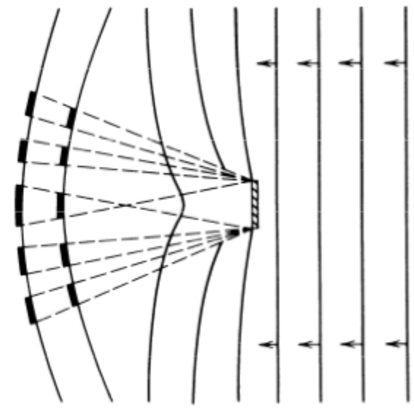
Atoms and nuclei

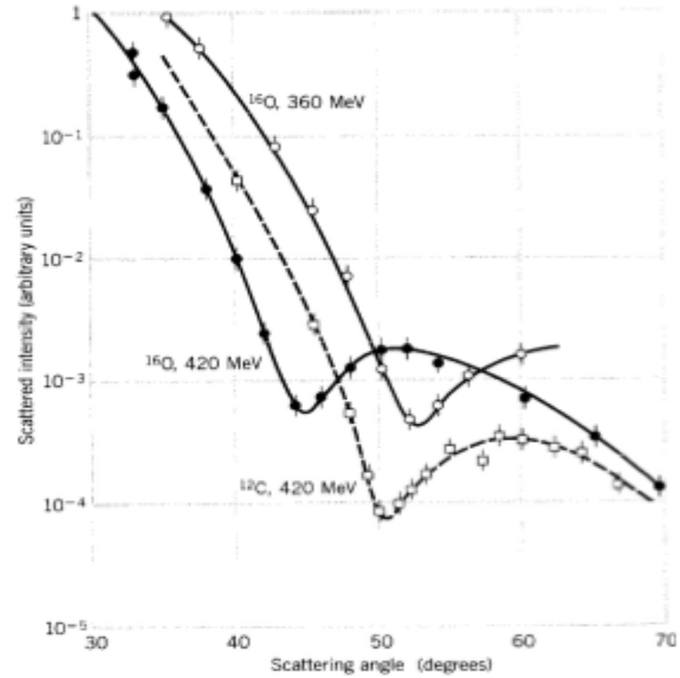
- **Atoms** are electrically neutral
  - Z electrons orbit a nucleus containing Z protons
  - Z is called the *atomic number* - and is the key to chemistry
  - Atomic size ~10^{-10}m
- **Nuclei** form the dense core of the atom – the nucleus
  - Consist of protons and neutrons
  - Size of the nucleus ~10^{-15} m

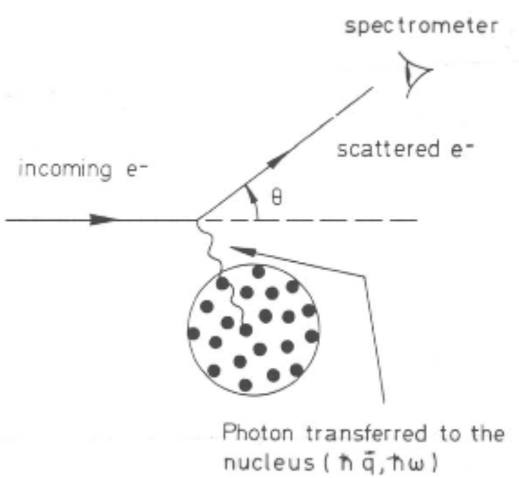


Measuring nuclear radii









- To ‘see’ a nucleus requires very small wavelengths -> one can use electrons
- Scattering electrons off a nucleus produces a diffraction pattern
- Note that this measures the *charge radius* since the electron scattering off the nucleus is governed by electromagnetic interaction

Numerical example

De Broglie wavelength is given by

$$\lambda = h/p$$

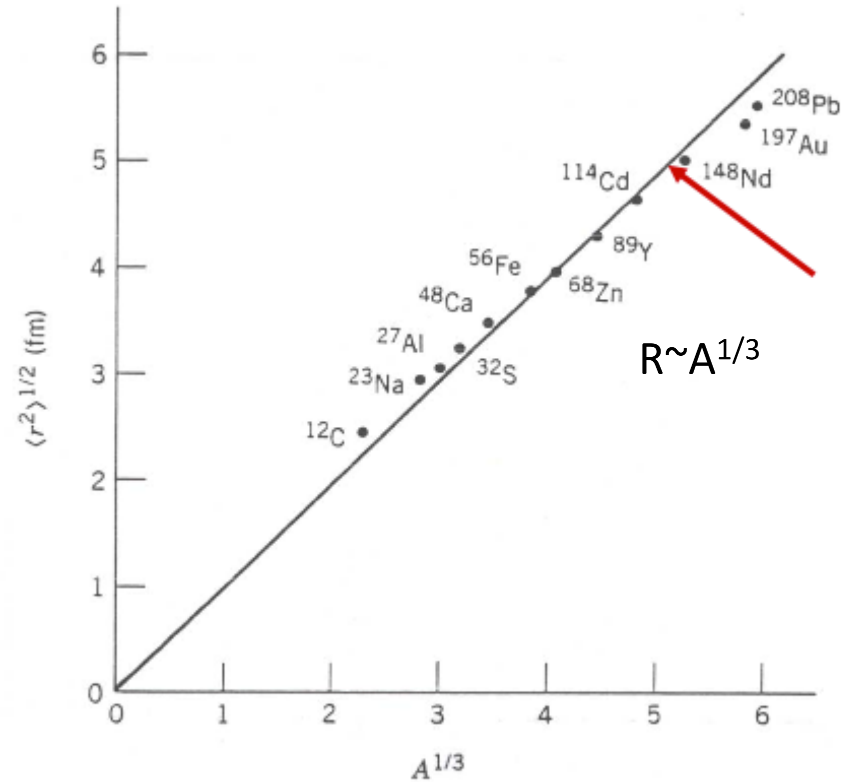
For an electron of 400 MeV energy, $p = 400\ \mathrm{MeV}/c$

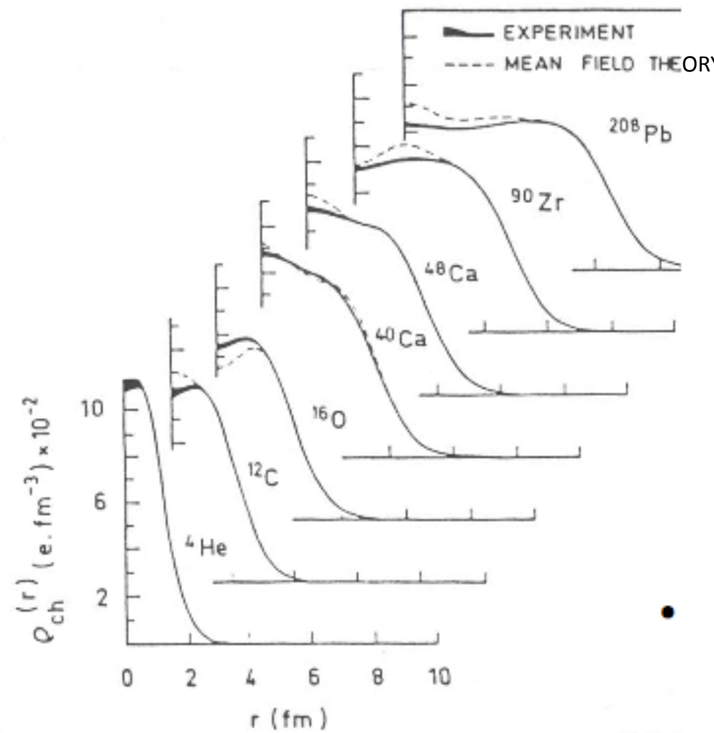
$$\lambda = (4.13\times10^{-21}\ \mathrm{MeV}\cdot\mathrm{s} \times 3\times10^{8})/400\ \mathrm{MeV}/c \approx 3\mathrm{fm}$$

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

This is comparable with the size of the nucleus.

Nuclear charge radius





The central density is the same for all nuclei

$$R = R_0 A^{1/3} \text{ where } R_0 = 1.2\, fm$$

Nuclear nomenclature

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

- X = chemical symbol
- Z = number of protons
- N = number of neutrons
  - (this often not quoted as it is redundant)
- A = mass number

  A = Z + N

Lead-208:

$$^{208}_{82}Pb_{126}$$

82 protons
126 neutrons (= 208 - 82)

Carbon-12:

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

Some more nomenclature

- Isotopes:
  - Nuclei with the same number of protons Z (same chemical element) but different numbers of neutrons

$$^{35}_{17}Cl_{18} \qquad ^{37}_{17}Cl_{20}$$

- Isotones:
  - Nuclei with the same number of neutrons but different proton number

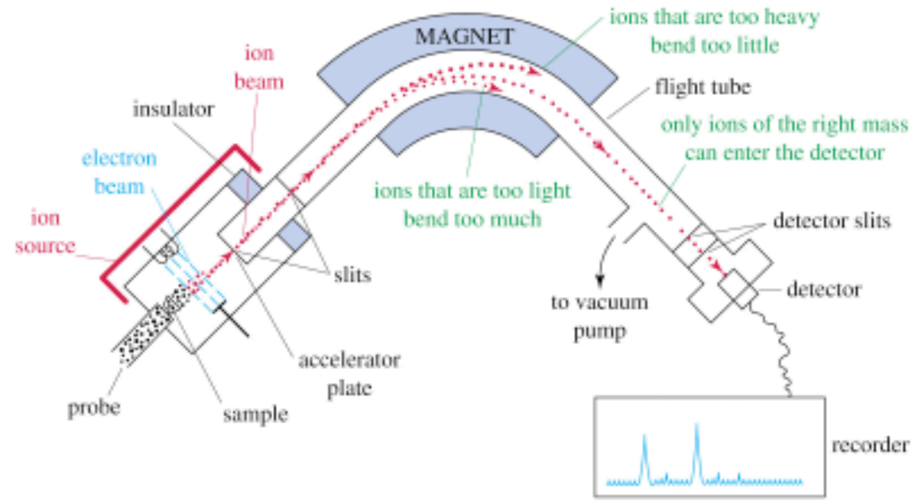
$$^{114}_{48}Cd_{66} \qquad ^{115}_{49}In_{66}$$

- Isobars:
  - Nuclei with the same mass number but different numbers of protons and neutrons

$$^{14}_{6}C_{8} \qquad ^{14}_{7}N_{7} \qquad ^{14}_{8}O_{6}$$

Nuclear masses

- Nuclear masses
  - Are measured using mass spectrometers
  - Masses are measured in atomic mass units: u
  - ^{12}C is defined to be exactly $12.0u$



$1u = 931.50\ MeV/c^2$

	Charge	Mass (u)	Mass (MeV/c^2)
Proton	+1e	1.00727647	938.280
Neutron	0	1.00866501	939.573
Electron	-1e	5.48580×10^{-3}	0.511003

Nuclear mass and binding energy

The mass of a nucleus can be written as:

$$m_N c^2 = m_A c^2 - Z m_e c^2 + \sum_{i=1}^{Z} B_e$$

Atomic mass energy　　Electron mass energy　　Electron binding energy

Electron binding energy can be ignored compared to the atomic mass energy

Electronic binding energy/atomic mass energy ~10-100keV/A x 1000MeV

How stable is a nucleus ? Binding energy

- The binding energy, B, of a nucleus is the difference in mass energy between the free particles and the bound state
- This is related to the stability of nuclei, the greater the binding energy the more stable the nucleus

- It is often useful to look at binding energy/nucleon: B/A
  i.e. the energy required to remove a nucleon from the nucleus, similar to atomic ionisation energy

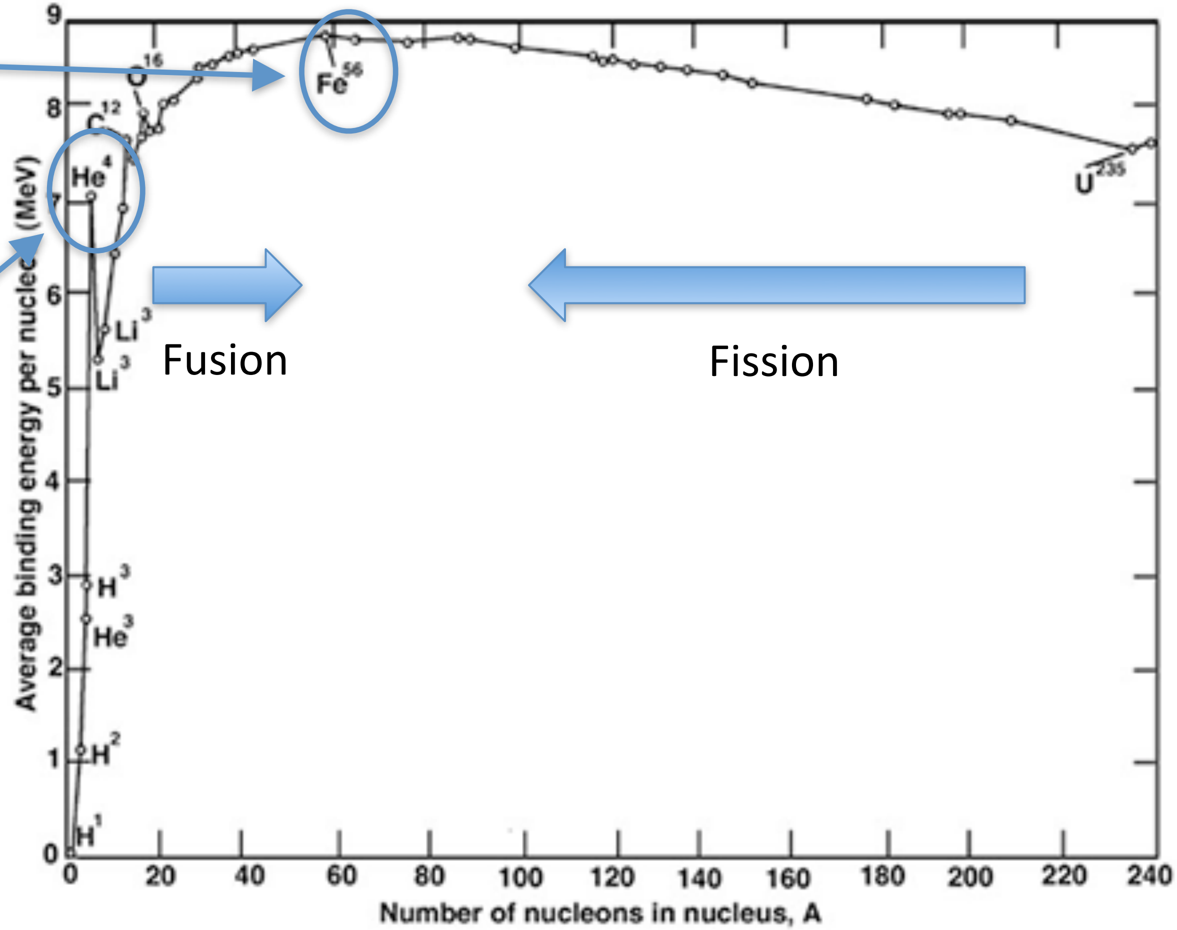
$$B = \{ \underbrace{Zm_p + Nm_n}_{\text{Free nucleons}} - \underbrace{[m(^A X) - Zm_e]}_{\text{Bound state}} \} c^2$$

$$B = [Zm(^1_1 H) + Nm_n - m(^A X)] c^2$$

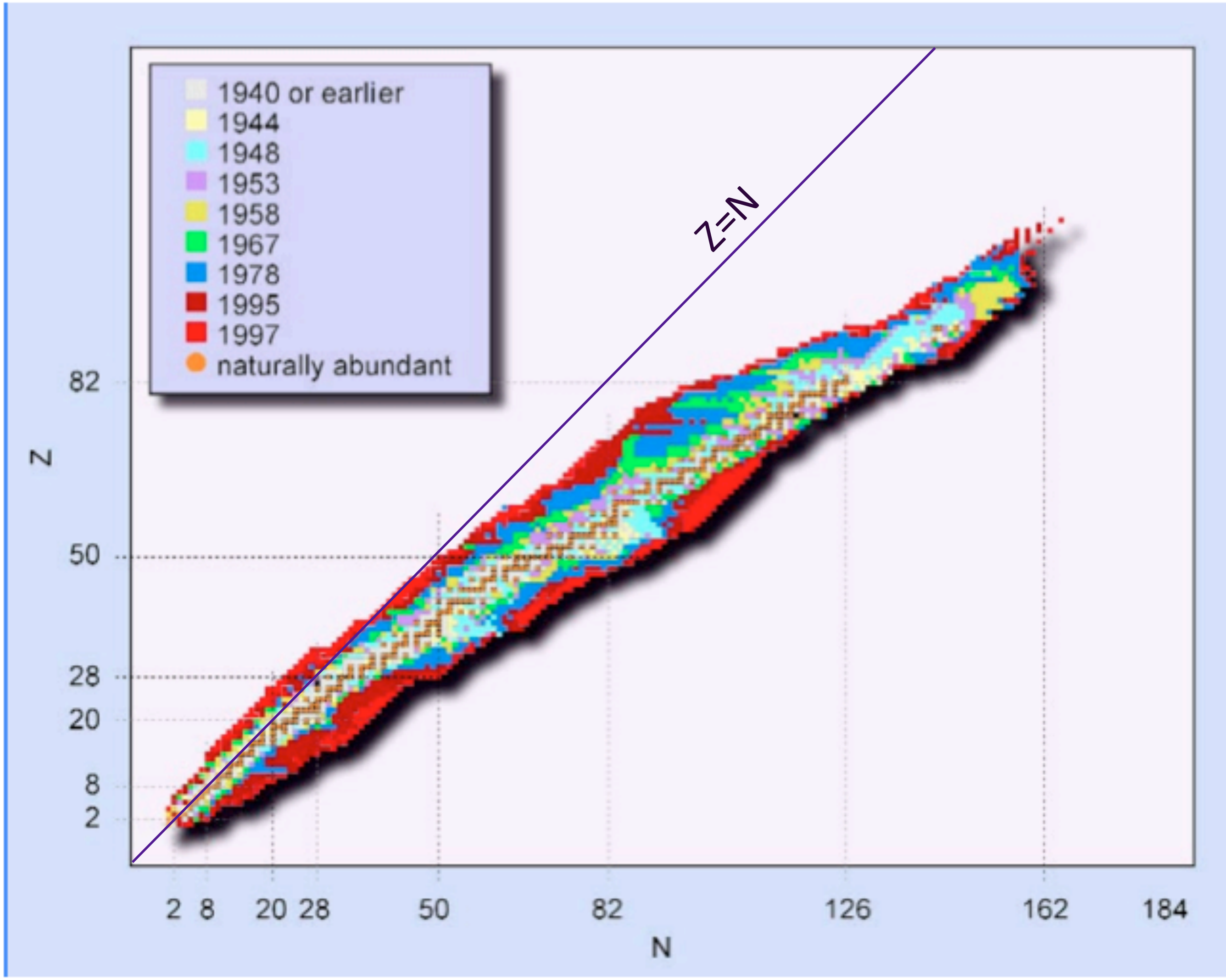
Binding energy per nucleon

Fe is the most stable nucleus

Light nuclei are not stable but ^4_2He – alpha particles are



What nuclei exist?



There are 214 stable nuclides, up to Z=82 (Pb)

There are 3896 nuclides known <u>today</u>

The search for new elements

Number	Name	Longest-lived isotope	Half-life
100	Fermium	^{257}Fm	101 days
101	Mendelevium	^{258}Md	52 days
102	Nobelium	^{259}No	58 minutes
103	Lawrencium	^{262}Lr	3.6 hours
104	Rutherfordium	^{267}Rf	1.3 hours
105	Dubnium	^{268}Db	29 hours
106	Seaborgium	^{271}Sg	1.9 minutes
107	Bohrium	^{270}Bh	61 seconds
108	Hassium	^{277}Hs	~12 minutes
109	Meitnerium	^{278}Mt	7.6 seconds
110	Darmstadtium	^{281}Ds	11 seconds
111	Roentgenium	^{281}Rg	26 seconds
112	Copernicium	^{285}Cn	29 seconds
113	Ununtrium	^{286}Uut	19.6 seconds
114	Ununquadium	^{289}Uuq	2.6 seconds
115	Ununpentium	^{289}Uup	220 ms
116	Ununhexium	^{293}Uuh	61 ms
117	Ununseptium	^{294}Uus	78 ms

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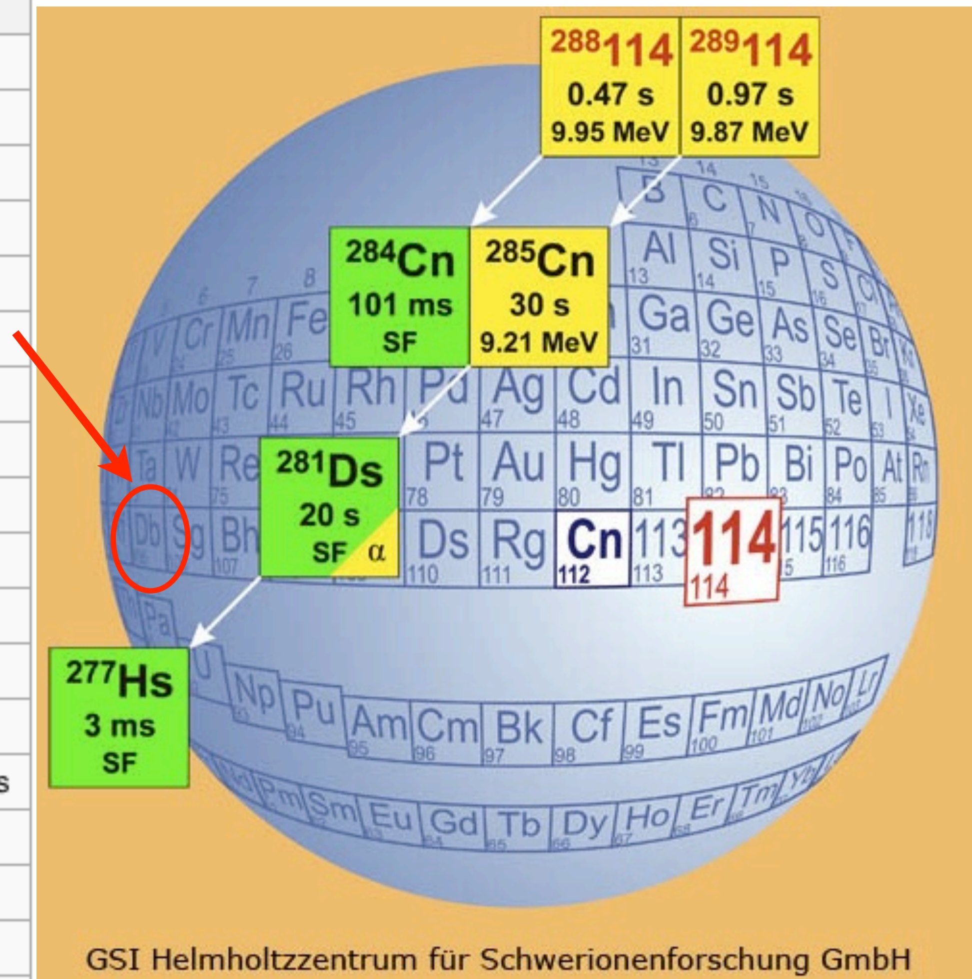
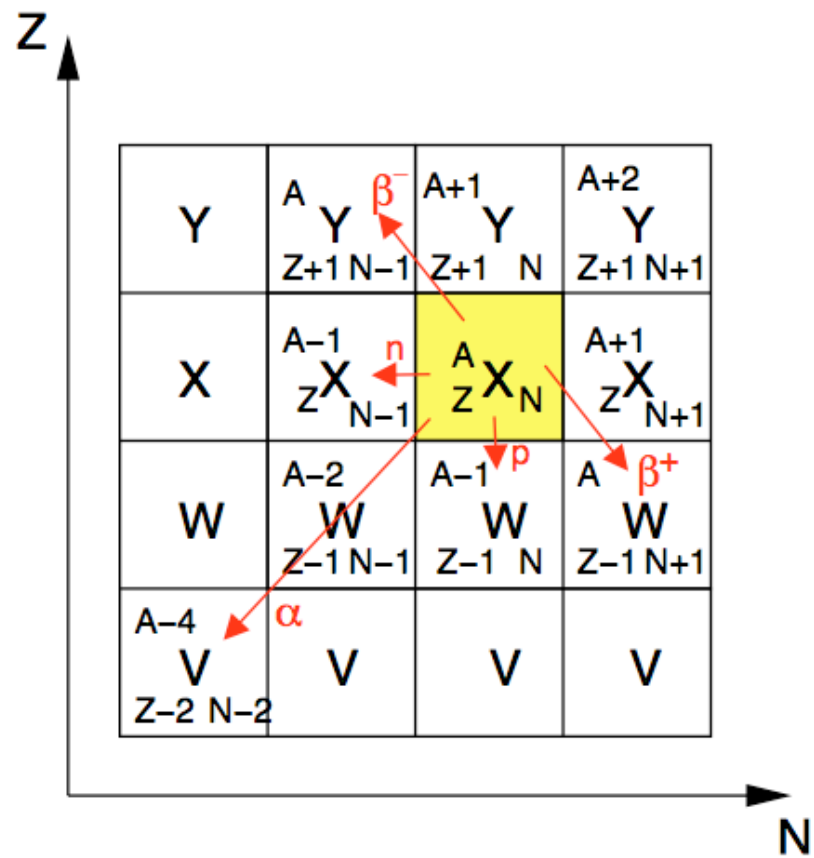


Nuclear decay and radioactivity

Change in nuclear state ⇔ Radiation

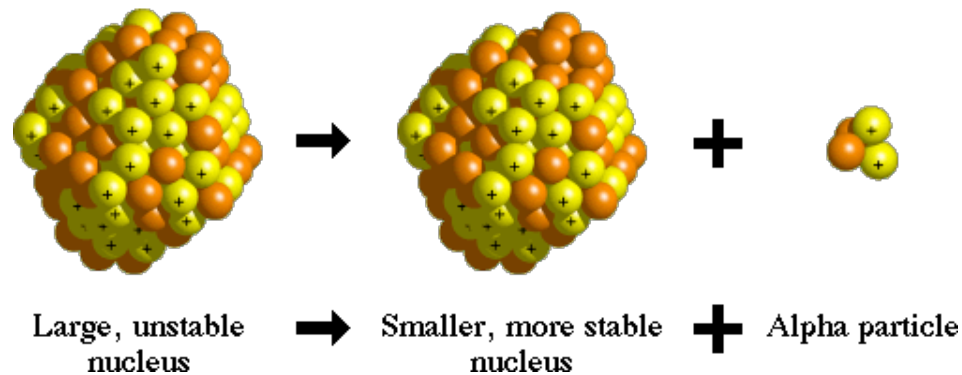
Nuclei decay via:

- α-decay
- β-decay
- γ-decay
  - nuclei have energy levels like atoms, γ-rays are emitted when an nucleus de-excites
  - does not change Z or N
- Nucleon emission
  - Emission of n or p, via a process similar to α-decay
- Spontaneous fission

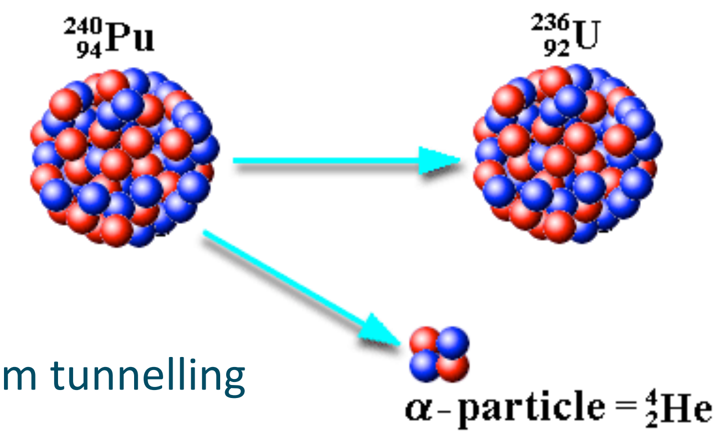


Alpha decay

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



$$^{240}_{94}Pu_{146} \rightarrow {}^{236}_{92}U_{144} + {}^{4}_{2}He_{2}$$

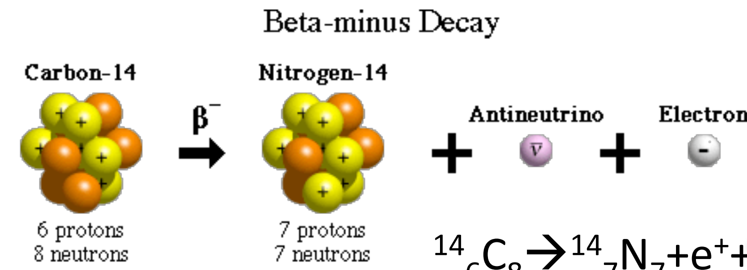


Quantum tunnelling

Beta decays

β^-decay: $n \rightarrow p + e^- + \nu$

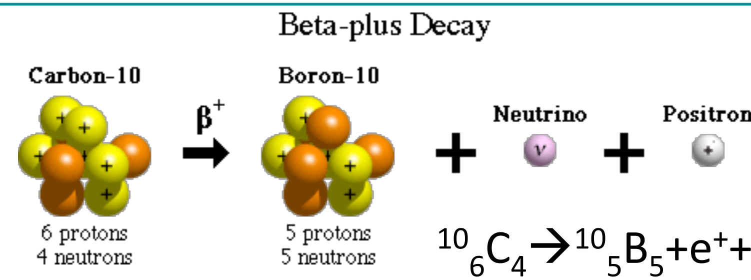
$$^A_ZX_N \rightarrow {}^A_{Z+1}Y_{N-1} + e^- + \bar{\nu}_e$$



$$^{14}_6C_8 \rightarrow {}^{14}_7N_7 + e^+ + \bar{\nu}_e$$

β^+-decay: $p \rightarrow n + e^+ + \nu$

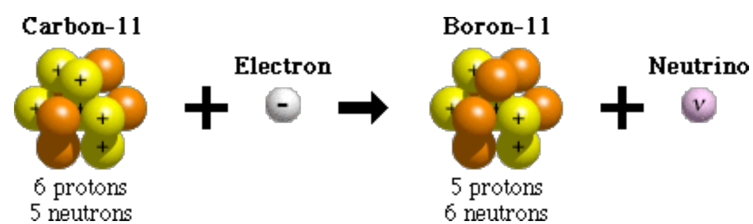
$$^A_ZX_N \rightarrow {}^A_{Z-1}Y_{N+1} + e^+ + \nu_e$$



$$^{10}_6C_4 \rightarrow {}^{10}_5B_5 + e^+ + \nu_e$$

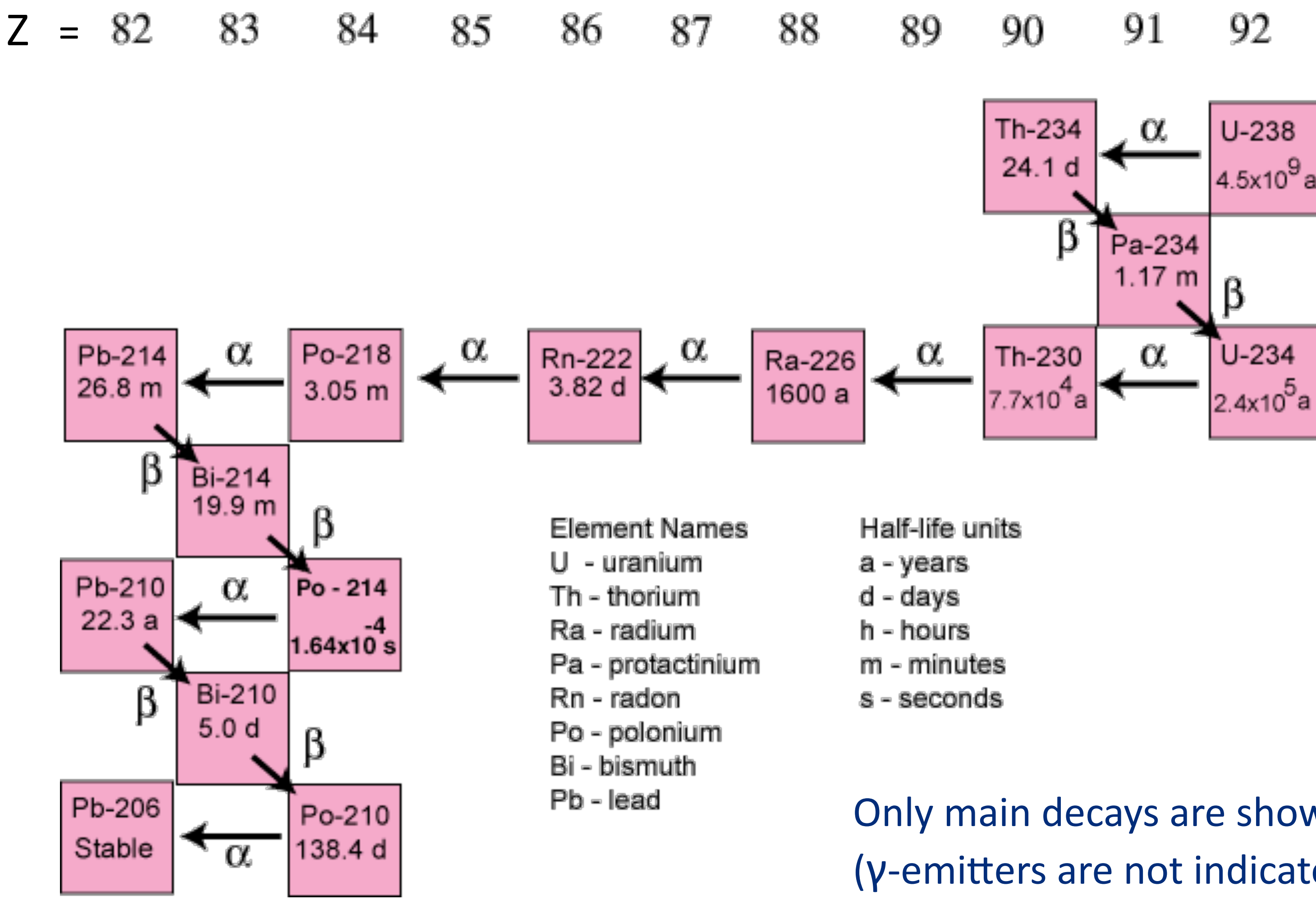
Electron capture: $e^- + p \rightarrow n + \nu$

$$e^- + {}^A_ZX_N \rightarrow {}^A_{Z-1}Y_{N+1} + \nu_e$$



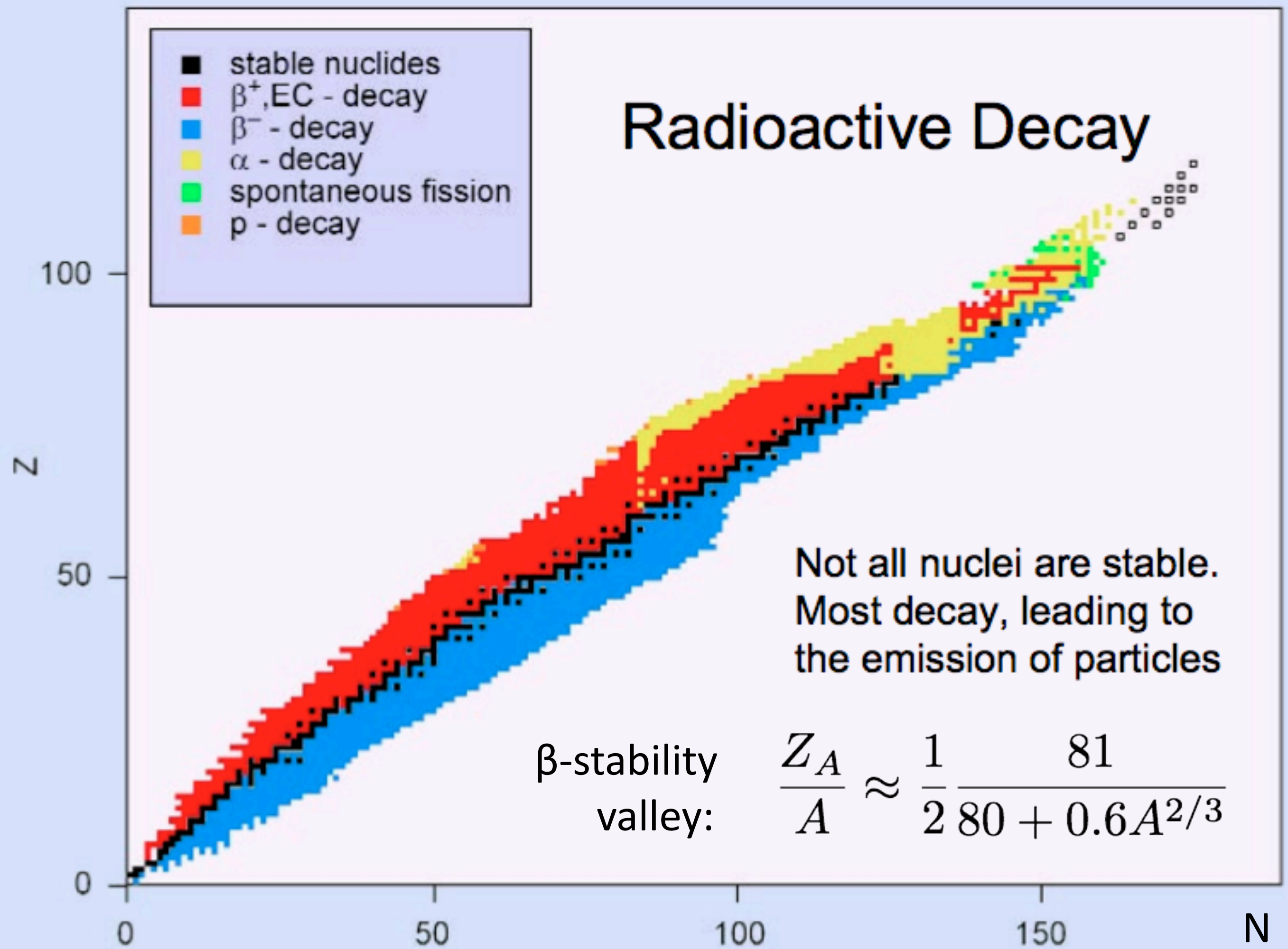
$$e^- + {}^{11}_6C_5 \rightarrow {}^{11}_5B_6 + \nu_e$$

The ^{238}U Decay Chain



Only main decays are shown
(γ-emitters are not indicated)

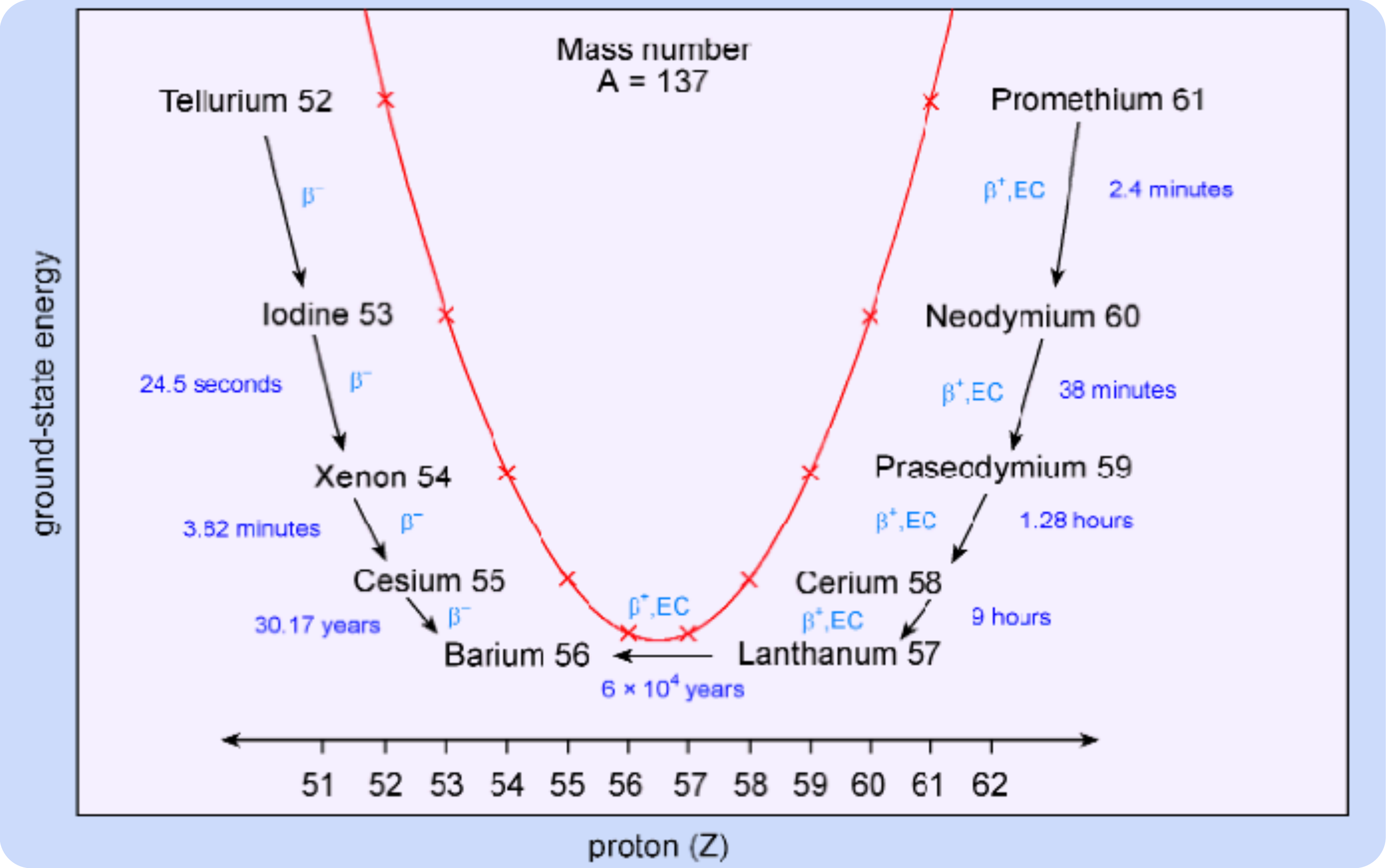
What nuclei exist



Not all nuclei are stable. Most decay, leading to the emission of particles

β-stability valley: $\frac{Z_A}{A} \approx \frac{1}{2}\frac{81}{80 + 0.6A^{2/3}}$

Stability



Mass number
A = 137
Tellurium 52
β⁻
Iodine 53
24.5 seconds
β⁻
Xenon 54
3.82 minutes
β⁻
Cesium 55
30.17 years
β⁻
Barium 56
β⁺,EC
6 × 10⁴ years
Lanthanum 57
β⁺,EC
9 hours
Cerium 58
β⁺,EC
1.28 hours
Praseodymium 59
β⁺,EC
38 minutes
Neodymium 60
β⁺,EC
2.4 minutes
Promethium 61
ground-state energy
51 52 53 54 55 56 57 58 59 60 61 62
proton (Z)

Beta-stability valley

Using the semi-empirical equation for the binding energy:

$$B_{tot}(Z,A) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_a \frac{(A-2Z)^2}{A}$$

$$M(Z,A) = Z\cdot M_p + (A-Z)M_n - B_{tot}(Z,A)$$

$$a_a \frac{(A-2Z)^2}{A} = a_a \frac{A^2 - 4AZ + 4Z^2}{A} = a_a\left(A - 4Z + \frac{4Z^2}{A}\right)$$

$$M = A\left[M_n - a_v + \frac{a_s}{A^{1/3}} + a_a\right] + Z\left[M_p - M_n - 4Za_a\right] + Z^2\left(\frac{a_c}{A^{1/3}} + \frac{4a_a}{A}\right)$$

This the equation of a parabola $M(Z) = a + bZ + cZ^2$

Minimising M:

$$\left(\frac{\partial M}{\partial Z}\right)_A = 0 = b + 2cZ_A$$

$$\frac{Z_A}{A} \approx \frac{1}{2}\frac{81}{80 + 0.6A^{2/3}}$$