8.4 Nuclear stability

We get more clues about the nuclear potential and shell structure inside the nucleus from unstable nucleii. around 2500 nuclei are known, but only 300 or so are stable. The others decay via (1) α decay ($^4_2He^{+2}$ i.e. helium nuclei) (2) β decay (electrons or positrons - plus also neutrino)

The Segre chart plots neutron number versus proton number N vs Z and shows the stable nuclei are confined to a very small range of N for a given $Z+N$ (line of constant A which is perpendicular to the line $Z=N$. generally 2-3. but a very few have 4. for low mass $N=Z$, then for larger masses it increases to $N/Z=1.6$. Points to the right have too many protons - too much nuclear repulsion. points to the left have too many neutrons. Free neutrons decay to a neutron to a proton plus an electron (and neutrino) $n \rightarrow p + e^- + \overline{\nu}_e$ as there is a mass deficit of 1.29 MeV. so put too many neutrons in and this energy becomes large!

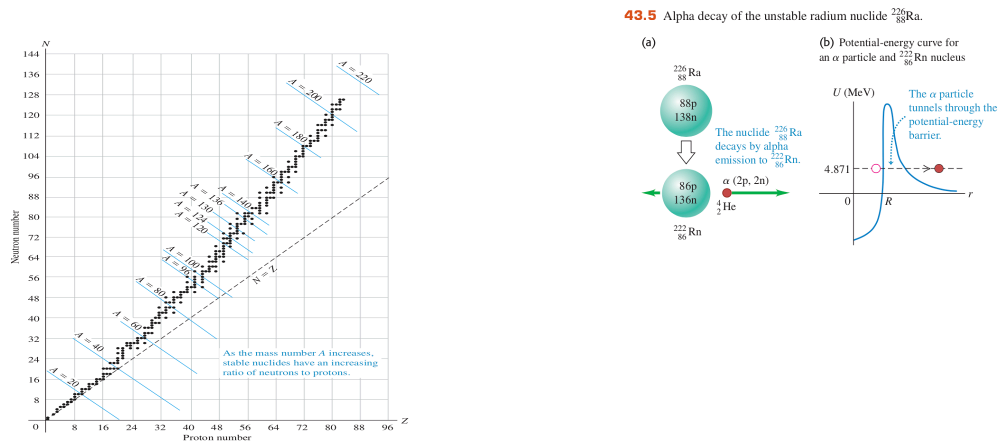

Figure 4:

All these decays happen if energy is released. e.g for *alpha* decay we need $m(A,Z) > m(A-4) + m(4,2)$

can also release energy as γ ray if excited state but doesn't change N, Z.

Example YF43.5 $^{226}_{88}Ra \rightarrow ^{222}_{86} Rn + ^4_2 He$. The neutral atomic masses are

226.025403u, 222.017571u and 4.002603u

LHS: (222.017571+4.002603)u = 226.020187u so difference is $+5.22\times10^{-3}u = 5.22\times10^{-3}931.5 = 4.86$ MeV.

Hence we expect the decay products to emerge with total energy of 4.86 MeV - but the nuclear recoil is fairly small so most of this goes to the α particle.

quantum tunnelling as α particle radioactive decay! we can think of the nucleus as a bound state of He and the nucleus which has $A-2, Z-2$.

example YF43.643.6 an electron β decay. we need $m(A,Z) > m(A,Z+1) + m(e^-)$ - generally OK to do $m(A,Z) > m(A,Z+1)$. e.g. for $^{60}_{27}Co \rightarrow ^{60}_{28} Ni + e^-$ where Co is 59.933822u and Ni is 59.930791u. difference is $3.03\times10^{-3}u$ i.e. 2.8 MeV so this is energetically favourable

9 fundamental particles and forces

We saw that the proton and neutron are NOT fundamental particles - their magnetic moments show that they are made up of smaller charged particles whose motion inside the nucleon gives rise to the currents which give rise to the magnetic moment. For the proton, this gives the larger than expected response, and for the neutron, it gives that there should even be ANY response! These are quarks. And they explain the TONS of odd particles which get produced in high energy collider experiments as there are 6 quarks so then there are a LOT of different ways to stick them together. Each quark has baryon number of 1/3

It turns out that there are 6 leptons as well. and each lepton has lepton number of 1.

all these have antiparticles, and these all charge and baryon/lepton number which is the same as their corresponding particle but sign reversed

we know we have to conserve charge, but it turns out we have to conserve baryon number, and also lepton number as well.

Table 44.5 Properties of the Six Quarks

Symbol	Q/e	Spin	Baryon Number, B	Strange-ness, S	Charm, C	Bottom-ness, B'	Topness, T
u	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	0
d	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	0
s	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	-1	0	0	0
c	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	$+1$	0	0
b	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	$+1$	0
t	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	$+1$

Figure 5:

Example: could a muon $\mu^- \rightarrow d + \overline{u}$ charge is OK as -1 to $-1/3 + -2/3$. baryon number is OK as 0 for μ^- and $1/3$ for d and $-1/3$ for $\overline{u}$. But lepton number is NOT conserved as we have 1 for μ^- and nothing for the quarks. so this decay cannot occur.

All interactions between particles fall into one of the four fundamental forces, each mediated by their own force carrier.

Together, these make the standard model of particle physics. Which is amazing in its power (and also predictions eg Higgs particle). But is incomplete! why does the universe consist of matter if particles and antiparticles are always made together to conserve baryon number and lepton number? There is still a LONG way to go before we understand the nature of matter!

Table 44.3 Some Hadrons and Their Properties

Particle	Mass (MeV/c^2)	Charge Ratio, Q/e	Spin	Baryon Number, B	Strangeness, S	Mean Lifetime (s)	Typical Decay Modes	Quark Content
Mesons								
π^0	135.0	0	0	0	0	8.4×10^{-17}	$\gamma\gamma$	$u\bar{u}$, $d\bar{d}$
π^+	139.6	+1	0	0	0	2.60×10^{-8}	$\mu^+\nu_\mu$	$u\bar{d}$
π^-	139.6	−1	0	0	0	2.60×10^{-8}	$\mu^-\bar{\nu}_\mu$	$\bar{u}d$
K^+	493.7	+1	0	0	+1	1.24×10^{-8}	$\mu^+\nu_\mu$	$u\bar{s}$
K^-	493.7	−1	0	0	−1	1.24×10^{-8}	$\mu^-\bar{\nu}_\mu$	$\bar{u}s$
η^0	547.3	0	0	0	0	$\approx 10^{-18}$	$\gamma\gamma$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$
Baryons								
p	938.3	+1	$\frac{1}{2}$	1	0	Stable	—	*uud*
n	939.6	0	$\frac{1}{2}$	1	0	886	$pe^-\bar{\nu}_e$	*udd*
Λ^0	1116	0	$\frac{1}{2}$	1	−1	2.63×10^{-10}	$p\pi^-$ or $n\pi^0$	*uds*
Σ^+	1189	+1	$\frac{1}{2}$	1	−1	8.02×10^{-11}	$p\pi^0$ or $n\pi^+$	*uus*
Σ^0	1193	0	$\frac{1}{2}$	1	−1	7.4×10^{-20}	$\Lambda^0\gamma$	*uds*
Σ^-	1197	−1	$\frac{1}{2}$	1	−1	1.48×10^{-10}	$n\pi^-$	*dds*
Ξ^0	1315	0	$\frac{1}{2}$	1	−2	2.90×10^{-10}	$\Lambda^0\pi^0$	*uss*
Ξ^-	1321	−1	$\frac{1}{2}$	1	−2	1.64×10^{-10}	$\Lambda^0\pi^-$	*dss*
Δ^{++}	1232	+2	$\frac{3}{2}$	1	0	$\approx 10^{-23}$	$p\pi^+$	*uuu*
Ω^-	1672	−1	$\frac{3}{2}$	1	−3	8.2×10^{-11}	Λ^0K^-	*sss*
Λ_c^+	2285	+1	$\frac{1}{2}$	1	0	2.0×10^{-13}	$pK^-\pi^+$	*udc*

Figure 6:

Table 44.2 The Six Leptons

Particle Name	Symbol	Anti-particle	Mass (MeV/c^2)	L_e	L_μ	L_τ	Lifetime (s)	Principal Decay Modes
Electron	e^-	e^+	0.511	+1	0	0	Stable	
Electron neutrino	ν_e	$\bar{\nu}_e$	$<3 \times 10^{-6}$	+1	0	0	Stable	
Muon	μ^-	μ^+	105.7	0	+1	0	2.20×10^{-6}	$e^-\bar{\nu}_e\nu_\mu$
Muon neutrino	ν_μ	$\bar{\nu}_\mu$	<0.19	0	+1	0	Stable	
Tau	τ^-	τ^+	1777	0	0	+1	2.9×10^{-13}	$\mu^-\bar{\nu}_\mu\nu_\tau$
Tau neutrino	ν_τ	$\bar{\nu}_\tau$	<18.2	0	0	+1	Stable	or $e^-\bar{\nu}_e\nu_\tau$

Figure 7:

Table 44.1 Four Fundamental Interactions

Interaction	Relative Strength	Range	Mediating Particle: Name	Mass	Charge	Spin
Strong	1	Short ($\sim$1 fm)	Gluon	0	0	1
Electromagnetic	$\frac{1}{137}$	Long ($1/r^2$)	Photon	0	0	1
Weak	10^{-9}	Short ($\sim$0.001 fm)	$W^{\pm}$, Z^0	80.4, 91.2 GeV/c^2	$\pm e$, 0	1
Gravitational	10^{-38}	Long ($1/r^2$)	Graviton	0	0	2

Figure 8: