Nuclear Physics

Fundamental Particles

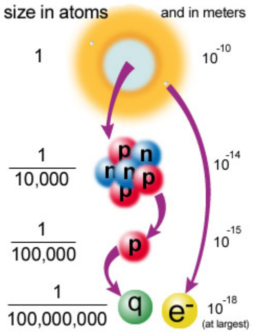
The ordinary world is made of four kinds of particles: photons, electrons, protons, and neutrons.

Before 1950, these four were thought to be the *fundamental particles.*

Now we know that photons and electrons are fundamental, but neutrons and protons are made of truly fundamental particles called *quarks.*

Neutrons and protons are termed nucleons; they have a size and structure depending on the way the quarks are arranged. The quarks are held together within the nucleon by means of particles called *gluons.*

Atoms, nuclei, nucleons and quarks



size in atoms — and in meters

Atom: 1 — 10^{-10}

Nucleus: $\frac{1}{10{,}000}$ — 10^{-14}

Nucleon: $\frac{1}{100{,}000}$ — 10^{-15}

Quark: $\frac{1}{100{,}000{,}000}$ — 10^{-18} (at largest)

The nucleus

A nucleus is a tightly-packed almost-spherical bundle of *nucleons*, much smaller than an atom.

There are two kinds of nucleons: neutrons and protons. They are *just alike* except the proton has electric charge, and the neutron mass is slightly greater.

Nucleons attract each other through the "*strong force*".

Nuclear Forces

The four fundamental forces of nature:

- Gravity
- The electromagnetic interaction
- The strong nuclear interaction
- The weak nuclear interaction

Nucleons attract each other through the *strong nuclear force*.

The strong force is *very short-range,* not inverse square, so that it has no effect on atomic physics and chemistry.

But it is *very strong* so that it overcomes the Coulomb repulsion to hold the nucleons inside the nucleus.

The *weak nuclear force* is extremely weak, but is responsible for some forms of nuclear radioactivity.

The THREE Forces of Nature

It is now understood that the electromagnetic interaction and the weak nuclear interaction are actually different aspects of the same fundamental force: *The Electroweak Interaction*

Also we now know that each force has its "messenger particle", a boson which carries the force.

1. Gravity force:	graviton
2. Electroweak force:	photon
3. Strong force:	gluon

Nuclear terminology

- Z = atomic number = number of ***protons***
- N = number of ***neutrons***
- A = mass number = Z + N = number of ***nucleons***
- Nuclide = a nuclear species, i.e. a combination of Z protons and N neutrons.
- Two nuclides with the same Z but different N are called ***isotopes***.
- A radioactive nuclide spontaneously changes into a different nuclide by emitting a particle. This ***radioactive decay*** is exponential, with a “half-life”.

Nuclear sizes

All nuclides have about the same density.

Crudely speaking the nucleons are in contact with each other, so the volume of the nucleus is proportional to A, the number of nucleons.

This means the radius is roughly proportional to the cube root of the atomic mass number:

$$r = r_0 A^{1/3}$$

$$r_0 = 1.2\ fm$$

$$1\ fm = 1\ femtometer = 10^{-15}\ m = 10^{-6}\ nm$$

Nuclear masses

The mass of the nucleus is also approximately proportional to A, the number of nucleons.

But not exactly, thanks to E = mc^2.

The strong force pulls the nucleons together. Work would be needed to pull apart the nucleons. This amount of work is called the binding energy ΔE.

So the nucleus has *less* energy than A separate nucleons. So the nucleus has less *mass* than A separate nucleons.

$$\boxed{M c^2 = Z m_p c^2 + N m_n c^2 - \Delta E}$$

The atomic mass unit

Rough idea:
u = mass of proton
= mass of neutron
= mass of H atom
= 2000 × electron mass
= 1 GeV/c^2

So that
helium mass = 4 u
carbon mass = 12 u
U_{238} mass = 238 u

But as we have seen that’s not right.

Correct definition: Carbon $^6C_{12}$ atom mass is exactly 12 u.

This means H atom mass is 1.007825 u.
Gold atom mass is 196.966552 u, etc.
And u = 1.66053873 × 10^{-27} kg.

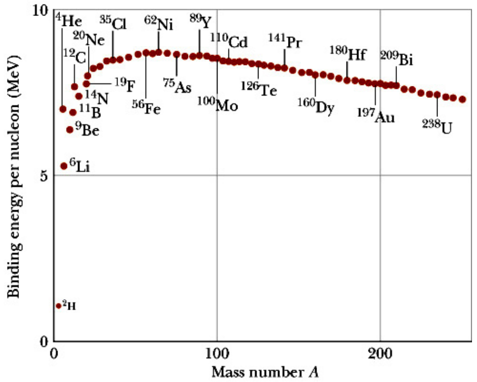
Example: Binding energy of helium

Helium mass = 4.0026 u
Hydrogen mass = 1.007825 u
Neutron mass = 1.008664 u
Mass excess = $2m_H + 2m_n - 4.0026\ u = 0.0304\ u$
So binding energy is $\Delta E = (.0304\ u)\ c^2$

But remember $m_p \approx 1$ u and $m_p c^2 \approx 1$ GeV
so approximately ΔE = .03 GeV = 30 Mev.
Convenient number is binding energy per nucleon, so that is about 30 MeV / 4 = 7 MeV.

Check with He point on graph in Fig. 42-6.

Binding energies per nucleon



Preference for neutrons

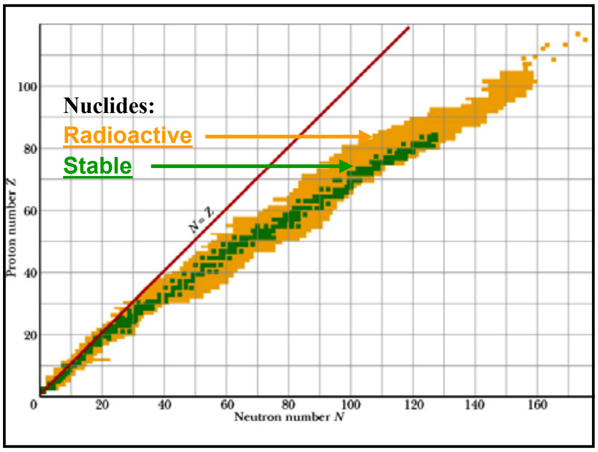
Light nuclei have about equal numbers of protons and neutrons. (A = 2Z) For example carbon, Z=6, Z=12.

Why do heavier nuclei prefer to have more neutrons?

Strong force is equally attractive, but protons have Coulomb repulsion. So that raises energy, makes them less tightly bound, reduces binding energy.

So why not all neutrons?

Pauli principle: Nucleons are fermions!



Alpha, Beta, Gamma Decay

Before they were fully understood, the radioactive decay processes were classified as the emission of alpha, beta, and gamma rays.

Alpha (α): **Emission of a helium nucleus (α particle).**

Beta (β): **Emission of an electron (β^-) or positron (β^+).**

Gamma (γ): **Emission of a photon (γ-ray).**

The first two change Z and N and so result in a different nuclide. Gamma emission just gets rid of excess energy as in the emission of a photon by an atom.

Alpha just rearranges nucleons to form two nuclides instead of one, but beta decay changes a neutron into a proton.

Alpha decay example

$$\boxed{{}^{238}U_{92} \rightarrow {}^{234}Th_{90} + {}^{4}He_{2}}$$

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

I would say $\quad U_{238} \rightarrow Th_{234} + He$

Conservation Laws:

Charge: (ΔZ=0) $\quad 92 = 90 + 2$

*Nucleons: (ΔA=0) $\quad 238 = 234 + 4$

Energy: (ΔE=0) $\quad M_U c^2 = M_{Th} c^2 + M_{He} c^2 + KE$

*More generally conservation of baryon number.

Beta decay

$$\boxed{n \rightarrow p + e^- + \bar{\upsilon}}$$

The fundamental beta-decay process changes a neutron into a proton, with the emission of an electron.
But there is also emission of an *antineutrino.*
Electrons (e^-) and neutrinos (υ) are *leptons.* (L=1)
Positrons (e^+) and antineutrinos ($\bar{\upsilon}$) are *antileptons.* (L=-1)
Neutrinos have zero mass, zero charge, but they have spin ½ like electrons, and are fermions.

Conservation Laws:

Charge: (ΔZ=0) $\quad 0 = 1 - 1 + 0$
Nucleons: (ΔA=0) $\quad 1 = 1 + 0 + 0$
Energy: (ΔE=0) $\quad M_n c^2 = M_p c^2 + M_e c^2 + KE$
Leptons: (ΔL=0) $\quad 0 = 0 + 1 - 1$

Beta decay example

This can improve the stability of a nuclide that has too many neutrons. For example

$${}^{32}P_{15} \rightarrow {}^{32}S_{16} + e^- + \bar{\upsilon}$$

Conservation Laws:

Charge: (ΔZ=0) $\quad 15 = 16 - 1 + 0$

Nucleons: (ΔA=0) $\quad 32 = 32 + 0 + 0$

Energy: (ΔE=0) $\quad M_P c^2 = M_S c^2 + m_e c^2 + KE$

Leptons: (ΔL=0) $\quad 0 = 0 + 1 - 1$

Another beta decay example

Or a nucleus can emit a *positron* (anti-electron) while changing a proton into a neutron. For example

$$^{64}Cu_{29} \rightarrow {}^{64}Ni_{28} + e^{+} + \upsilon$$

Conservation Laws:

Charge: (ΔZ=0) 29 = 28 + 1 + 0

Nucleons: (ΔA=0) 64 = 64 + 0 + 0

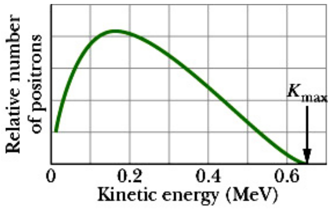
Energy: (ΔE=0) $M_{Cu} c^2 = M_{Ni} c^2 + m_e c^2 + KE$

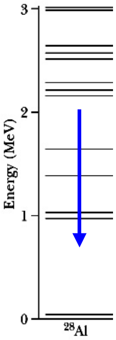
Leptons: (ΔL=0) 0 = 0 - 1 + 1

Positron emission spectrum

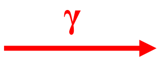
$$^{64}Cu_{29} \rightarrow {}^{64}Ni_{28} + e^{+} + \upsilon + K$$

$$K_{\max} = M({}^{64}Cu)c^2 - M({}^{64}Ni) - m_e$$





Gamma rays

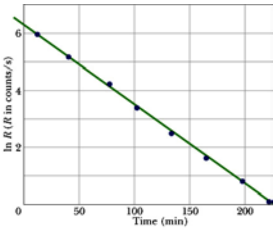


Gamma-ray emission during quantum jump between excited states of an aluminum nucleus.

$$E_\gamma = hf = \frac{hc}{\lambda} \approx 1.2\ MeV$$

$$\lambda = \frac{hc}{E} = \frac{1240\ eV \cdot nm}{1.2\ MeV} = 10^{-3}\ nm = 10^{3}\ fm$$

Radioactive decay



Spontaneous process.

Cannot predict when any particular nucleus will decay.

Result is just like decay of charge on a capacitor in an RC circuit. The number of nuclei remaining decreases *exponentially* with time. So the *decay rate R* (and intensity of the emitted radiation) does also.

$$\boxed{R = R_0 e^{-t/\tau}}$$

Meanlife is τ

Halflife is $T_{1/2} = (\ln 2)\tau$

Semilog plot shows straight line. $\ln R = \ln R_0 - t/\tau$