The Nucleus

- Atoms consist of a nucleus and an electron shell.
- A nucleus consists of nucleons: protons and neutrons. As the mass of a nucleon is about 2000 times the mass of an electron the nucleus carries practically all the mass of an atom.
- A nucleon consists of 3 quarks (and gluons).
- 1 fm (femtometer, Fermi) = $10^{-15}$ m is the typical length scale of nuclear physics.
- 1 MeV (Mega-electron volt) = $1.602 \times 10^{-13}$ J is the typical energy scale of nuclear physics.
<table>
<thead>
<tr>
<th>size (m)</th>
<th>object</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{27}$</td>
<td>Universe = age $\times c = 2 \cdot 10^{10} \text{ys} \times c$</td>
</tr>
<tr>
<td>$10^{23}$</td>
<td>Intergalactic distance $2 \times 10^{25} \text{cm}$</td>
</tr>
<tr>
<td>$10^{20}$</td>
<td>Galactic size $6 \times 10^{22} \text{cm}$</td>
</tr>
<tr>
<td>$10^{15}$</td>
<td>Nearest Star $2 \times 10^{17} \text{cm}$</td>
</tr>
<tr>
<td>$10^{12}$</td>
<td>Planetary Orbit $6 \times 10^{14} \text{cm}$ (Pluto)</td>
</tr>
<tr>
<td>$10^{11}$</td>
<td>Distance to sun $1.5 \times 10^{13} \text{cm}$</td>
</tr>
<tr>
<td>$10^{4}$</td>
<td>Satellite orbit</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>Atomic radius</td>
</tr>
<tr>
<td>$10^{-15}$</td>
<td>Nucleon radius</td>
</tr>
<tr>
<td>$10^{-18}$</td>
<td>Range of weak force</td>
</tr>
</tbody>
</table>
Nuclear Physics Experiments

Nuclear physics experiments can be classified as scattering or spectroscopic experiments (the same holds true for hadron physics).

In a scattering experiment, a beam of particles with known energy and momentum is directed towards the object to be studied (the target). The achievable resolution is determined by the de-Broglie-wavelength \( \lambda = \frac{h}{p} \) of the particles. Nuclear radii can be measured with electron beams of about \( 10^8 \) eV, proton radii with \( 10^9 \) eV.

The term 'spectroscopy' is used to describe those experiments which determine the decay products of excited states. In this way, one can study the properties of the excited states as well as the interactions between the constituents. 'States' can be different nuclids or in hadron physics different mesons or baryons. The energies required to produce excited states are similar to those for scattering experiments.
Nuclear Theory and Experiment

Atomic physics has a single consistent theory - Quantum Electrodynamics (QED). This is unfortunately not true for nuclear physics: There is a fundamental theory of the strong interaction - Quantum Chromodynamics (QCD) - but it describes the interactions between quarks, not nucleons.

The energies involved in nuclear decays are of the order of 1-10 MeV, less than 0.1% of the mass of the nucleus. As a result non-relativistic QM can be used to describe the nucleus.

This is not true for the study of the structure of the nucleon, where the incident beam energy in a scattering experiment may be 100 times the proton mass equivalent.

Both nuclei and nucleons are complex systems involving many constituents. The theories and models that describe them are therefore often phenomenological in nature and nuclear physics is rather led by experiment than by theory.
THE STRUCTURE OF MATTER

Constituents of ordinary matter.

ATOM

ELECTRON

NUCLEUS

PROTON

NEUTRON

QUARKS

LEPTONS

These particles exist on their own

<table>
<thead>
<tr>
<th>FAMILY</th>
<th>PARTICLE</th>
<th>Charge</th>
<th>Mass (MeV/c²)</th>
<th>Additional Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st FAMILY</td>
<td>ELECTRON (e⁻)</td>
<td>-1</td>
<td>0.51</td>
<td>Responsible for electricity and chemical reactions.</td>
</tr>
<tr>
<td>1st FAMILY</td>
<td>ELECTRON NEUTRINO (νₑ)</td>
<td>0</td>
<td></td>
<td>Rarely interacts with other matter.</td>
</tr>
<tr>
<td>2nd FAMILY</td>
<td>MUON (μ⁻)</td>
<td></td>
<td>106</td>
<td>A heavier relative of the electron. Discovered 1937.</td>
</tr>
<tr>
<td>3rd FAMILY</td>
<td>TAU (τ⁻)</td>
<td></td>
<td>178</td>
<td>A heavier relative of the electron and muon. Discovered 1975.</td>
</tr>
<tr>
<td>3rd FAMILY</td>
<td>TAU NEUTRINO (νₜ)</td>
<td></td>
<td></td>
<td>Not yet discovered.</td>
</tr>
</tbody>
</table>

QUARKS

These particles only exist bound together

<table>
<thead>
<tr>
<th>FAMILY</th>
<th>PARTICLE</th>
<th>Charge</th>
<th>Mass (MeV/c²)</th>
<th>Additional Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP</td>
<td>UP (u)</td>
<td>+2/3</td>
<td>5</td>
<td>Protons are made up of two up quarks and one down quark.</td>
</tr>
<tr>
<td>DOWN</td>
<td>DOWN (d)</td>
<td>-1/3</td>
<td>10</td>
<td>Neutrons are made up of one up quark and two down quarks.</td>
</tr>
<tr>
<td>CHARM</td>
<td>CHARM (c)</td>
<td></td>
<td>1.3</td>
<td>A heavier relative of the up quark. Discovered 1973.</td>
</tr>
<tr>
<td>STRANGE</td>
<td>STRANGE (s)</td>
<td></td>
<td>0.2</td>
<td>A heavier relative of the down quark. Discovered 1947.</td>
</tr>
<tr>
<td>TOP</td>
<td>TOP (t)</td>
<td></td>
<td>180</td>
<td>The heaviest quark. Discovered 1994.</td>
</tr>
<tr>
<td>BOTTOM</td>
<td>BOTTOM (b)</td>
<td></td>
<td>4.3</td>
<td>A heavier relative of the down and strange quark. Discovered 1977.</td>
</tr>
</tbody>
</table>

ALL OF THE ABOVE PARTICLES HAVE AN ANTIPARTICLE COUNTERPART.

A particle and its antiparticle can annihilate to produce the bosons that carry forces e.g. $e^+e^- \rightarrow \gamma + \gamma$.

A particle - antiparticle pair can be produced from a force-carrying boson e.g. $Z \rightarrow bb$, $\gamma \rightarrow e^+e^-$. No. 2
L'interazione elettromagnetica tra due cariche elettriche è descritta da un potenziale $U(r) \propto QQ'/r$ e per l'ampiezza di transizione si ha $\langle f | H_I | i \rangle \propto 4\pi QQ'/q^2$.

Teoria di Fermi del decadimento $\beta$ dei nuclei l'interazione debole è descritta con un potenziale di interazione a contatto, $U(r) \propto \delta(r)$, e l'ampiezza di transizione è costante.

**Nucleare**

$U(r) \propto e^{-\mu r}/r$, \hspace{1cm} $\langle f | H_I | i \rangle \propto 4\pi/(q^2 + \mu^2)$

<table>
<thead>
<tr>
<th>interazione</th>
<th>campo</th>
<th>propagatore</th>
<th>costante di accoppiamento</th>
</tr>
</thead>
<tbody>
<tr>
<td>elettromagnetica</td>
<td>$\alpha \hbar c/r$</td>
<td>$\alpha/q^2$</td>
<td>$\alpha = 1/137$</td>
</tr>
<tr>
<td>debole</td>
<td>$g \delta(r)$</td>
<td>$g/(\hbar c)^3$</td>
<td>$G = 1.16 \times 10^{-5} \text{ GeV}^{-2}$</td>
</tr>
<tr>
<td>nucleare</td>
<td>$\alpha_s \hbar c e^{-\mu r}/r$</td>
<td>$\alpha_s/(q^2 + \mu^2)$</td>
<td>$\alpha_s \approx \mu/m_p$</td>
</tr>
</tbody>
</table>

Vite medie

Debole $10^{-10-8}s$

elettr $10^{-16-18}s$

Forte $10^{-21-23}s$

$GM^2_w = \alpha$
Nuclids

- A **nuclid** is a specific combination of a number of protons and neutrons.

\[
\frac{A}{Z}X_N
\]

is the complete symbol for a nuclid, but the information is redundant and \( ^A_X \) is sufficient.

- \( X \) is the chemical symbol of the element

- \( Z \) is the atomic number, giving the number of protons in the nucleus (and electrons in the shell)

- \( N \) is the number of neutrons

- \( A = Z + N \) is the mass number

- Nuclids with the same atomic number \( Z \) are called **isotopes**, same \( A \) **isobars**, same \( N \) **isotones** (isos (gr.) - the same).
Basic Constituents of Atomic Nuclei

Helium

\[ \frac{A}{Z} \times \frac{N}{2} = He \]

\( A \) nucleons: protons (H\(^+\)) plus neutrons

\( Z \) protons (equals the number of electrons in a neutral atom)

\( N = A - Z \) neutrons

Masses

\( m_p = 1.673 \cdot 10^{-27} \text{kg} = 938.279 \text{ MeV/c}^2 = 1.00728 \text{ u} \) (mass units)

\( m_n = 1.675 \cdot 10^{-27} \text{kg} = 939.573 \text{ MeV/c}^2 = 1.00867 \text{ u} \)

\( 1 \text{u} = m(^{12}\text{C})/12 = 1.6606 \cdot 10^{-27} \text{kg} = 931.502 \text{ MeV/c}^2 \)

Charges

\( e_p = +e = 1.602 \cdot 10^{-19} \text{C} \) (Coulomb) \( e_n = 0 \)

Useful parameter \( e^2 = 1.440 \cdot 10^{-15} \text{ MeV} \cdot \text{m} = 1.440 \text{ MeV} \cdot \text{fm} \)
The Electron

Cathode rays are negatively charged particles, “electrons”

\[ J.J.\, Thomson: \frac{e}{m} = 1.76 \cdot 10^{11} \text{C/kg} \]

\[ R.A.\, Millikan: e = -1.602 \cdot 10^{-19} \text{C} \]

\[ \rightarrow m = 9.11 \cdot 10^{-31} \text{kg} \]

The elementary charge was the same found in Faraday’s earlier electro-chemical experiments.

Where do these electrons come from? Must come from inside the atom.
Consistency of Stable Nuclei

An important detail:

Of the 280 stable nuclides,

- 170  have \( N \) even  \( Z \) even
- 50-60  have \( N \) or \( Z \) even, the other quantity odd
- 4  have \( N \) odd and \( Z \) odd (extremely rare!)

Preference of “paired” nucleons.
nuclids can be put onto a chart, not unlike a periodic table for nuclear physics.

typically the chart plots $Z$ vs $N$.

the different radioactive decays can easily be connected with movement in the chart, e.g. $\alpha$-decay corresponds to two-left, two-down.

this allows to visualise entire decay chains in an effective fashion.

it also allows to visualise other properties, e.g. lifetime or date of first detection.
Transmutation of Nuclei

By nuclear reactions, example:

Reaction $^9Be + \alpha \rightarrow ^{12}C + n$

Notation $^9Be(\alpha, n)^{12}C$

Important application:
Transmutation of nuclear waste (weapons, spent fuel)

Inverse reaction:

Reaction $^9Be + n \rightarrow ^6He + \alpha$

Notation $^9Be(n, \alpha)^6He$

Large changes are possible with heavy-ion reactions
Solar Abundances of Elements

CORRELATION COEFFICIENT -77.0%