

Nuclear Fuel Cycle 2011

Lecture 2: Basic Nuclear Chemistry, Part 1

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Home page of the course: KTH Social

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

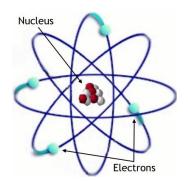


What is Nuclear Chemistry?

- 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

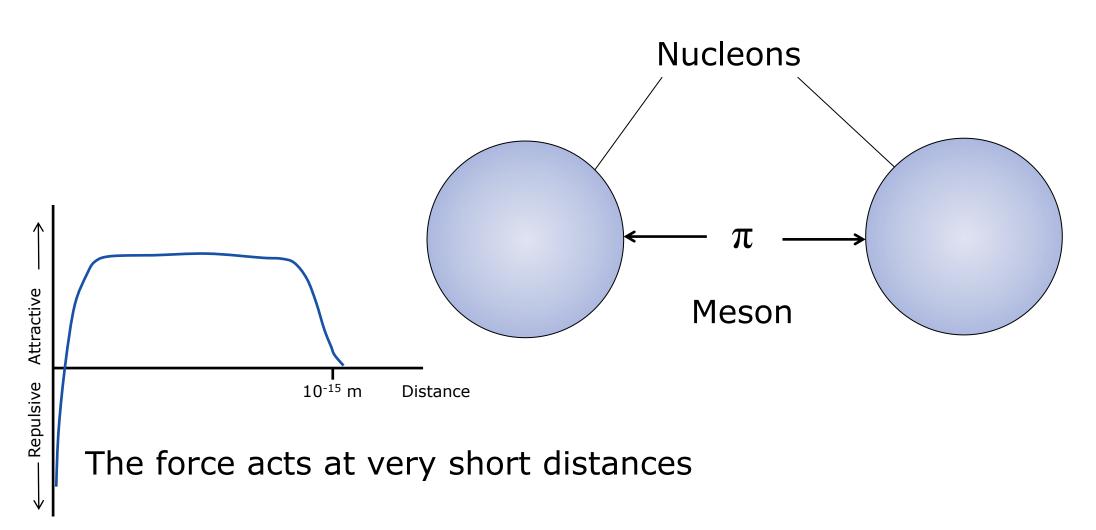
| | Proton | Neutron |
|--------|---------------------------|---------------------------|
| Mass | 1.673×10 ⁻²⁴ g | 1.675×10 ⁻²⁴ g |
| Charge | +1 | 0 |
| Spin | $s = \frac{1}{2}$ | $s = \frac{1}{2}$ |



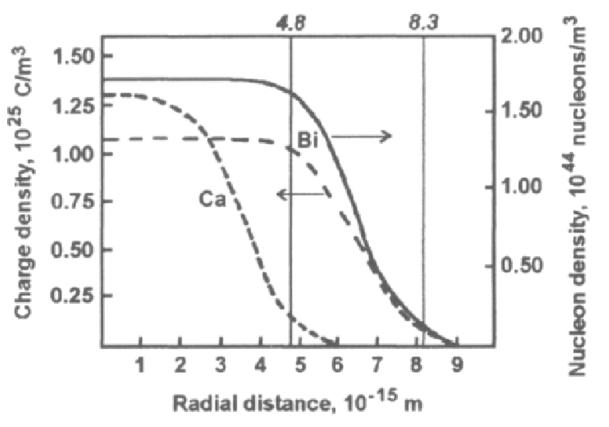
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The Strong Nuclear Force

Exchange of mesons keep the nucleons together







Measured charge and nuclear density for ⁴⁰Ca and ²⁰⁹Bi as a function of nuclear radius

Density: 0.2 nucleons/fm³ => 10^{14} g/cm³!



The Nucleus

$$^{A}_{Z}R$$
 $Z+N = A$

- Z = Number of protons
- N = Number of neutrons

A = Mass number (number of nucleons)

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

 $\stackrel{99m}{_{43}}\mathsf{TC} \xrightarrow{_{t_{1/2}}=6.01h} \xrightarrow{_{99}}_{43}\mathsf{TC} + \gamma$

Chart of Nuclides

Note! Colors may change between different charts

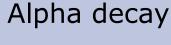
More than 1 700 isotopes

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- 80 elements have together 246 stable isotopes
- Lightest element with no stable isotopes: Tc
- Heaviest element with (almost) stable isotope: 209 Bi (t_{1/2}=2×10¹⁹y) (else Pb)
- Heaviest naturally occurring element: U
- Most stable isotopes: Sn; 10 stable isotopes
- 26 monoisotopic elements

Stable







Positron decay



Electron capture



Negatron decay



Spontaneous fission

Proton decay

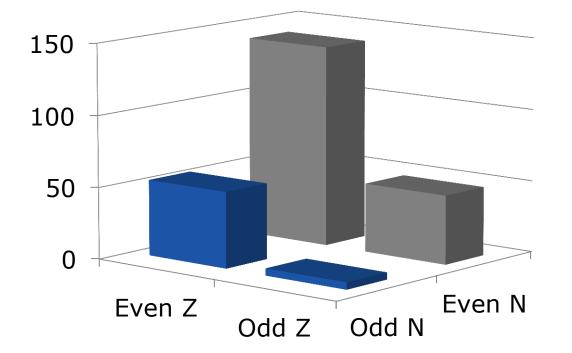


Neutron decay





Number of Nucleons on the Stability of the Nuclei



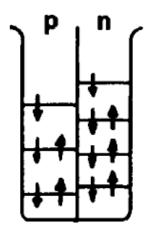
Magic numbers of protons or neutrons: 2, 8, 20, 82 and 126 ${}^{135}_{54} Xe \quad \left(\sigma_n = 2.6 \times 10^6 \text{ barns}\right) N = 81$ ${}^{136}_{54} Xe \quad \left(\sigma_n = 0.28 \times 10^6 \text{ barns}\right) N = 82$

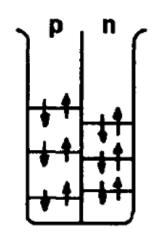


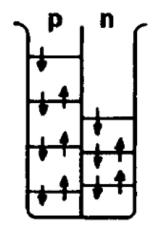
Nuclear Stability: Nucleon Orbitals

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¹²₅B ¹²₆C ¹²₇N



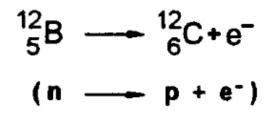




UNSTABLE



UNSTABLE



$$^{12}_{7}N - ^{12}_{6}C + e^+$$

(p - - n + e^+)



Mass Defect (ΔM) and Mass Excess (δ_A)

$$\begin{split} \Delta M_A &= M_A - Z M_p - N M_n \\ M_A &= Mass of atom \\ M_H &= Mass of Proton (hydrogen) \\ M_n &= Mass of Neutron \end{split}$$

Deuterium, ${}_{1}^{2}$ H $M_{p} + M_{n} = 1.007\ 825 + 1.008\ 665$ $= 2.016\ 490\ u$ $M_{A} = 2.014\ 102\ u$ $= > \Delta M_{\Delta} = -0.002\ 388\ u$

All stable isotopes have negative mass defect, ΔM_A

Mass excess: $\delta_A = M_A - A$ (sometimes used in tables, no practical use)

M = atomic mass unit, measured in u.



Binding energy

$$\Delta E = \Delta mc^2$$
 "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 10¹¹ J/mol) Covalent bond: 4.4 \times 10⁵ J/mol



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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



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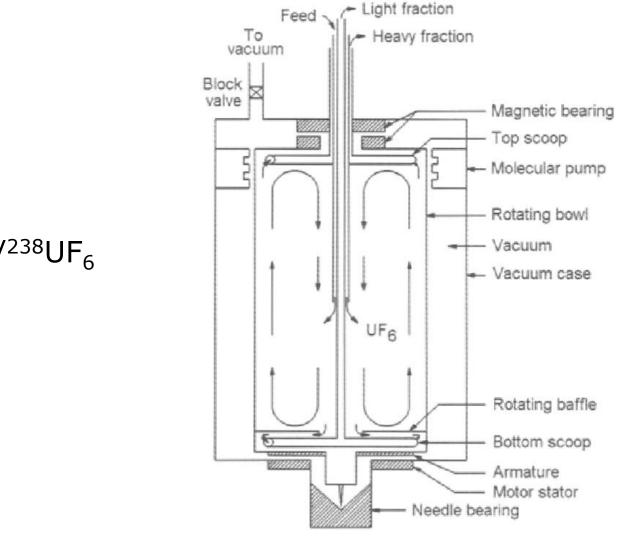
Isotope separation

- 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



 $^{235}\text{UF}_6/^{238}\text{UF}_6$



Other methods of isotope separation

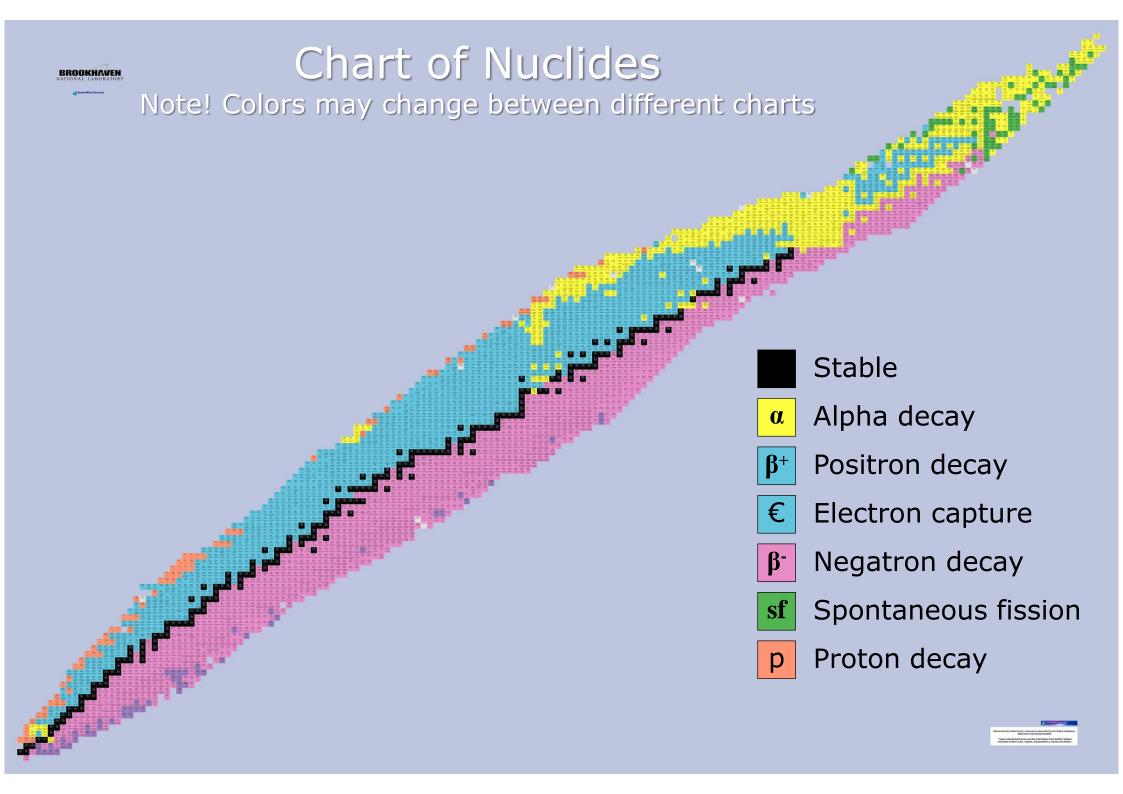
- Distillation
- Extraction
- Ion-exchange
- Photoionization
- Photoexcitation



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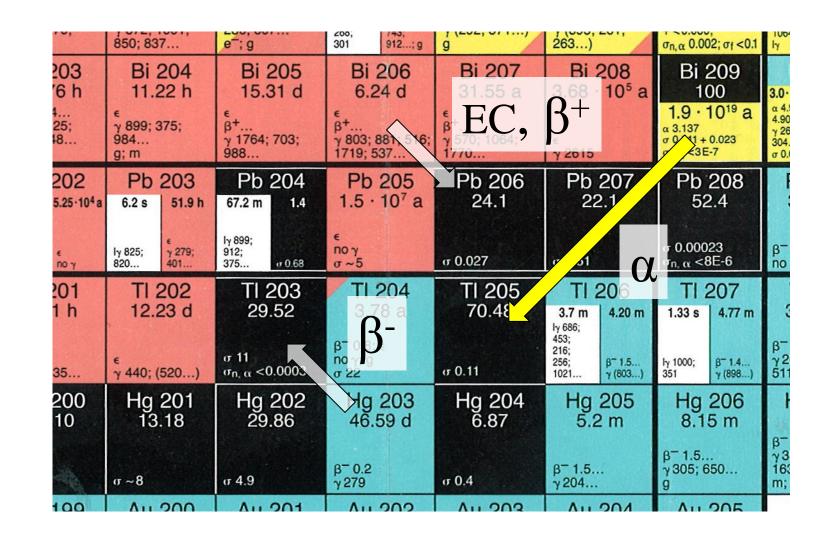
Radioactive decay

- α-decay (He-nucleus)
- β -decay (electron/positron)
- γ-decay
- Unusual modes of decay (proton, neutron, heavy particles)
- Spontaneous fission





Nuclide chart





Decay chain of ²³⁸U

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| | | | | | | | | | | U 226 | U 227 | U 228 | U 229 | U 230 | U 231 | U 232 | U 233 | U 234 | U 235 | U 236 | U 237 | U 238 |
|--|--|--|--|--|--|--------------------------------------|---|---|--|--|--|---|---|---|--|---|--|---|---|---|---|---|
| | | | | | | | | | | 0.28 s | 1.1 m | 9.1 m α 6.68; 6.59 | 58 m ε; α 6.362; | 20.8 d | 4.2 d ε; α 5.456; 5.471; 5.404 | 68.9 a α 5.320; 5.262 | 1.592 · 10 ⁵ a α 4.824; 4.783 | a 0.0054 2.455 · 10*4 | 0.7204 a 26 m 7.038-10 ⁴ a | 120 ns 2.342 · 10 ⁷ a α 4.494; 4.445; | 6.75 d β ⁻ 0.2 γ 60; 208 | 99.2742 298 ns 4.468 · 10 ⁹ a |
| | | | | | | | | | | 555; 7.374 12 | α 6.86; 7.06; 6.74 γ247; 310; e | ε γ (246; 187) e ⁻ | 6.334; 6.297 γ 123; 88; 199; e | γ (72; 154; 230); e ⁻ σι~25 | 5.471; 5.404 γ 26; 84; 102 e ; σ ₁ ~250 | Ne 24; γ (58; 129); e ⁻ σ 73; σ ₁ 74 | Ne 25; γ (42; 97); e ⁻ σ 47; σ ₁ 530 | 1 15 121. of 0.0 | 4.398; s Ne; γ 186 σ 95; σγ 585 | ly 1783: sf; γ (49; 642 df e ⁻ ; σ 5.3 | φ ⁻ σ~100; σ ₁ <0.35 | 4.198 |
| | | | | | | | | | | Pa 225 1.8 s | Pa 226 1.8 m | Pa 227 38.3 m | Pa 228 22 h | Pa 229 1.50 d | Pa 230 17.4 d | Pa 231 3.276 · 10 ⁴ a | Pa 237 | Pa 233 27.0 d | Ra 234 | Pa 235 24.2 m | Pa 238 9.1 m | Pa 237 8.7 m |
| | | | | | | | | | | .25; 7.20 | α 6.86; 6.82 ε | α 6.456; 6.416 ε γ 65; 110 | ε; α 6.078; 6.105 5.799; 6.118 γ 911; 463; 969; | ε; α 5.580; 5.670; 5.615 γ(119; 40; 146 | ε; β ⁻ 0.5 α 5.345; 5.326 γ 952; 919; 455; 899; 444; στ 1500 | α 5.014; 4.952; 5.028; Ne 24; F 23 γ 27; 300; 303; e σ 200; σ: 0.020 | β ⁻ 0, 13, 14 7 99 89 1 7 469, στ 1500 | β ⁻ 0.3; 0.6 γ 312; 300; 341; e ⁻ σ 20 + 19; σ ₁ < 0. | В 0.5; 1 (100); 767) 1 у (74); е | $\beta^{-} 1.4$ $\gamma 128 - 659$ | 1 | β 1.4; 2.3 γ 854; 865; 529; 541 |
| | | | | | | | | | | Th 224 | Th 225 8.72 m | Th 226 31 m | Th 227 18.72 d | Th 228 1.913 a | Th 229 7880 a | Th 250 7.54 · 10 ⁴ a | Th 231 25.5 h | Th 232 100 | Th 233 22.3 m | h 2 | Th 235 7.1 m | Th 236 37.5 m |
| | | | | | | | | | | 17; 7.00 | α 6.482; 6.445; 6.504 | α 6.336; 6.230 γ111; (242; 131) | α 6.038; 5.978; 5.757 γ 236; 50; 256 | α 5.423; 5.340 γ 84; (216); e ⁻ Ο 20 | α 4.845; 4.901; 4.815; γ 194; 211; 86; 31; e ⁻ | α 4.687; 4.621 γ 68; 144); e | | 1.405 · 10 ¹⁰ a a 4.013; 3.950; s | β-1.2 | β ⁻ 0.2 γ 63; 92; 93 | β ⁻ 1.4 γ 417; 727; | β ⁻ 1.0 |
| Ac 213 | Ac 214 | Ac 215 | Ac 216 | Ac 217 | Ac 218 | Ac 219 | Ac 220 | Ac 221 | Ac 222 | Ac 223 | γ 321; 246; 359; 306 Ac 224 | Ac 225 | γ 236; 50; 256 e ⁻ ; σ _f 200 | σ 120; σt <0.3 Ac 227 | c ~60; σ ₁ 30 Ac 228 | Ac 229 | e ⁻ Ac 230 | γ (64); e ⁻ σ 7.37; σ _f 0.000000 Ac 231 | 409; e σ 1500; σ ₁ 15 Ac 232 | o 1.8; σt <0.01 | Ac 234 | γ 111; (647; 196) |
| 0.80 s | 8.2 s α 7.215; 7.081 | 0.17 s α 7.600; 7.211 | 0.44 ms α 9.029; 9.105 | 0.74 μs 69 ns ly 660; 486; | 1.1 μs | 11.8 µs | 26 ms | 52 ms | 63 s 5.0 s α 6.81; | 2.10 m | 2.9 h | 10.0 d α 5.830; 5.793; | 29 h B ⁻ 0.9; 1.1 | 21.773 а в= 0.04 | 6.18 h β ⁻ 12:2.1 | 62.7 m | 122 s | 7.5 m | 119 s | 145 s | 44 s | |
| α 7.36 | ε γ 139; 244 | α 7.600; 7.211 ε γ (396) | γ 83; 854; 771 | 486; 382 α 10.54 α 9.65 | α 9.205 9 | α 8.664 | α 7.85; 7.61; 7.68 γ 134 | α 7.65; 7.44; 7.38 | 6.89; 7.00; m fy ?; ε g | α 6.647; 6.662; 6.564; ε γ (99; 191; 84) | α 6.142; 6.060; 6.214 γ 216; 132 | 5.732; C 14 γ 100; (150; 188; 63); e ⁻ | ε; α 5.34 γ 230; 158; 254; 186 | α 4.953; 4.941 γ(100; 84); e ⁻ σ 880; σ ₁ <0.0003 | 911:69; 338:965 | β ⁻ 1.1 γ 165; 569; 262; 146; 135 | γ 455; 508; 1244 e | β ⁻ γ 282; 307; 221; 186; 369 | γ 665; 1899; 1959; 1948; 612 | β γ 523; 540 | β γ 1847; 1912; 689; 1954 | |
| Ra 212 13.0 s | Ra 213 2.1 ms 2.74 m b 546 g 6.624 | Ra 214 2.46 s | Ra 215 1.67 ms | Ra 216 2.0 ns 0.18 μs | Ra 217 1.6 μs | Ra 218 25.6 μs | Ra 219 10 ms | Ra 220 23 ms | Ra 221 28 s | Ra 222 38 s | Ra 223 11.43 d | Ra 224 3.66 d | Ra 225 14.8 d | Ra 226 1600 a | Ra 227 42.2 m | Ra 228 5.75 a | Ra 229 4.0 m | Ra 230 93 m | Ra 231 103 s | Ra 232 4.2 m | Ra 233 30 s | Ra 234 30 s |
| . α 6.899 ε ? γ (635) | 1063; 6.731; 161;e ⁻ 6.521. α 8.466; ε; γ 110; 8.357 215e ⁻ | α 7.137; 6.505 €; g γ (642) | α 8.700; 7.879 γ 834; 540 | 476; 344 α 9.551; 11.028 α 9.349 | α 8.99 | α 8.39 | α 7.679; 7.989 γ 316; 214; 592 | α 7.46 γ 465 | α 6.613; 6.761; 6.668 γ 149; 93; 174 C 14 | α 6.559; 6.237 γ 324; (329; 473) C 14 | α 5.7162; 5.6067 γ 269; 154; 324 C 14; σ 130; σ ₁ <0.7 | α 5.6854; 5.4486 γ 241; C 14 σ 12.0 | β 0.3; 0.4 γ 40 | α 4.7843; 4.601 γ 186; C 14 | β ⁻ 1.3 | β ⁻ 0.04 γ (14; 16) θ ⁻ | β= 1.8 | β ⁻ 0.8 γ 72; 63; 203; 470 | β γ 410; 205; | β ⁻ γ 471; 98; 479; | | |
| Fr 211 3.10 m | Fr 212 20.0 m | Fr 213 34.6 s | Fr 214 3.35 ms 5.0 ms | Fr 215 0.09 μs | Fr 216 0.70 μs | Fr 217 | Fr 218 | Fr 219 | Fr 220 | Fr 221 | Fr 222 | Fr 223 | Fr 22 | Fr 225 | γ 27; 300; 303 Fr 226 | Fr 227 | γ Fr 228 | Fr 229 | 469; 456 Fr 230 | 105; 373 Fr 231 | β ⁻ Fr 232 | β- |
| α 6.535 ε γ 540; 918; | ε α 6.262; 6.384; | α 6.775 | | 0.05 μ5 | | 16 μs | 22 ms 1.0 ms α 7.615; 7.680; 7.656 α 7.867; | 21 ms | 27.4 s α 6.68; 6.63: 6.58 | 4.9 m α 6.341; 6.126 γ 218; (101; | 14.2 m β ⁻ 1.8 γ 206; 211; 242 | 21.8 m β ⁻ 1.1 | 3.3 m | 4.0 m β ⁻ 1.6 | 48 s β ⁻ 3.2; 3.5 | 2.47 m | 39 s β ⁻ | 50.2 s | 19.1 s β ⁻ | 17.5 s | 5 s | 146 |
| Rn 210 | 6.408; 6.340 γ 1274; 227; 1185 Rn 211 | e 8.775 Rn 212 | α 8.477; 8.547 Rn 213 | α 9.36 Rn 214 | α 9.01 g Rn 215 | α 8.315 Rn 216 | 7.656 m; g hγ g Rn 217 | α 7.312 γ (352; 517) Rn 218 | γ 45; 106; 162 Rn 219 | 411) C 14 Rn 220 | α? Rn 221 | α 5.34 γ 50; 80; 235 Rn R22 | Rn 223 | γ 182; 32; 225; 200 Rn 224 | β ⁻ 3.2; 3.5 γ 254; 186; 1323 | β ⁻ 1.8; 2.4 γ 90; 586 | γ 474; 410; 141; 835 | γ 310; 336; 143; 350 | γ 711; 129; 728; 677 | β γ 433; 454; 96 | β ⁻ γ 125 | |
| 2.4 h α 6.040 | 14.6 h | 24 m | 19.5 ms | 6.5 ns 0.7 ns 0.27 μs | | 45 µs | 0.54 ms | 35 ms | 3.96 s | 55.6 s | 25 m β ⁻ 0.8; 1.1 | 3.825 d | 23.2 m | 1.78 h | Rn 225 4.5 m | Rn 226 7.4 m | Rn 227 22.5 s | Rn 228 65 s | | 144 | | |
| € γ 458; (571; 649; 73…) | α 5.783; 5.851 γ 674; 1363; 678; g | α 6.264 γ | α 8.088; 7.252 γ 540 | hy 182 446; m1 302 α10.63 α10.46 α9.037 | α 8.67 g | α 8.05 g | α 7.740 | α 7.133 γ (609) | α 6.819; 6.553; 6.425 γ 271; 402 | α 6.288 γ (550) σ <0.2 | α 6.037; 5.788; 5.778 γ 186; 150 | α 5.48948 1 (50) σ 0 4 | β γ 593; 417; 636; 655 | β γ 261; 266 | β γ 29-207 | β- | β γ 162; 739; 686; 805 | β γ 125; 63; 156; 112 | | 144 | | |
| At 209 5.4 h | At 210 8.3 h | At 211 7.22 h | At 212 | At 213 0.11 μs | At 214 0.76µs 0.27µs 0.56µs | At 215 0.1 ms | At 216 ? 0.3 ms | At 217 32.3 ms | At 218 ~2 s | At 219 0.9 m | At 220 3.77 m | At 221 2.3 m | At 222 54 s | At 223 50 s | | | | | _ | | | |
| ε α 5.647 γ 545; 782; | ε; α 5.524; 5.442; 5.361 γ 1181; 245; | ε α 5.867 γ (687) | α 7.84; α 7.68; 7.90 7.62 γ 63 γ 63 e ⁻ e ⁻ | | α 8.782 ; m α8.877; g | α 8.026 | α 7.488 α 7.804; α 7.488 7.691; g m ₁ γ (115; γ 103 418) | α 7.069 β γ (259; 334; 595) | α 6.694; 6.653 β ⁻ | α 6.27 | β ⁻ 0, 493 1, 241, 293; | | | | | 140 | | 142 | | | | |
| Po 208 | 1483 Po 209 | Po 210 | Po 211 | α 9.08 Po 212 | Po 213 | γ (405) Po 214 | Po 215 | Po 216 | γ Po 217 | β ⁻ Po 216 | 422 / Po 219 | β ⁻ Po 220 | β- | β- | 1 | | | | | | | |
| 2.898 a | 102 a α 4.881 ε | 138.38 d α 5.30438 γ (803); σ < 0.0005 | 25.2 s 0.516 s α 7.275; 8.883 γ 570; α 7.450 | 45.1 s 17.1 ns 0.3 μs α 11.65 ly 728; y 2615; 406; | | 164 μs | 1.78 ms | 0.15 s | 1.53 s | 3.05 m < | >300 ns | >300 ns | | 138 | | | | | | | | |
| γ (292; 571) 9 Bi 007 | γ (895; 261; 263) | γ (803); σ <0.0005 + 0.30; 0.22; σ <0.1 | 1064 γ (898; 570) | 583 223 hy α 10.22 α 8.785 | α 8.376 γ (779) | Bi 213 | β ⁻ γ (439) | α 6.7783 γ (805) | α 6.543 β ⁻ | \sim | β ⁻ ? α? | β-? | | | | | | | | | | |
| Bi 207 31.55 a | Bi 208 3.68 · 10 ⁵ a | Bi 209 100 1.9 · 10 ¹⁹ a | 3.5 10 ⁶ 5.013 d 4.9 6 ^{-1.2} | Bi 211 2.17 m α 6.6229; 6.2788 | Bi 212 9m 25m 6.50m | 45.59 m | Ri 214 | Bi 215 36.9 s 7.7 m ^{1γ 414;} 746; 187 β | Bi 210 3.6 m 2.17 m | Bi 217 98.5 s | Bi 218 33 s | 100 | | | | | | | | | | |
| β ⁺ γ 570; 1064; 1770 | 201 | α 3.137 σ 0.011 + 0.023 σ _{n,α} <3E-7 | 4.908 γ 266; 4 86 304 σ 0.054 2 | $\beta^- \dots$ $\gamma 351 \dots$ $\alpha \rightarrow 9; \beta^- \rightarrow 9$ | 3- 10.55 | α 5.87 γ 440; (293; 1100) | α 5.450; 5.513 γ 609; 1764; 1120 βα 9.079 | 746; 187 β ⁻ γ 294; γ 308; 271; 256; 419 1105 | 8-550; 419; 360; 223 | β γ 265; 254; 890; 436 | β 3.5; 3.7 γ 510; 386; 426; 263 | 136 | | | | | | | | | | |
| Pb 206 24.1 | Pb 207 22.1 | Pb 208 52.4 | Pb 209 3.253 h | 223 a | 7b 211 36.1 m | Pb 212 10.64 h | Pb 213 10.2 m | No. | | | | | | | | | | | | | | |
| | | or 0.00023 | β ⁻ 0.6 | β ^{-0.02; 0.06} γ 47; e ⁻ ; g α 3.72 σ < 0.5 | β ⁻ 1.4 γ 405; 832; 427 | β 0.3; 0.6 γ 239; 300 | | β ⁻ 0.7; 1.0 γ 352; 295; 242 | | 134 | | × | | | | | | | | | | |
| τι 205 | σ 0.61 TI 206 | σ _{n. α} <8E-6 TI 207 | πο γ TI 208 | TI 209 | TI 210 | g TI 211 | β ⁻ TI 212 | 242 | | | | | | | | | | | | | | |
| 70.48 | 3.7 m ¹ y 686; 453; 216; 453; | 1.33 s 4.77 m | 3.053 m | 2.16 m | 1.30 m β ⁻ 1.9; 2.3 | >300 ns | >300 ns | 132 | | | | | | | | | | | | | | |
| σ 0.11 | 216; 256; β [~] 1.5 1021 γ (803) | ly 1000; β ⁼ 1.4 351 y (898) | γ2615; 583; 511; 860; 277 | γ 1567; 465; 117 | γ 800; 298 βn | β-? | β- ? | | | | 3 | | | | | | | | | | | |

 238 U(α) 234 Th(β ⁻) 234 Pa(β ⁻) 234 U(α) 230 Th(α) 226 Ra...

Or simplified

. . .

 230 Th $\rightarrow ^{226}$ Ra + α

 $^{234}U \rightarrow ^{230}Th + \alpha$

 234 Pa $\rightarrow ^{234}$ U + β^{-}

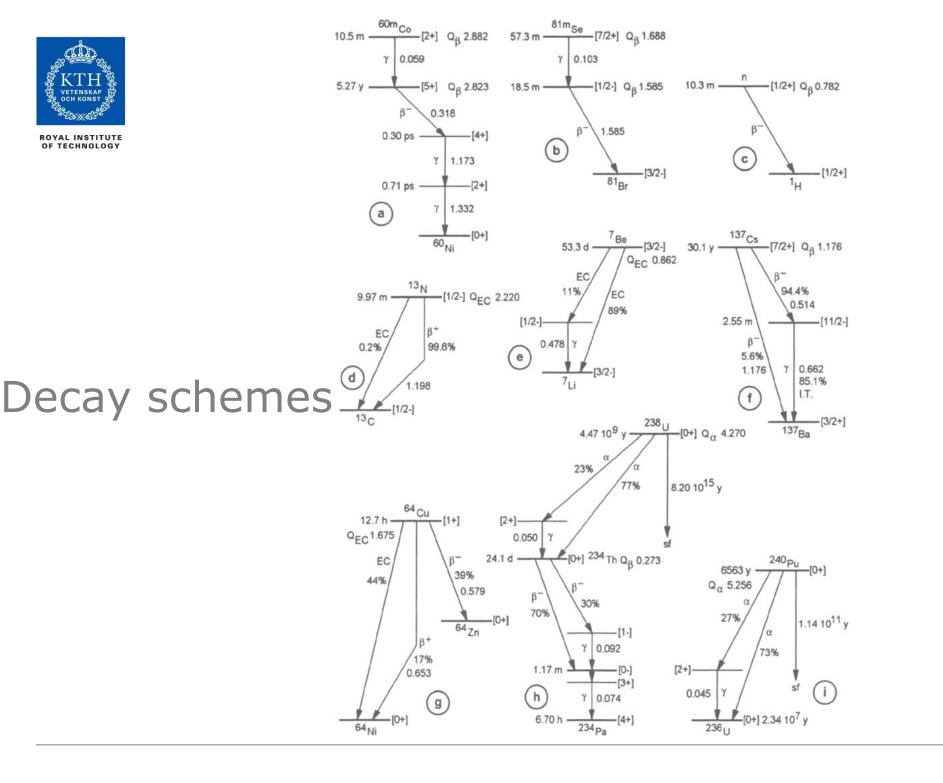
 234 Th $\rightarrow ^{234}$ Pa + β^{-}

 $^{238}U \rightarrow ^{234}Th + \alpha$





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Conservation laws

Nuclear Reaction: $X_1 + X_2 \rightarrow X_3 + X_4$

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: $A_1 + A_2 = A_3 + A_4$



 α -decay

 $^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He$

$^{238}U \rightarrow ^{234}Th + ^{4}He$



Decay energy (Q-value)

$$E=mc^{2}$$
1 u = 1/6.022×10²³ = 1.66×10⁻²⁴ g
 $c^{2} = 8.99\times10^{16} m^{2}/s^{2}$
1 J = 6.24×10¹² MeV
E = 1.66×10⁻²⁴ * 8.99×10¹⁶ * 6.24×10¹² = 931.5 MeV/u

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

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

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

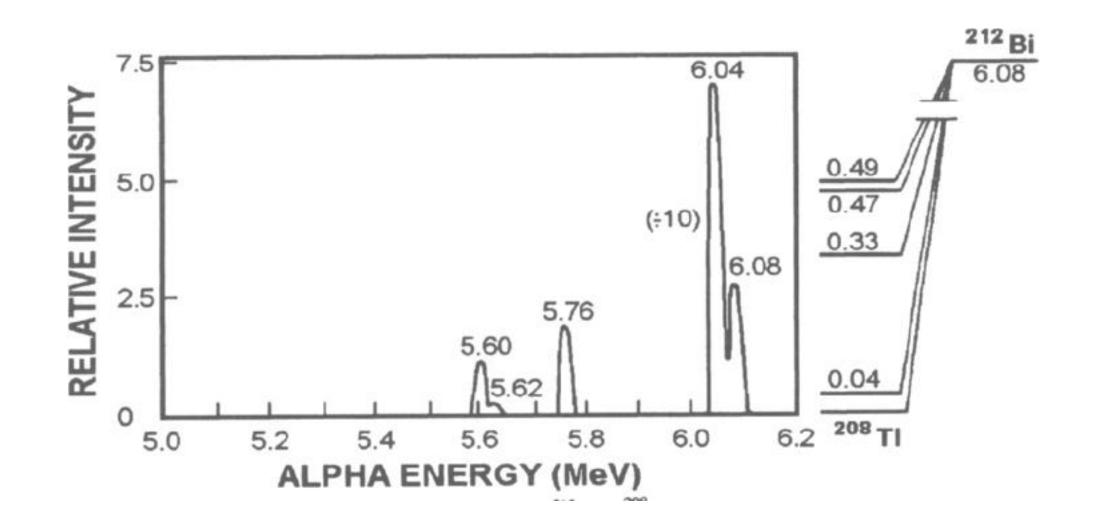
 $Q_{\alpha} > 0 =>$ Spontaneous decay

For α -particles the Q-value is 2–10 MeV



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Alpha spectrum





 β -decay

 $^{A}_{7}X \rightarrow ^{A}_{7+1}Y + \beta^{-}$

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

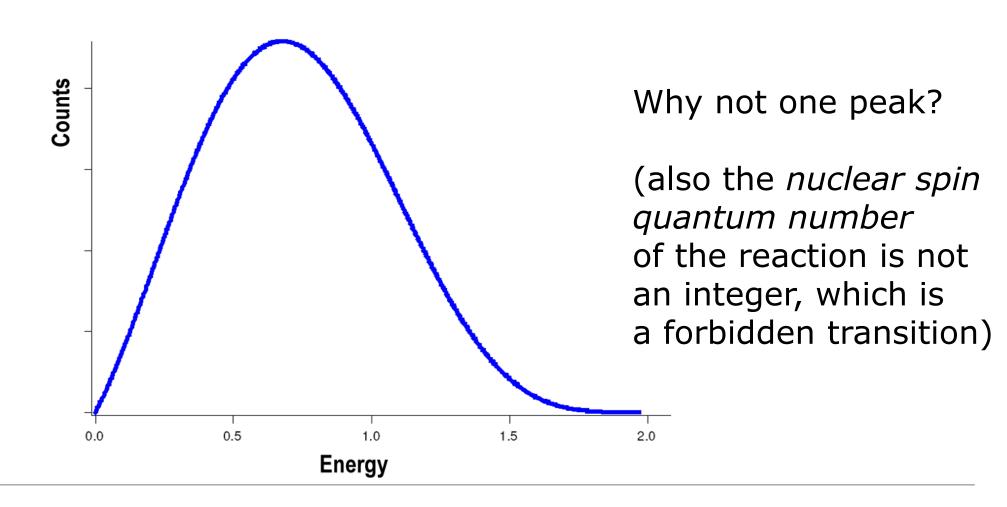
 $^{A}_{7}X \rightarrow ^{A}_{7-1}Y + \beta^{+}$

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



 β -decay

$^{137}Cs \rightarrow ^{137m}Ba + \beta^{-}$





 β -decay continued

\Rightarrow Another particle is emitted: a neutrino (v)

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

$^{137}Cs \rightarrow ^{137m}Ba + \beta^{-} + \overline{\nu}$

 $\overline{\nu}$ is an anti-neutrino, emitted in a $\beta^{\text{-}}$ -decay ν is a neutrino, emitted in a $\beta^{\text{+}}$ -decay



Energy of β^- decay

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + \beta^{-} + \overline{\nu}$$

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

=> The mass of the β^{-} -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 β^+ decay

$$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y^{-} + \beta^{+} + \nu \rightarrow ^{A}_{Z-1}Y + e^{-} + \beta^{+} + \nu$$

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

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

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

Example: ${}^{13}_{7}N \rightarrow {}^{13}_{6}C + \beta^+$

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



Electron capture

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$$^{A}_{Z}X \xrightarrow{EC} ^{A}_{Z-1}Y + v$$

An inner shell electron is captured by the nucleus. Energy similar to β^{-} decay.

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



 γ -emisson

Most α and β -decays do not go all the way to the daughter's ground state. The remaining energy is released as γ -rays.

Isomeric transition

When the meta-stable state is more long-lived



Spontaneous fission

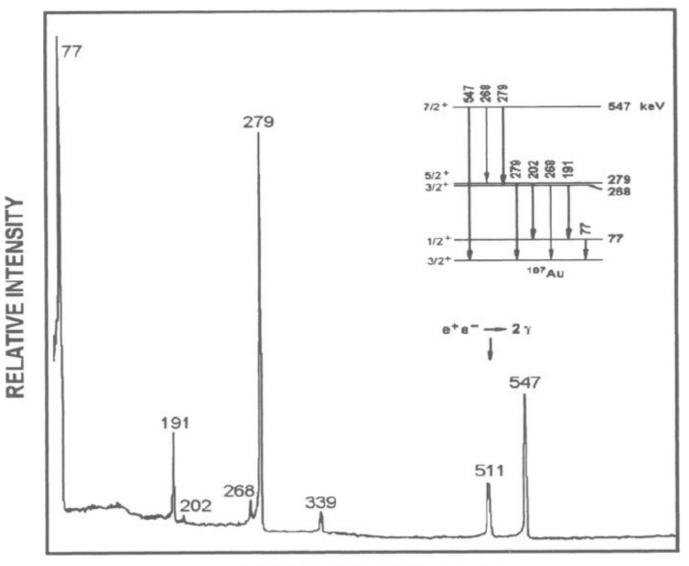
Some heavy radionuclides are so unstable that they undergo spontaneous fission

Rare modes of decay

Proton emission Neutron emission



Gamma spectrum



GAMMA ENERGY (keV)



Radioactive decay

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

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

$$-\int_{N_0}^{N} \frac{1}{N} dN = \int_{0}^{t} \lambda dt \Longrightarrow InN - InN_0 = -\lambda t$$

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



Half-life

$$-\int_{N_0}^{N} \frac{1}{N} dN = \int_{0}^{t} \lambda dt \Longrightarrow \ln N - \ln N_0 = -\lambda t$$

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

$$t_{\nu_{2}} = \frac{\ln N_{0} - \ln \left(\frac{N_{0}}{2}\right)}{\lambda} = \frac{\ln 2}{\lambda}$$



Units

<u>SI unit:</u> 1 Becquerel (Bq) = 1 decay / s

<u>Older unit:</u> 1 Curie (Ci) = 3.7×10^{10} Bq

(1 Ci is approximately the activity of 1 gram ²²⁶Ra)