



ROYAL INSTITUTE  
OF TECHNOLOGY

# Nuclear Fuel Cycle 2011

Lecture 2: Basic Nuclear Chemistry, Part 1



# Home page of the course: KTH Social

<https://www.kth.se/social/course/KD2430/>

---

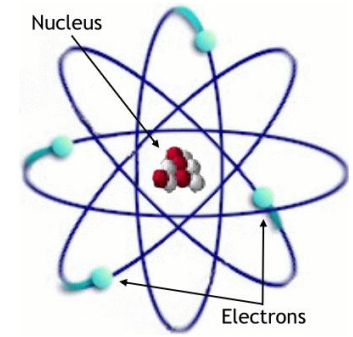


ROYAL INSTITUTE  
OF TECHNOLOGY

# What is Nuclear Chemistry?

- Chemistry related to nuclear technology
  - Chemistry of radionuclides
  - Studies of chemical processes by using radionuclides as tracers: **Radiochemistry**
  - Radiation induced chemical reactions: **Radiation Chemistry**
-

# The Nucleus

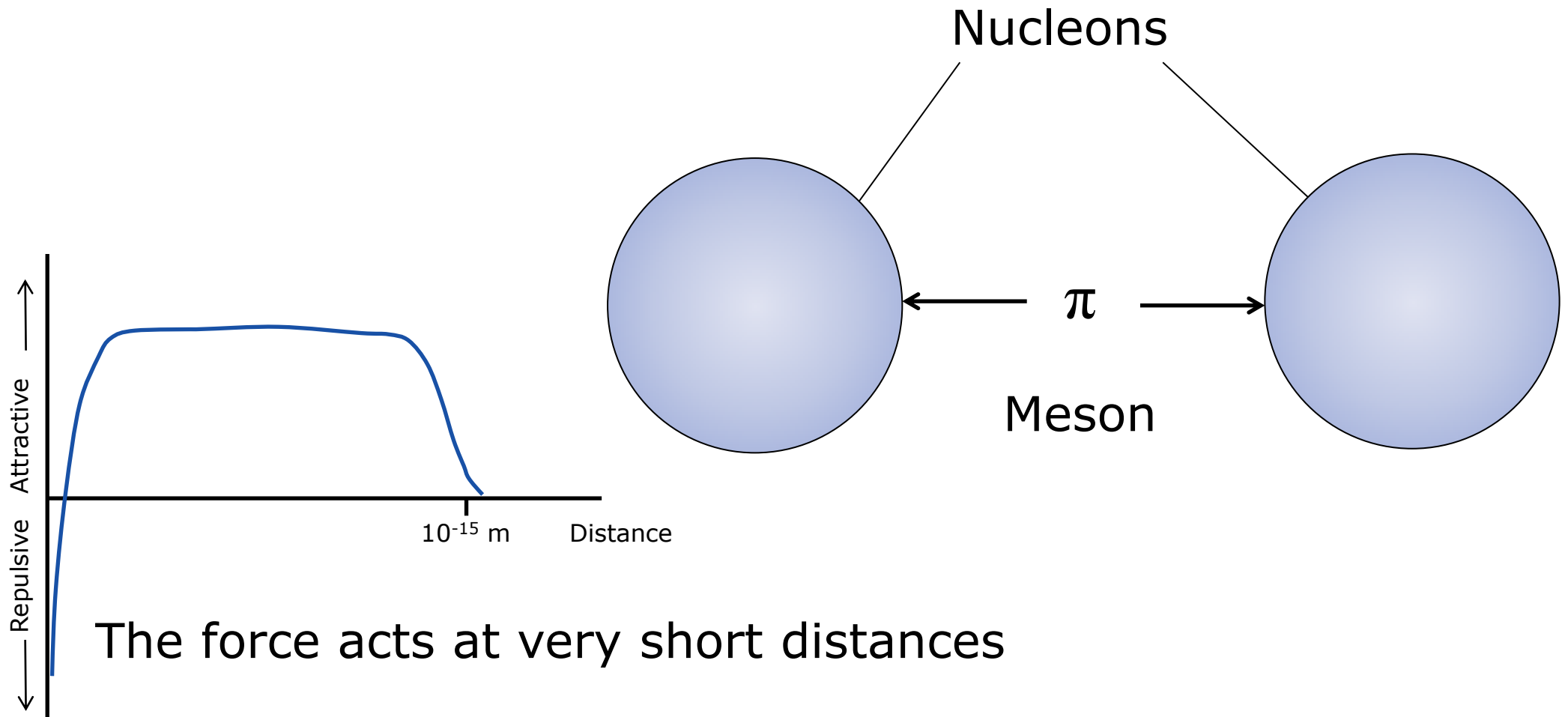


- Building blocks: Protons and neutrons
- Forces: Electromagnetic forces and the strong nuclear force

|        | <b>Proton</b>             | <b>Neutron</b>            |
|--------|---------------------------|---------------------------|
| Mass   | $1.673 \times 10^{-24}$ g | $1.675 \times 10^{-24}$ g |
| Charge | +1                        | 0                         |
| Spin   | $s = \frac{1}{2}$         | $s = \frac{1}{2}$         |

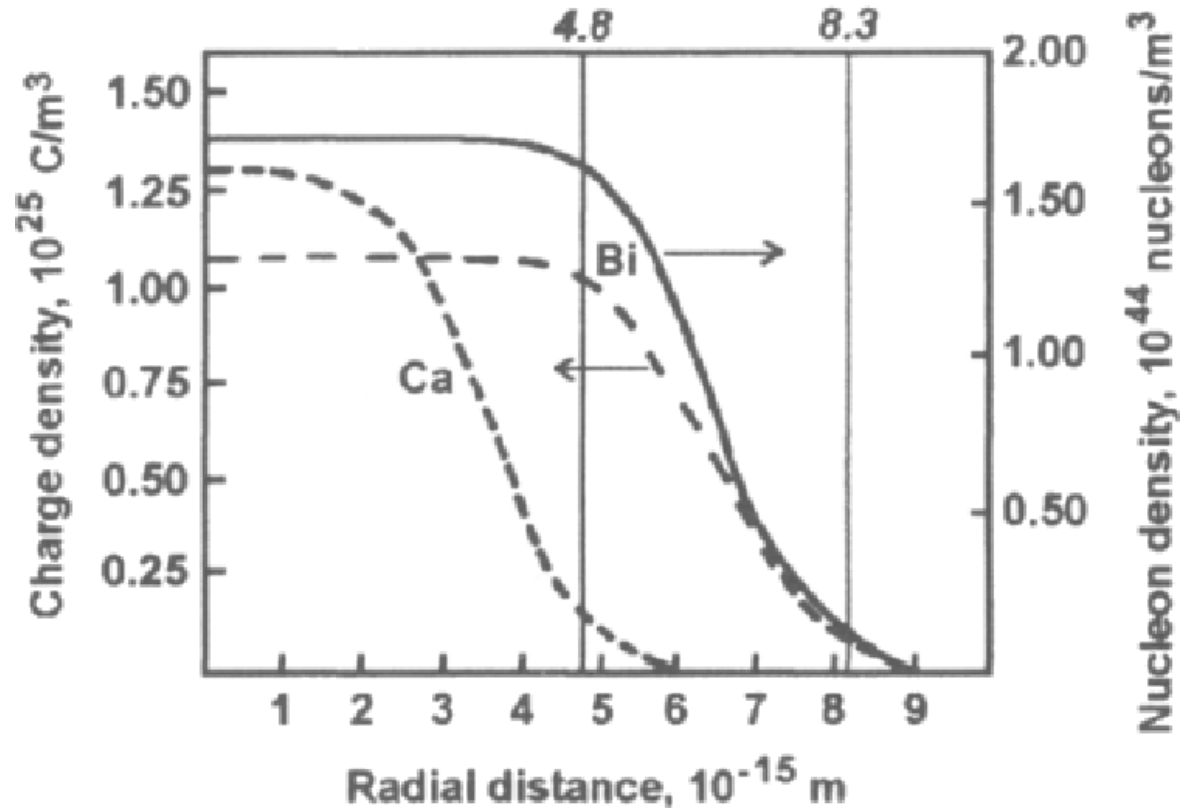
# The Strong Nuclear Force

Exchange of mesons keep the nucleons together



The force acts at very short distances

# Nuclear density and radius



*Measured charge and nuclear density for  $^{40}\text{Ca}$  and  $^{209}\text{Bi}$  as a function of nuclear radius*

Density:  $0.2 \text{ nucleons/fm}^3 \Rightarrow 10^{14} \text{ g/cm}^3!$

# The Nucleus

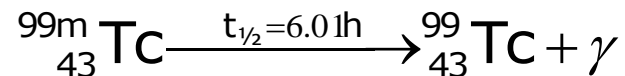
$${}^A_Z\text{R} \quad Z+N = A$$

Z = Number of protons

N = Number of neutrons

A = Mass number (number of nucleons)

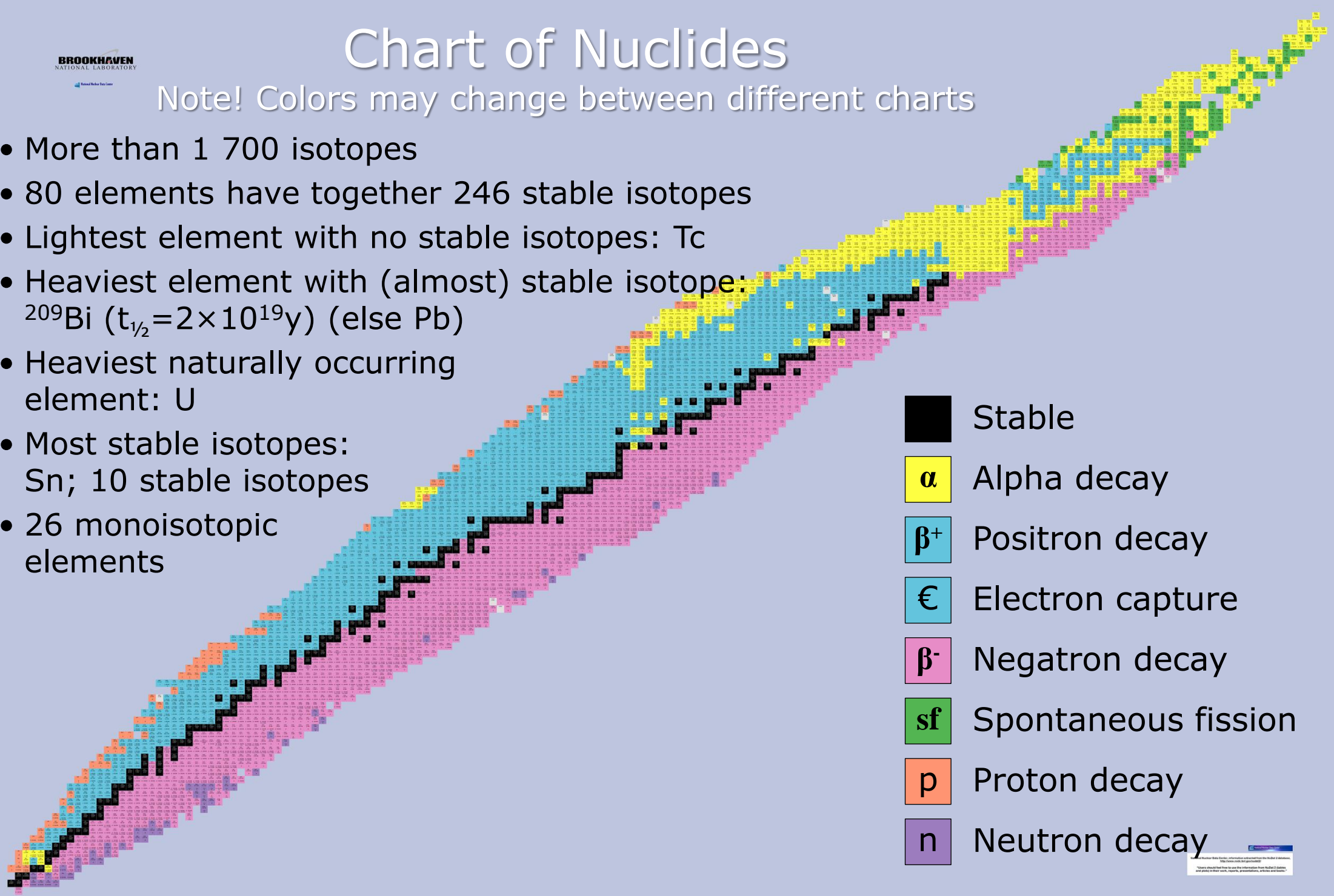
| Nuclide  | Specific nuclear species | Examples  |
|----------|--------------------------|---|
| Isotopes | Identical Z              | ${}^{234}_{92}\text{U}$ ${}^{235}_{92}\text{U}$ ${}^{238}_{92}\text{U}$   |
| Isotones | Identical N              | ${}^{36}_{16}\text{S}$ ${}^{37}_{17}\text{Cl}$ ${}^{38}_{18}\text{Ar}$ ${}^{39}_{19}\text{K}$ ${}^{40}_{20}\text{Ca}$ |
| Isobars  | Identical A              | ${}^{96}_{38}\text{Sr}$ ${}^{96}_{39}\text{Y}$ ${}^{96}_{40}\text{Zr}$  |
| Isomers  | Identical Z and A        | ${}^{99m}_{43}\text{Tc}$ ${}^{99}_{43}\text{Tc}$  |



# Chart of Nuclides

Note! Colors may change between different charts

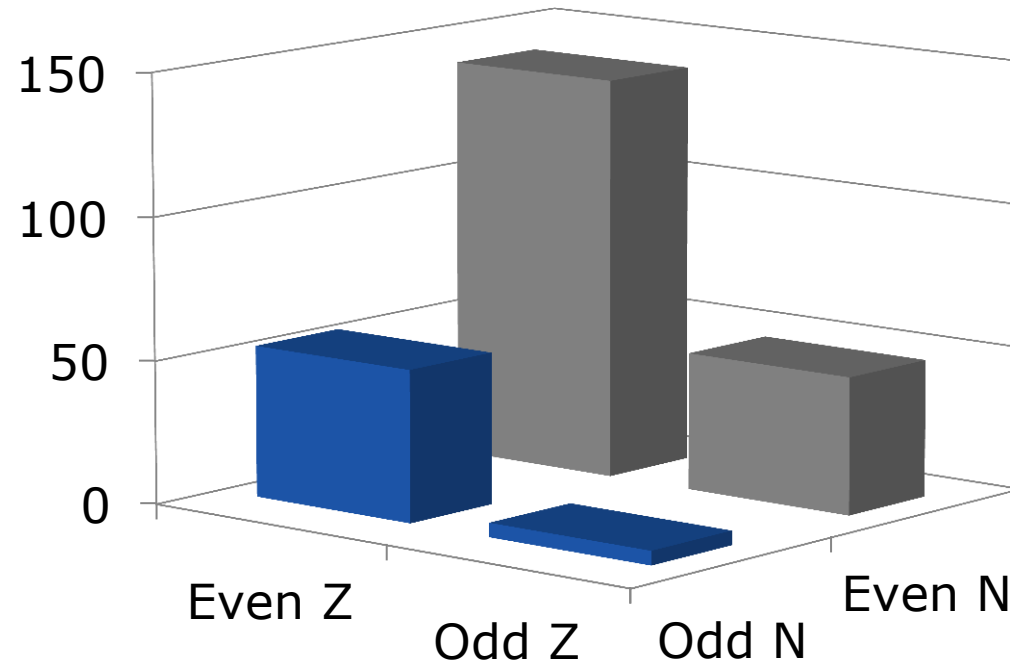
- More than 1 700 isotopes
- 80 elements have together 246 stable isotopes
- Lightest element with no stable isotopes: Tc
- Heaviest element with (almost) stable isotope:  
 $^{209}\text{Bi}$  ( $t_{1/2} = 2 \times 10^{19}\text{y}$ ) (else Pb)
- Heaviest naturally occurring element: U
- Most stable isotopes:  
Sn; 10 stable isotopes
- 26 monoisotopic elements



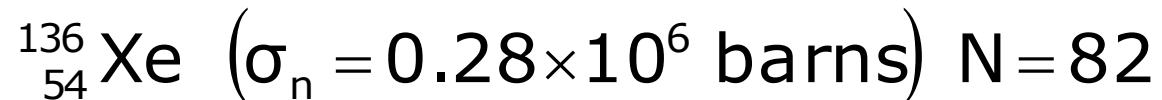
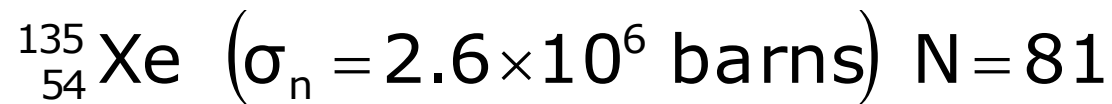
- Stable
- $\alpha$  Alpha decay
- $\beta^+$  Positron decay
- $\epsilon$  Electron capture
- $\beta^-$  Negatron decay
- sf Spontaneous fission
- p Proton decay
- n Neutron decay



# Number of Nucleons on the Stability of the Nuclei

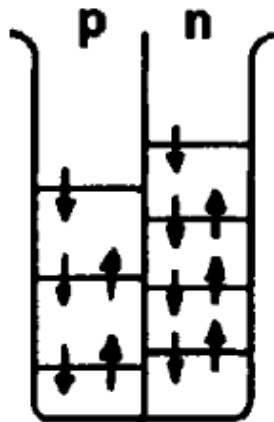


Magic numbers of protons or neutrons: 2, 8, 20, 82 and 126



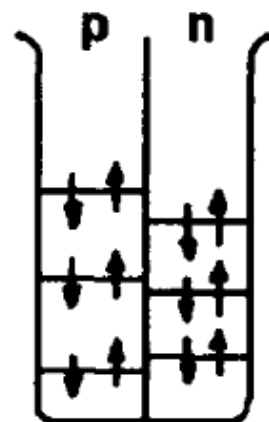
# Nuclear Stability: Nucleon Orbitals

$^{12}_5\text{B}$



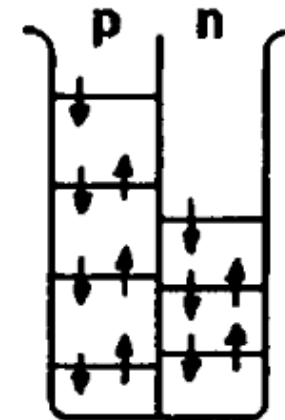
**UNSTABLE**

$^{12}_6\text{C}$

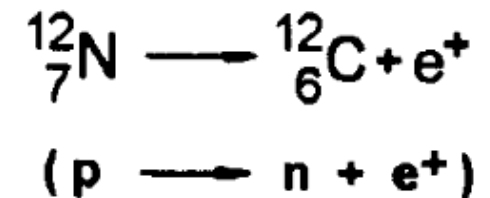
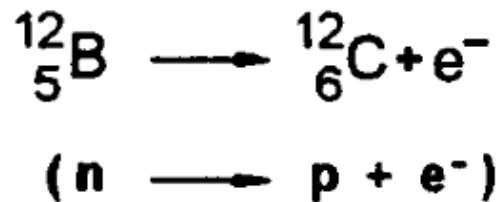


**STABLE**

$^{12}_7\text{N}$



**UNSTABLE**



# Mass Defect ( $\Delta M$ ) and Mass Excess ( $\delta_A$ )

$$\Delta M_A = M_A - Z M_p - N M_n$$

$M_A$  = Mass of atom

$M_H$  = Mass of Proton (hydrogen)

$M_n$  = Mass of Neutron

Deuterium,  ${}^2_1\text{H}$

$$M_p + M_n = 1.007\,825 + 1.008\,665 \\ = 2.016\,490\text{ u}$$

$$M_A = 2.014\,102\text{ u}$$

$$\Rightarrow \Delta M_A = -0.002\,388\text{ u}$$

All stable isotopes have negative mass defect,  $\Delta M_A$

Mass excess:  $\delta_A = M_A - A$

(sometimes used in tables, no practical use)

# Binding energy

$$\Delta E = \Delta mc^2 \quad \text{"Nuclear Heat of formation"}$$

$$\Delta m = M_A - (Z m_p + N m_n)$$

$$c = 3 \times 10^8 \text{ m/s}$$

Nucleus: 5-10 MeV / nucleon ( $5-10 \times 10^{11}$  J/mol)

Covalent bond:  $4.4 \times 10^5$  J/mol

---

# Isotope effects

Due to the difference in nucleons there are very small differences between two isotope's

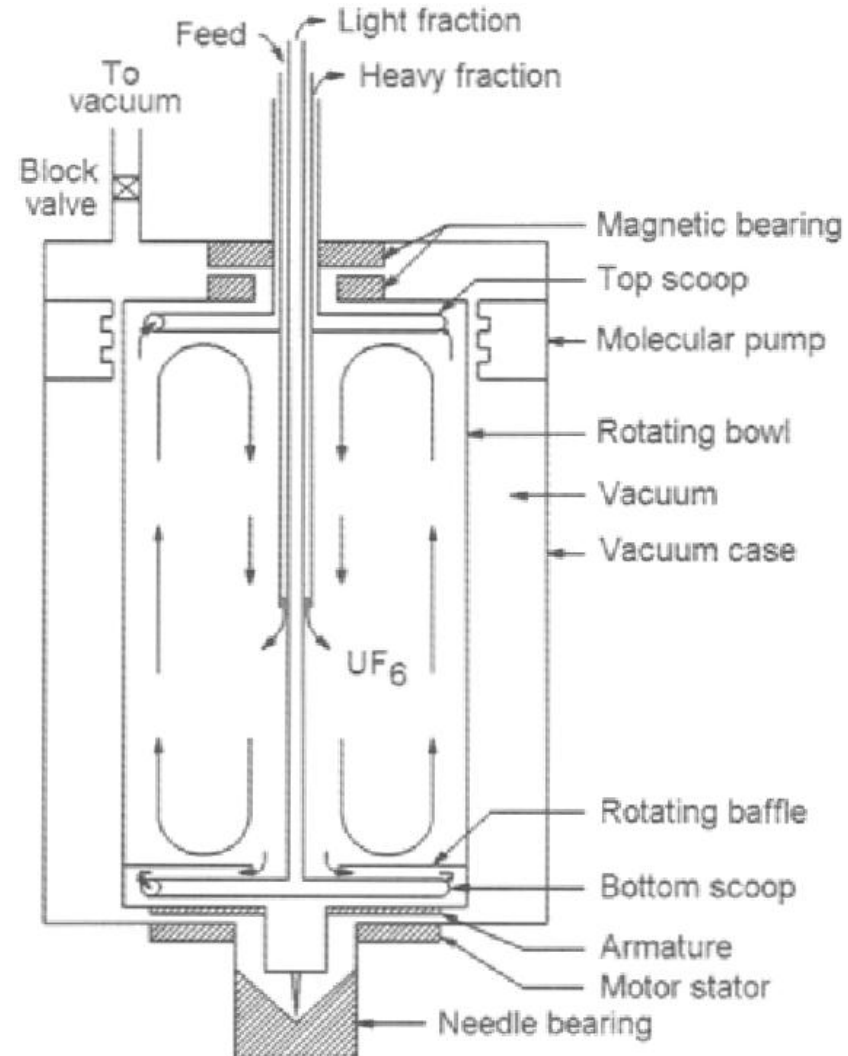
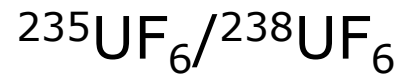
- Freezing point
  - Boiling point
  - Density
  - Heat of vaporization
  - Viscosity
  - Surface tension
  - Optical emission spectra
-

# Isotope separation

- i. Equilibrium processes (light elements)
  - ii. Rate processes
    - Multi-stage processes (for instance distillation)
    - Chemical exchange
    - Electrolysis
    - Gaseous diffusion
    - Electromagnetic separation
    - Gas centrifugation
-

# Gaseous diffusion

Lighter isotopes diffuse faster than heavy isotopes



# Other methods of isotope separation

- Distillation
  - Extraction
  - Ion-exchange
  - Photoionization
  - Photoexcitation
-

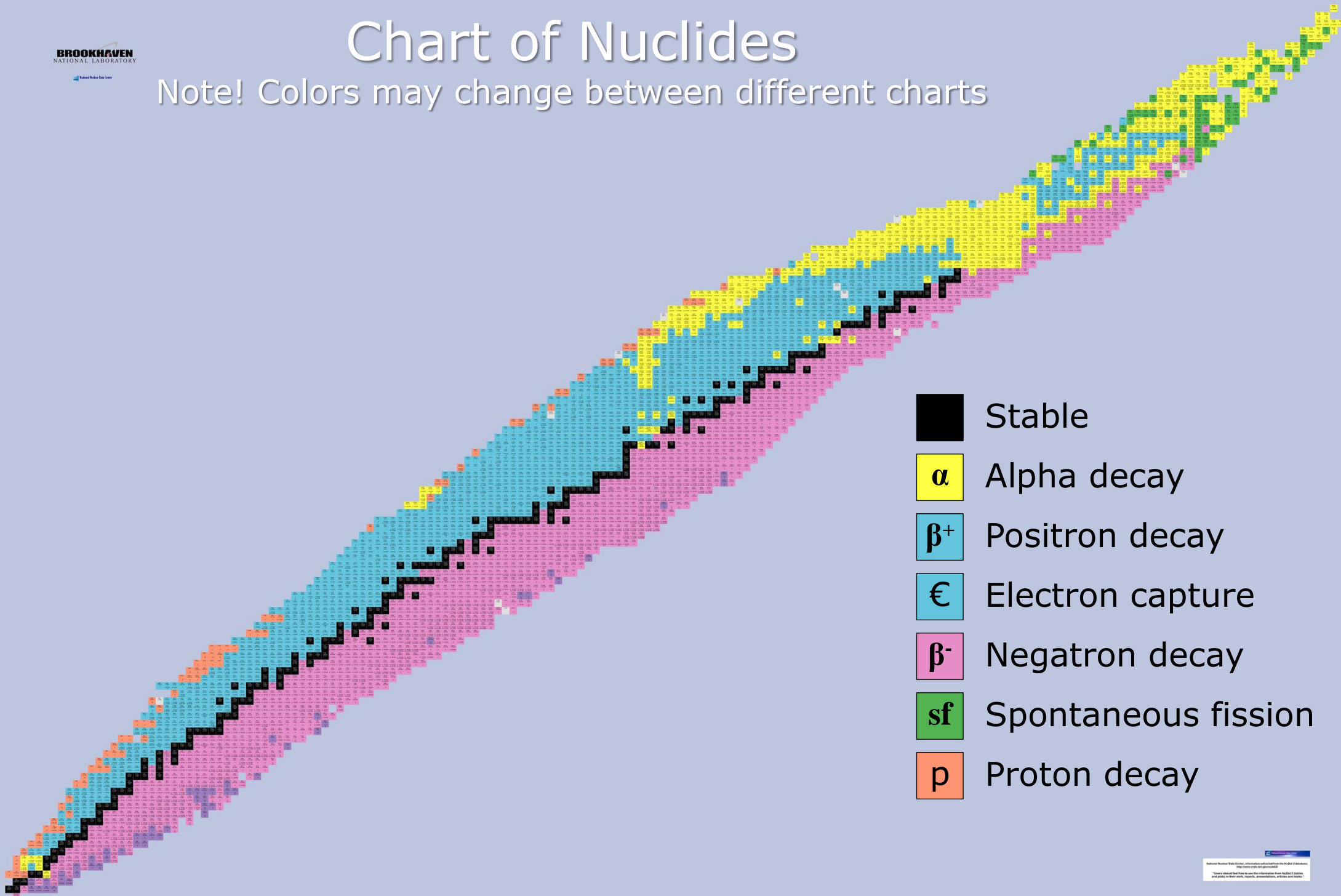









# Radioactive decay

- $\alpha$ -decay (He-nucleus)
  - $\beta$ -decay (electron/positron)
  - $\gamma$ -decay
  - Unusual modes of decay (proton, neutron, heavy particles)
  - Spontaneous fission
-

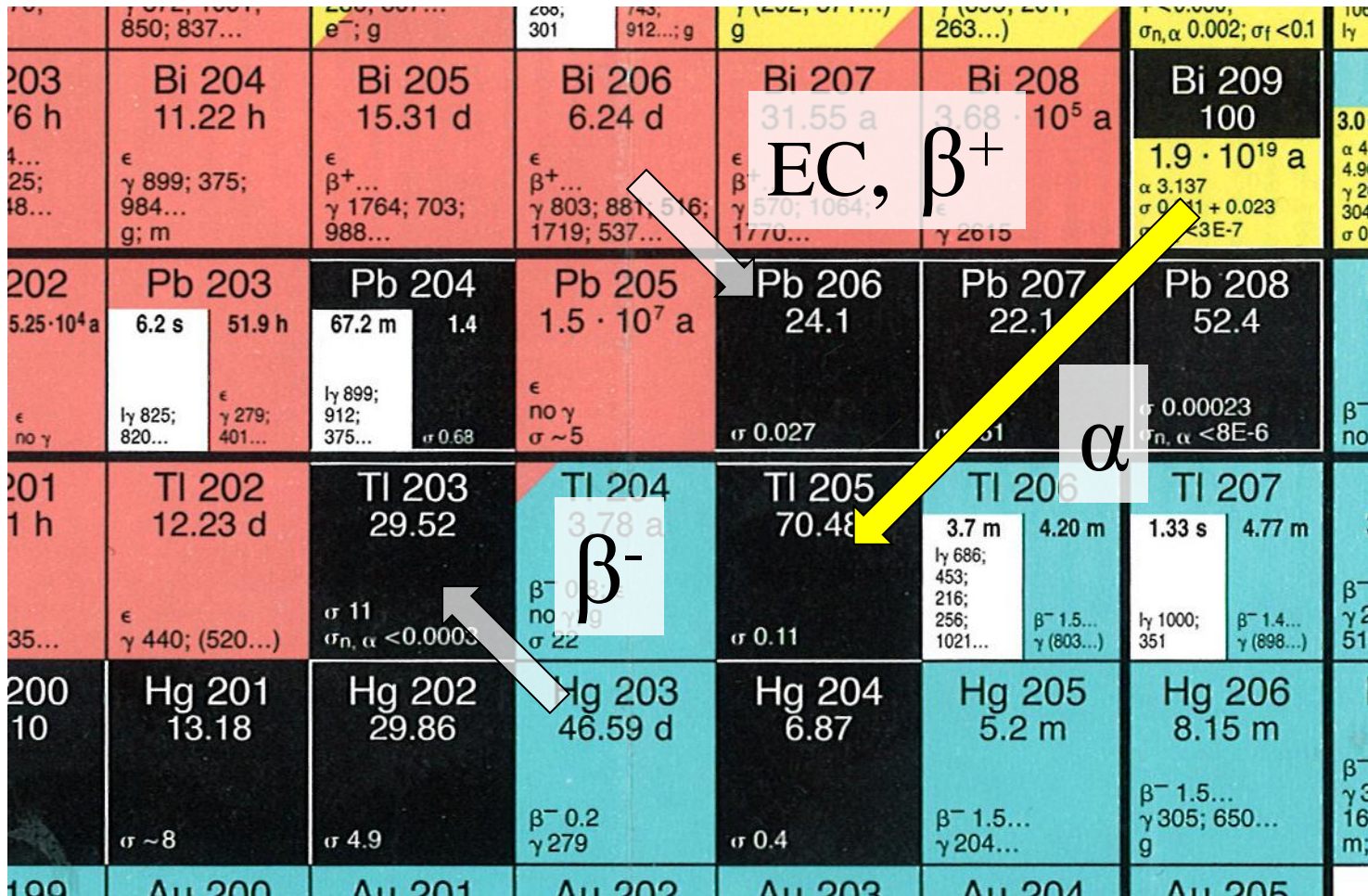
# Chart of Nuclides

Note! Colors may change between different charts



-  Stable
-   $\alpha$  Alpha decay
-   $\beta^+$  Positron decay
-   $\epsilon$  Electron capture
-   $\beta^-$  Negatron decay
-  sf Spontaneous fission
-  p Proton decay

# Nuclide chart







ROYAL INSTITUTE OF TECHNOLOGY

# Decay chain of $^{238}\text{U}$

|  |                                    |   |  |  |   |   |   |   |   |   |   |   |
|--|------------------------------------|---|--|--|---|---|---|---|---|---|---|---|
| U 226<br>0.28 s  | U 227<br>1.1 m                     | U 228<br>9.1 m  | U 229<br>58 m  | U 230<br>20.8 d  | U 231<br>4.2 d  | U 232<br>68.9 a   | U 233<br>1.592 · 10 <sup>5</sup> a  | U 234<br>0.0054 a   | U 235<br>0.7204 a   | U 236<br>2.342 · 10 <sup>7</sup> a  | U 237<br>6.75 d   | U 238<br>99.2742 a  |
| α 6.86; 7.06; 6.74...<br>γ 247; 310...; e <sup>-</sup> | α 6.68; 6.59...<br>γ (246; 187...) | α 6.362; 6.334; 6.297...<br>γ 123; 88; 199...; e <sup>-</sup> | α 5.898; 5.818...<br>γ (72; 154; 230...); e <sup>-</sup> | α 5.456; 5.471; 5.404...<br>γ 26; 84; 102...<br>e <sup>-</sup> ; σ 250 | α 5.320; 5.262...<br>No 24; No 25; γ (42; 97...); e <sup>-</sup><br>σ 47; σ 530 | α 4.824; 4.783...<br>No 24; No 25; γ (42; 97...); e <sup>-</sup><br>σ 47; σ 530 | α 4.824; 4.783...<br>No 24; No 25; γ (42; 97...); e <sup>-</sup><br>σ 47; σ 530 | α 4.824; 4.783...<br>No 24; No 25; γ (42; 97...); e <sup>-</sup><br>σ 47; σ 530 | α 4.824; 4.783...<br>No 24; No 25; γ (42; 97...); e <sup>-</sup><br>σ 47; σ 530 | α 4.824; 4.783...<br>No 24; No 25; γ (42; 97...); e <sup>-</sup><br>σ 47; σ 530 | α 4.824; 4.783...<br>No 24; No 25; γ (42; 97...); e <sup>-</sup><br>σ 47; σ 530 | α 4.824; 4.783...<br>No 24; No 25; γ (42; 97...); e <sup>-</sup><br>σ 47; σ 530 |

|                       |  |                                    |  |  |                                       |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
|-----------------------|--|------------------------------------|--|--|---------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------------|
| Ac 213<br>0.80 s      | Ac 214<br>8.2 s                                      | Ac 215<br>0.17 s                   | Ac 216<br>0.44 ms  | Ac 217<br>0.74 μs / 69 ns              | Ac 218<br>1.1 μs                      | Ac 219<br>11.8 μs               | Ac 220<br>26 ms                 | Ac 221<br>52 ms                 | Ac 222<br>63 s / 5.0 s          | Ac 223<br>2.10 m                | Ac 224<br>2.9 h                 | Ac 225<br>10.0 d                | Ac 226<br>9.1 m                 | Ac 227<br>22.3 a                | Ac 228<br>6.13 h                | Ac 229<br>62.7 m                | Ac 230<br>122 s                 | Ac 231<br>7.5 m                 | Ac 232<br>119 s                 | Ac 233<br>145 s                 | Ac 234<br>44 s                  |                       |
| α 7.36                | α 7.215; 7.081...<br>γ 139; 244...<br>e <sup>-</sup> | α 7.600; 7.211...<br>γ (396...)    | α 9.029; 9.105...<br>γ 83; 854; 771...<br>e <sup>-</sup> | α 8.477; 8.426; 8.356...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540       | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 | α 8.700; 8.787...<br>γ 834; 540 |                       |
| Ra 212<br>13.0 s      | Ra 213<br>2.1 ms / 2.74 m                            | Ra 214<br>2.46 s                   | Ra 215<br>1.67 ms  | Ra 216<br>2.0 ns / 0.18 μs             | Ra 217<br>1.6 μs                      | Ra 218<br>25.6 μs               | Ra 219<br>10 ms                 | Ra 220<br>23 ms                 | Ra 221<br>38 s                  | Ra 222<br>3.8 s                 | Ra 223<br>11.43 d               | Ra 224<br>3.66 d                | Ra 225<br>14.8 d                | Ra 226<br>4.2 m                 | Ra 227<br>42.2 m                | Ra 228<br>5.75 a                | Ra 229<br>4.0 m                 | Ra 230<br>93 m                  | Ra 231<br>103 s                 | Ra 232<br>4.2 m                 | Ra 233<br>30 s                  | Ra 234<br>30 s        |
| α 6.899...<br>γ (635) | α 6.899...<br>γ (635)                                | α 6.899...<br>γ (635)              | α 6.899...<br>γ (635)                                    | α 6.899...<br>γ (635)                  | α 6.899...<br>γ (635)                 | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635)           | α 6.899...<br>γ (635) |
| Fr 211<br>3.10 m      | Fr 212<br>20.0 m                                     | Fr 213<br>34.6 s                   | Fr 214<br>3.35 ms / 5.0 ms                               | Fr 215<br>0.09 μs                      | Fr 216<br>0.70 μs                     | Fr 217<br>16 μs                 | Fr 218<br>22 ms / 1.0 ms        | Fr 219<br>21 ms                 | Fr 220<br>27.4 s                | Fr 221<br>4.9 m                 | Fr 222<br>14.2 m                | Fr 223<br>21.8 m                | Fr 224<br>3.9 m                 | Fr 225<br>4.0 m                 | Fr 226<br>48 s                  | Fr 227<br>2.47 m                | Fr 228<br>39 s                  | Fr 229<br>50.2 s                | Fr 230<br>19.1 s                | Fr 231<br>17.5 s                | Fr 232<br>5 s                   |                       |
| α 6.535               | α 6.535  | α 6.535                            | α 6.535  | α 6.535                                | α 6.535                               | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         | α 6.535                         |                       |
| Rn 210<br>2.4 h       | Rn 211<br>14.6 h                                     | Rn 212<br>24 m                     | Rn 213<br>19.5 ms  | Rn 214<br>6.5 ns / 0.7 ns / 0.27 μs    | Rn 215<br>2.3 μs                      | Rn 216<br>45 μs                 | Rn 217<br>0.54 ms               | Rn 218<br>35 ms                 | Rn 219<br>3.96 s                | Rn 220<br>55.6 s                | Rn 221<br>25 m                  | Rn 222<br>3.825 d               | Rn 223<br>3.9 m                 | Rn 224<br>1.78 h                | Rn 225<br>4.5 m                 | Rn 226<br>7.4 m                 | Rn 227<br>22.5 s                | Rn 228<br>65 s                  |                                 |                                 |                                 |                       |
| α 6.040...            | α 6.040...   | α 6.040...                         | α 6.040...   | α 6.040...                             | α 6.040...                            | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      | α 6.040...                      |                                 |                                 |                                 |                       |
| At 209<br>5.4 h       | At 210<br>8.3 h                                      | At 211<br>7.22 h                   | At 212<br>119 ms / 314 ms                                | At 213<br>0.11 μs                      | At 214<br>0.78 μs / 0.27 μs / 0.56 μs | At 215<br>0.1 ms                | At 216<br>0.3 ms                | At 217<br>32.3 ms               | At 218<br>~2 s                  | At 219<br>0.9 m                 | At 220<br>3.7 m                 | At 221<br>2.3 m                 | At 222<br>54 s                  | At 223<br>50 s                  |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| α 5.647               | α 5.647  | α 5.647                            | α 5.647  | α 5.647                                | α 5.647                               | α 5.647                         | α 5.647                         | α 5.647                         | α 5.647                         | α 5.647                         | α 5.647                         | α 5.647                         | α 5.647                         | α 5.647                         |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| Po 208<br>2.898 a     | Po 209<br>102 a                                      | Po 210<br>138.38 d                 | Po 211<br>25.2 s / 0.516 s                               | Po 212<br>45.1 s / 17.1 ns / 0.3 μs    | Po 213<br>4.2 μs                      | Po 214<br>164 μs                | Po 215<br>1.78 ms               | Po 216<br>0.15 s                | Po 217<br>1.53 s                | Po 218<br>3.05 m                | Po 219<br>>300 ns               | Po 220<br>>300 ns               |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| α 5.1152...           | α 5.1152...  | α 5.1152...                        | α 5.1152...  | α 5.1152...                            | α 5.1152...                           | α 5.1152...                     | α 5.1152...                     | α 5.1152...                     | α 5.1152...                     | α 5.1152...                     | α 5.1152...                     | α 5.1152...                     |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| Bi 207<br>31.55 a     | Bi 208<br>3.68 · 10 <sup>5</sup> a                   | Bi 209<br>1.9 · 10 <sup>19</sup> a | Bi 210<br>5.013 d  | Bi 211<br>2.17 m                       | Bi 212<br>1.9 m                       | Bi 213<br>45.59 m               | Bi 214<br>1.9 m                 | Bi 215<br>7.7 m                 | Bi 216<br>3.6 m / 2.17 m        | Bi 217<br>98.5 s                | Bi 218<br>33 s                  |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| α 5.411               | α 5.411  | α 5.411                            | α 5.411  | α 5.411                                | α 5.411                               | α 5.411                         | α 5.411                         | α 5.411                         | α 5.411                         | α 5.411                         | α 5.411                         |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| Pb 206<br>24.1        | Pb 207<br>22.1                                       | Pb 208<br>52.4                     | Pb 209<br>3.253 h  | Pb 210<br>2.3 a                        | Pb 211<br>36.1 m                      | Pb 212<br>10.64 h               | Pb 213<br>10.2 m                | Pb 214<br>26.8 m                | Pb 215<br>2.8 m                 | Pb 216<br>35.8 m                | Pb 217<br>4.81 m                | Pb 218<br>3.1 m                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| α 0.027               | α 0.027  | α 0.027                            | α 0.027  | α 0.027                                | α 0.027                               | α 0.027                         | α 0.027                         | α 0.027                         | α 0.027                         | α 0.027                         | α 0.027                         | α 0.027                         |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| Tl 205<br>70.48       | Tl 206<br>4.20 m                                     | Tl 207<br>1.33 s / 4.77 m          | Tl 208<br>3.053 m  | Tl 209<br>2.16 m                       | Tl 210<br>1.30 m                      | Tl 211<br>>300 ns               | Tl 212<br>>300 ns               |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |
| α 0.11                | α 0.11   | α 0.11                             | α 0.11   | α 0.11                                 | α 0.11                                | α 0.11                          | α 0.11                          |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                                 |                       |

146

144

140

142

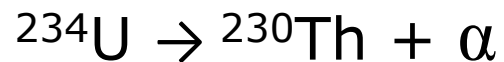
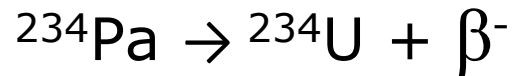
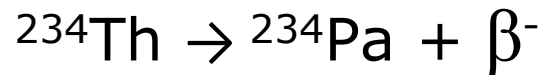
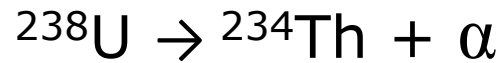
138

136

134

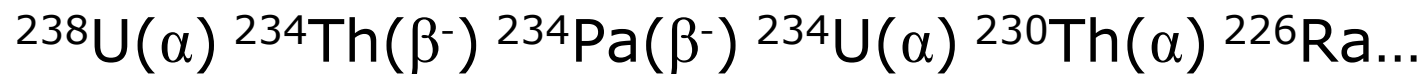
132

# Decay chain of $^{238}\text{U}$

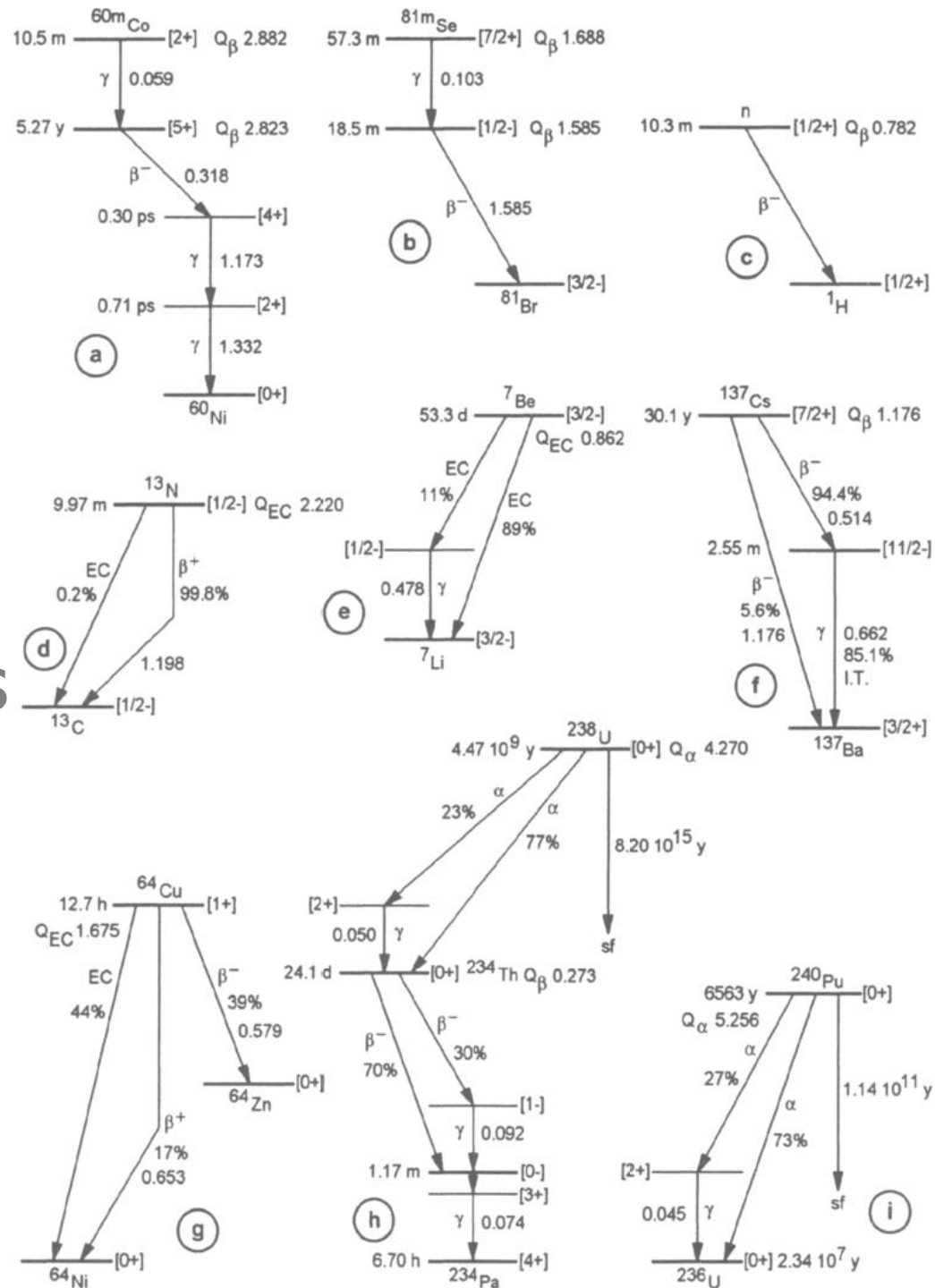


...

Or simplified



# Decay schemes



# Conservation laws



Energy:  $E_1 + E_2 = E_3 + E_4$

Linear momentum:  $p = mv$

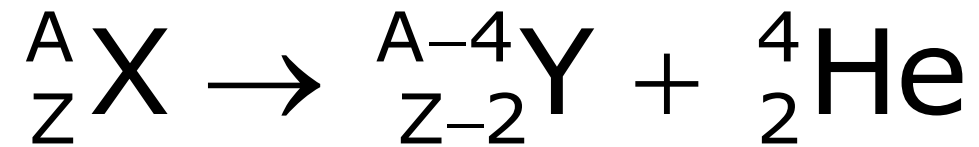
$$p_1 + p_2 = p_3 + p_4$$

Charge:  $Z_1 + Z_2 = Z_3 + Z_4$

Mass number:  $A_1 + A_2 = A_3 + A_4$

---

# $\alpha$ -decay







ROYAL INSTITUTE  
OF TECHNOLOGY

# Decay energy (Q-value)

$$E = mc^2$$

$$1 \text{ u} = 1/6.022 \times 10^{23} = 1.66 \times 10^{-24} \text{ g}$$

$$c^2 = 8.99 \times 10^{16} \text{ m}^2/\text{s}^2$$

$$1 \text{ J} = 6.24 \times 10^{12} \text{ MeV}$$

$$E = 1.66 \times 10^{-24} * 8.99 \times 10^{16} * 6.24 \times 10^{12} = 931.5 \text{ MeV/u}$$

$$Q(\text{MeV}) = -931.5 \Delta M (\text{u})$$

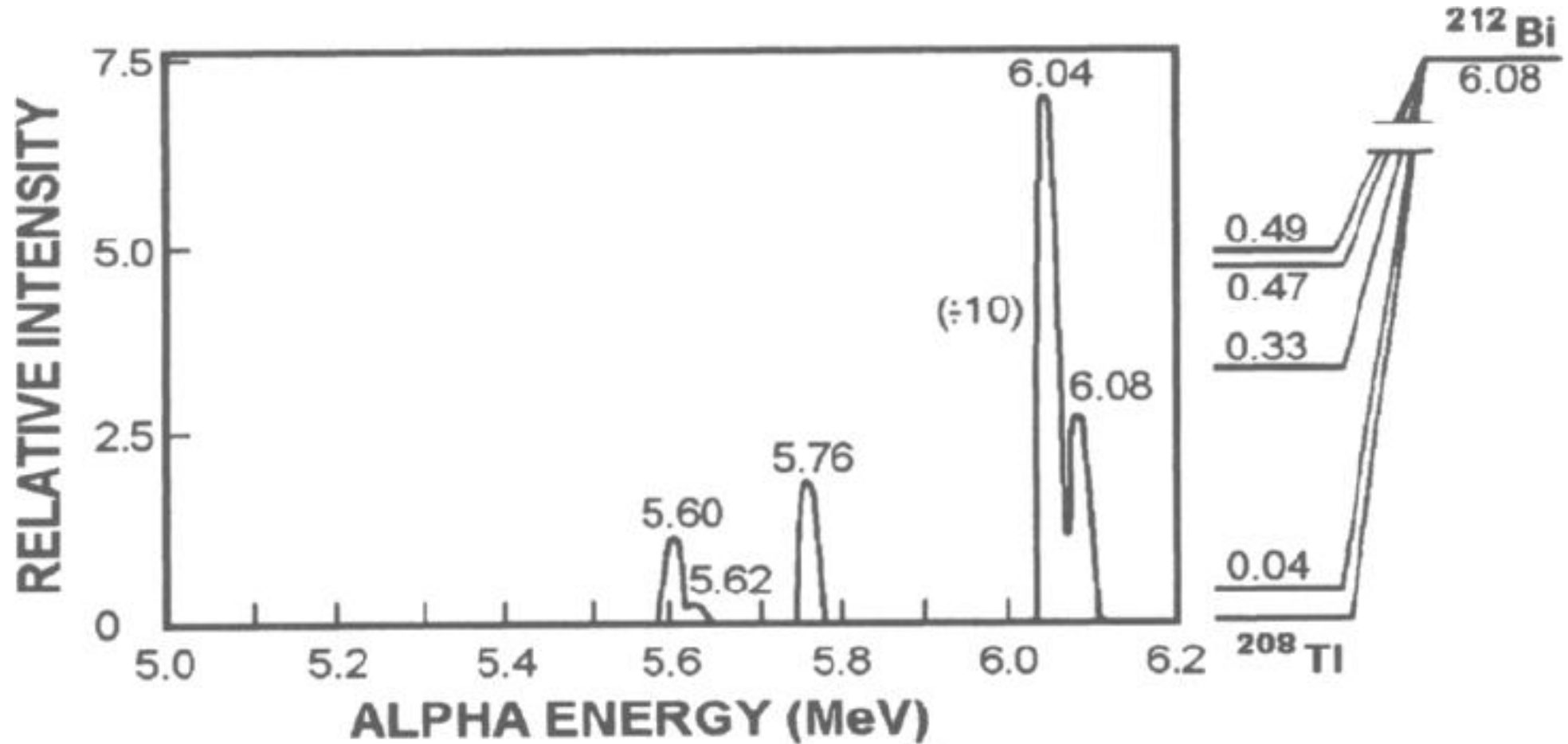
$$Q_{\alpha} = -931.5 (M_{Z-2} + M_{\text{He}} - M_Z)$$

$$Q_{\alpha} > 0 \quad \text{if} \quad (M_{Z-2} + M_{\text{He}} - M_Z) < 0$$

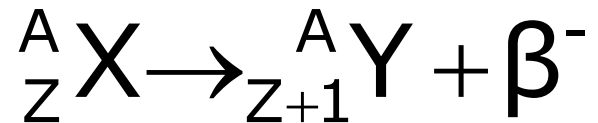
$$Q_{\alpha} > 0 \Rightarrow \text{Spontaneous decay}$$

For  $\alpha$ -particles the Q-value is 2–10 MeV

# Alpha spectrum



# $\beta$ -decay



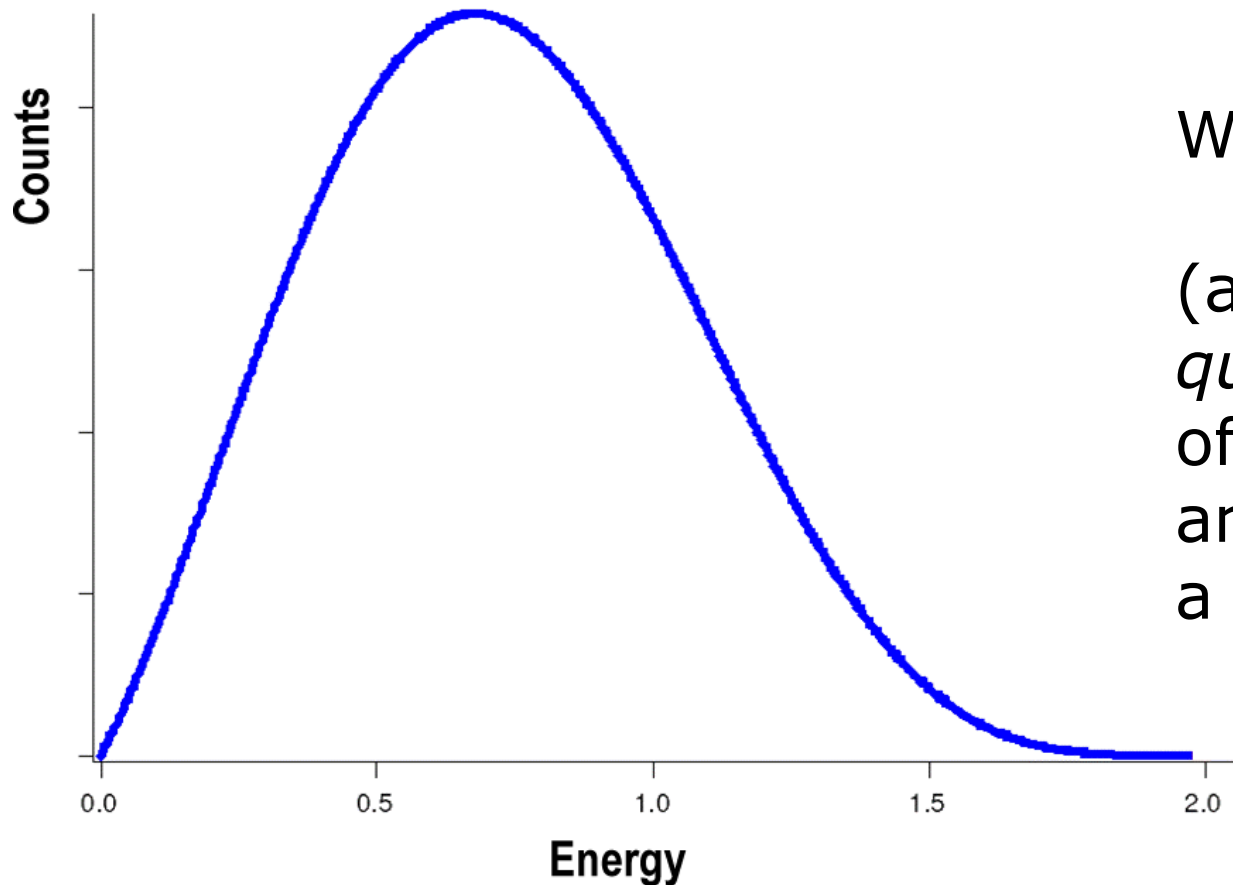
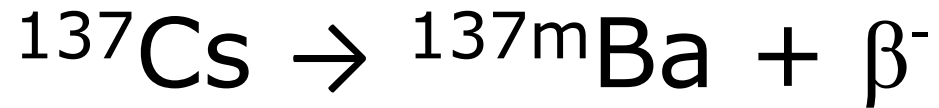
A negatron (electron) is emitted  
A proton in the nucleus is  
'converted' to a neutron



A positron (anti-particle to the  
electron) is emitted.  
A neutron in the nucleus is  
'converted' to a proton

---

# $\beta$ -decay



Why not one peak?

(also the *nuclear spin quantum number* of the reaction is not an integer, which is a forbidden transition)

## $\beta$ -decay continued

⇒ Another particle is emitted: a neutrino ( $\nu$ )

The neutrino has no charge and very small or no mass and does not interact readily with matter

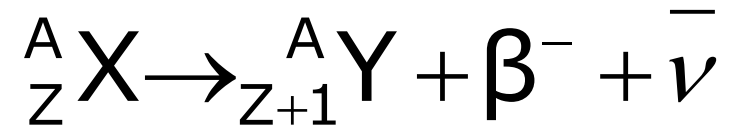


$\bar{\nu}$  is an anti-neutrino, emitted in a  $\beta^{-}$ -decay

$\nu$  is a neutrino, emitted in a  $\beta^{+}$ -decay

---

# Energy of $\beta^-$ decay



The formed Y has Z orbit electrons and must capture one electron from the surroundings.

=> The mass of the  $\beta^-$ -particle needs not to be included when calculating the energy of the decay.

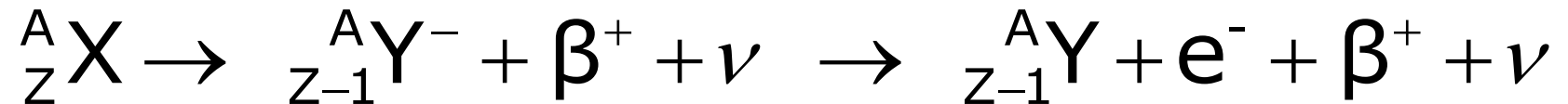
$$Q_{\beta^-} = -931.513 (M_{Z+1} - M_Z)$$

Example:  $n \rightarrow H + \beta^-$

$$Q_{\beta^-} = -931.513(1.007825 - 1.008665) = 0,782 \text{ MeV}$$

---

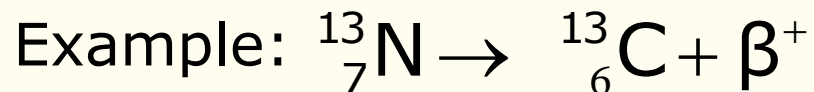
## Energy of $\beta^+$ decay



The formed Y has now one extra orbit electron which it must loose.

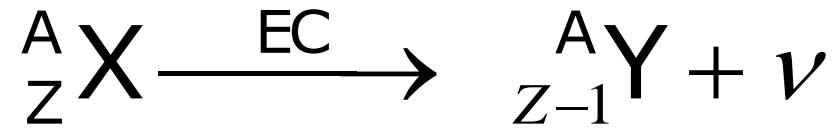
=> Both emitting a  $\beta^+$  -particle and loosing an electron must be included when calculating the energy of the decay.

$$Q_{\beta^-} = -931.513 (M_{Z-1} + 2 M_e - M_Z)$$



$$Q_{\beta^-} = -931.513(13.003355 - 13.005739) + 2 * 0.511) = 1,2 \text{ MeV}$$

# Electron capture



An inner shell electron is captured by the nucleus.  
Energy similar to  $\beta^-$  decay.

$$Q_{\beta^-} = -931.513 (M_{Z-1} - M_Z)$$

---



## $\gamma$ -emission

Most  $\alpha$  and  $\beta$ -decays do not go all the way to the daughter's ground state.

The remaining energy is released as  $\gamma$ -rays.

## Isomeric transition

When the meta-stable state is more long-lived

---

# Spontaneous fission

Some heavy radionuclides are so unstable that they undergo spontaneous fission

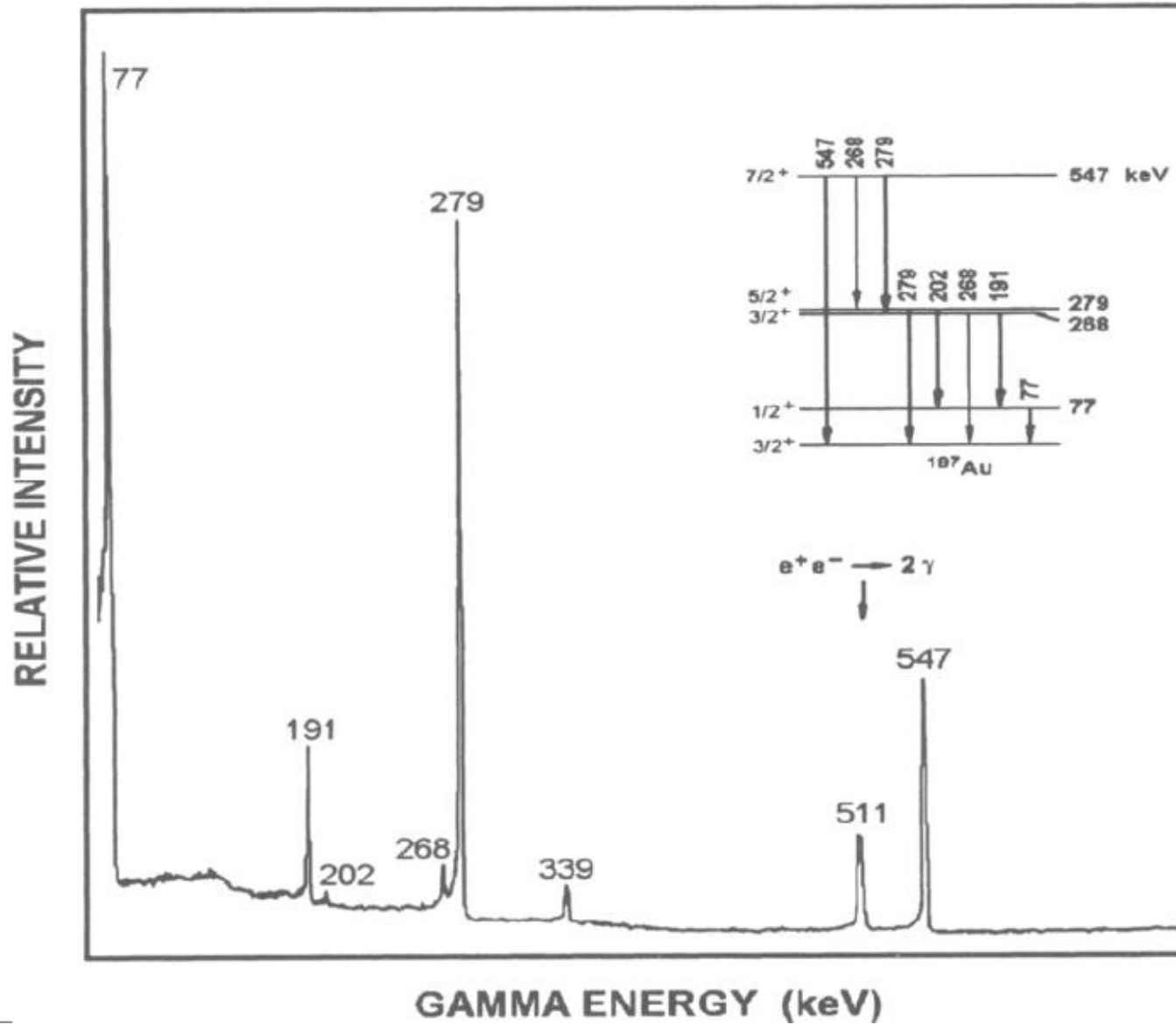
Rare modes of decay

Proton emission

Neutron emission

---

# Gamma spectrum



# Radioactive decay

$$A = -\frac{dN}{dt} = \lambda N$$

$$-\frac{dN}{N} = \lambda dt$$

$$-\int_{N_0}^N \frac{1}{N} dN = \int_0^t \lambda dt \Rightarrow \ln N - \ln N_0 = -\lambda t$$

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

---

# Half-life

$$-\int_{N_0}^N \frac{1}{N} dN = \int_0^t \lambda dt \Rightarrow \ln N - \ln N_0 = -\lambda t$$

$$N = \frac{N_0}{2}$$

$$t_{1/2} = \frac{\ln N_0 - \ln\left(\frac{N_0}{2}\right)}{\lambda} = \frac{\ln 2}{\lambda}$$

---

# Units

## SI unit:

1 Becquerel (Bq) = 1 decay / s

## Older unit:

1 Curie (Ci) =  $3.7 \times 10^{10}$  Bq

(1 Ci is approximately the activity of 1 gram  $^{226}\text{Ra}$ )

---