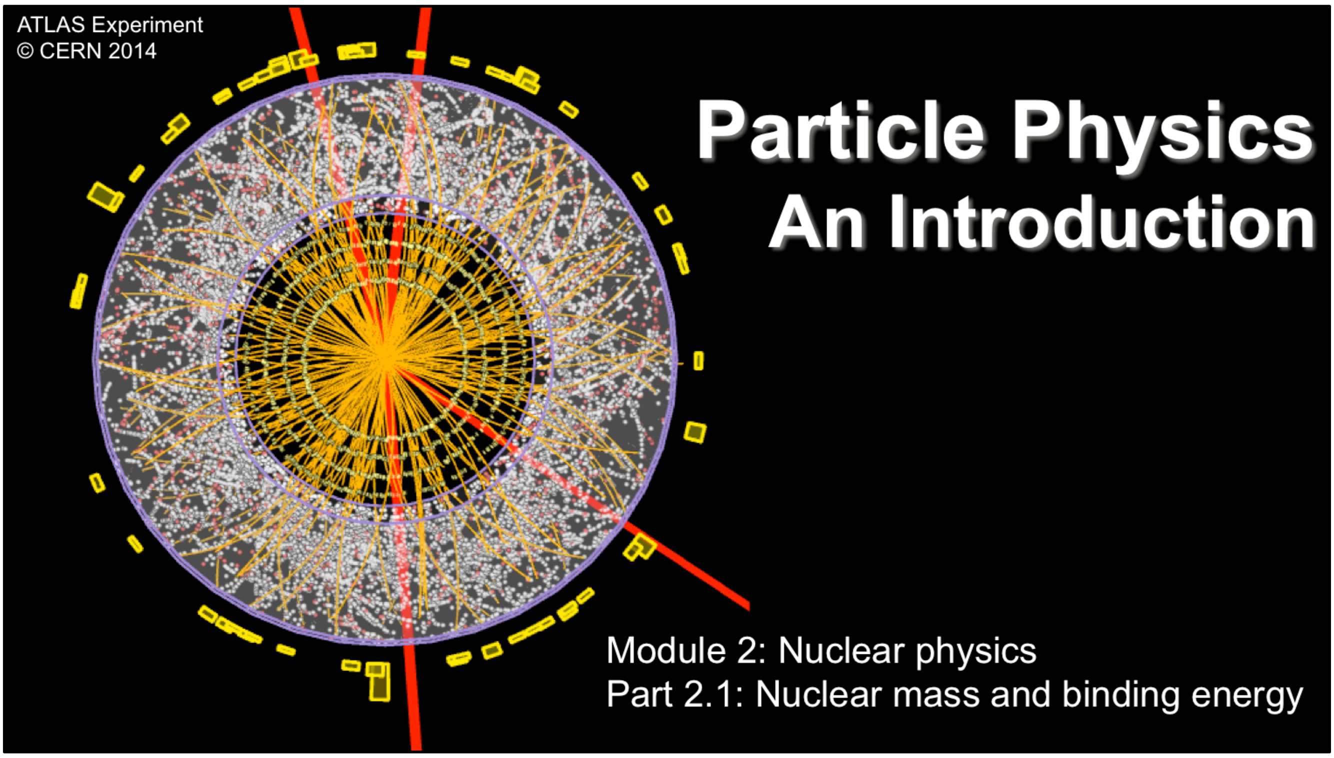
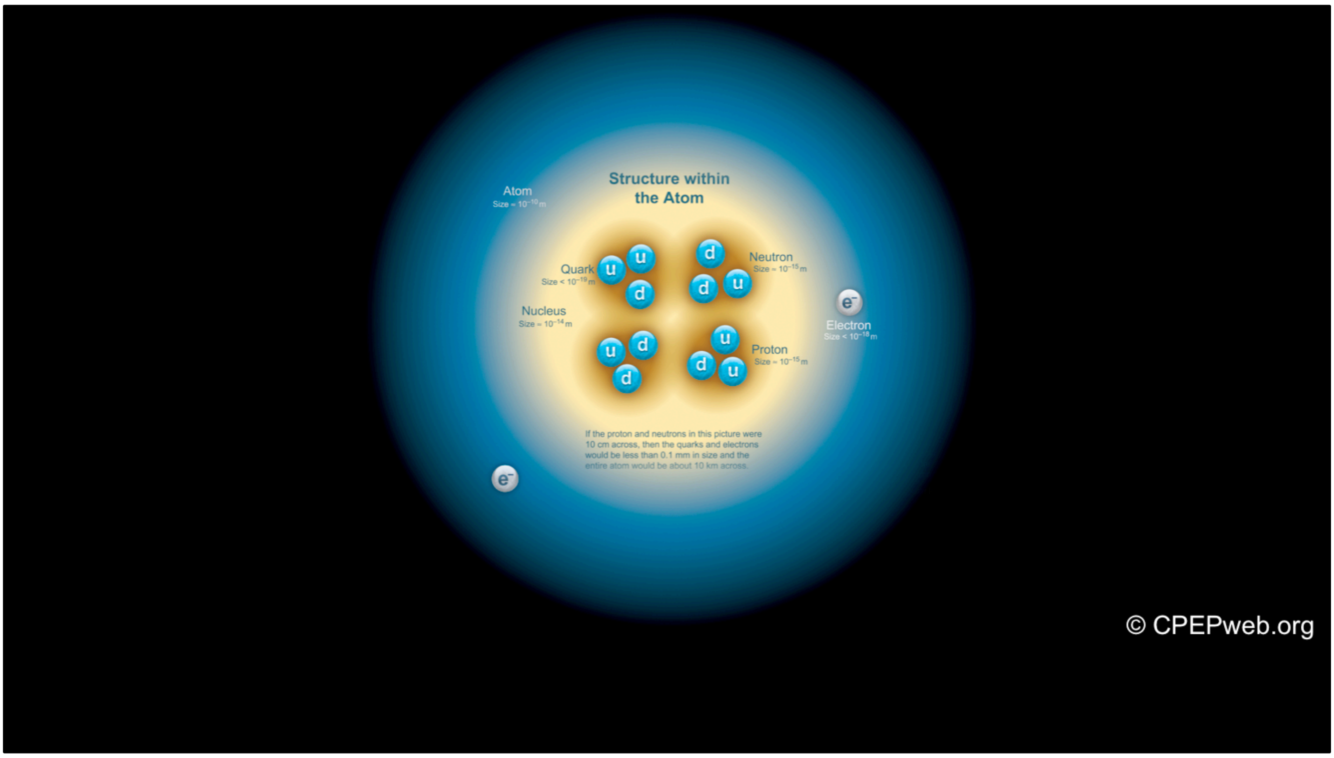


During this second module, we deal with nuclear physics and its applications. At the end of the module we will visit the Tokamak of the Swiss Institute of Technology in Lausanne and the Beznau nuclear power plant, the oldest one still in operation.

This is a rather self-contained module. If your main interest is nuclear physics, you will be well served. You will also notice that the module is somewhat longer than others. Juts take your time to digest the material without pressure.

In this first video, we will review what is known about the mass of nuclei, The goals for you are the following:

- To know the nomenclature of atomic nuclei and their periodic system;
- To be able to qualitatively describe the mass and binding energy of nuclei.



- Experiments of the **Rutherford** type demonstrate the existence of a positively charged nucleus, four orders of magnitude smaller than the size of the atom. These experiments only require to understand **electromagnetic interactions** between the projectile and the target.
- Scattering experiments can also yield information about nuclear properties, and thus establish a catalogue of the properties of the **nuclear interaction** that holds protons and neutrons together inside the nucleus.

- One must not confuse this **nuclear force** with the **strong force** introduced in the first module and more extensively discussed in Module 5.
- The **strong force binds quarks** inside hadrons by gluon exchange. It does not permit quarks to leave their hadrons. So hadrons in general and **nucleons** in particular **do not carry a net color charge**. Thus gluons cannot bind protons and neutrons to form a nucleus.
- The **nuclear force** is more like a long distance residue of the strong force. In that it resembles the Van der Waals force, which is a residue of the electromagnetic interaction which acts between neutral molecules.

Atoms:

- Electromagnetic force, well known properties
- Atomic spectra motivate quantum mechanics
- Perturbative calculations feasible

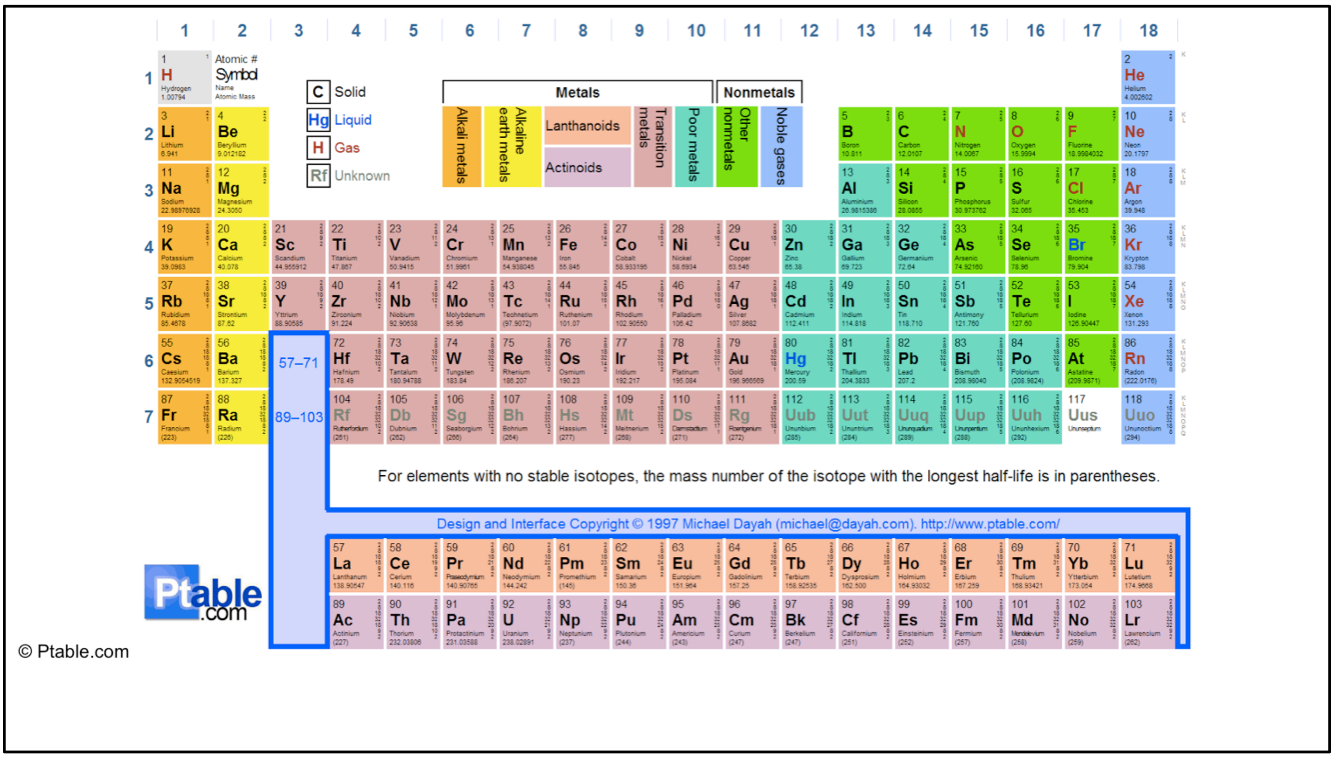
Nuclei:

- Nuclear force much stronger
- Very short range
- No classical analogue
- Only empirical models

Let us compare some basic properties of **atoms and the electromagnetic force**, to **nuclei and the nuclear force**.

- The **electromagnetic force** is responsible for holding atoms together. Its properties are well known classically and rather easy to extrapolate to quantum distances.
- The study of atomic spectra gave rise to **quantum mechanics**, which qualitatively and quantitatively explains many phenomena of condensed matter physics.
- The **fine structure constant** $\alpha \approxeq 1/137$ is small, which makes perturbative calculations feasible.
- The **nuclear force** must be much stronger, since it wins over the Coulomb repulsion between tightly packed protons.
- It must be of **short range**, since it does not make itself felt outside the nucleus.
- It has **no classical analogue**, only experimental results can help to understand its properties.
- One thus uses experiments as a guide towards **empirical models** of the nucleus and the nuclear force.

We will come back to the relation between experiments and models as we go along.



Let us first summarize how we identify nuclei:

- We denote by ***Z*** the **nuclear charge**, which is equal to the atomic number in the periodic table. It is given by the number of protons in the nucleus.
- ***A*** is the **number of nucleons**, the sum of protons and neutrons. It is also called mass number.
- Nuclei are thus completely identified by their electric charge and their number of nucleons, with a notation $^{A}_{Z}X$. The element name denoites *Z*, normally supplemented by *A*, like in ^{14}C.
- The number of neutrons is evidently ***N=A-Z.***
- The **chemical properties** of the elements are determined by the elecron cloud surrounding the nucleus, the **periodic table** is therefore organised according to *Z*.
- Nuclei with the same number of protons, but a different number of neutrons, $^{A}_{Z}X$ and $^{A'}_{Z}X$, are called **isotopes.** They have very similar chemical properties, but not necessarily similar nuclear properties. Examples are ^{235}U and ^{238}U (92 protons), ^{1}H, ^{2}H et ^{3}H (hydrogen, deuterium and tritium: 1 proton with 0, 1 and 2 neutrons).
- Nuclei with the same number of nucleons, but a different number of protons, $^{A}_{Z}X$ et $^{A}_{Z'}Y$, are called **isobars**. Examples are ^{12}C and ^{12}B (12 nucleons).
- Nuclei can also be excited to higher energy states keeping the number of protons and neutrons constant. These are called resonances or **isomers.**

Nuclear mass:

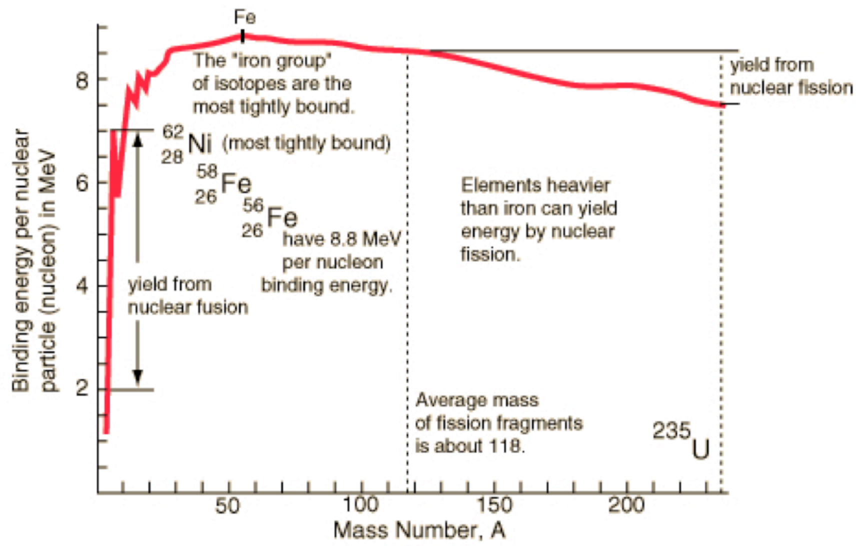
$$M(A,Z) < Zm_p + (A-Z)m_n$$
$$m_p \simeq 938.28 \text{ M}eV \quad ; \quad m_n \simeq 939.56 \text{ M}eV$$

Binding energy:

$$\Delta M(A,Z) = M(A,Z) - Zm_p - (A-Z)m_n < 0$$

$$\frac{\Delta M(A,Z)}{A} = \frac{M(A,Z)}{A} - \frac{Z}{A}m_p - \left(1 - \frac{Z}{A}\right)m_n \ll m_{p/n}$$

- Naively one might assume that the mass of a nucleus is simply given by the **sum of the proton and neutron masses**. But in reality it is of course diminished by the **binding energy** between the nucleons.
- The **mass deficit *ΔM*** must always be negative so that the nucleus is in a bound state. We call it **binding energy**, it has been measured for practically all nuclei.
- The absolute value of the binding energy is the energy required to decompose the nucleus into separate nucleons.
- The **binding energy per nucleon *ΔM/A*** is the energy required to separate the average nucleon from its nucleus. It is much smaller than the mass of the nucleons p and n. The mass of the nucleus is thus indeed dominated by the mass of its constituents.
- For the nucleons themselves, the situation is very different: the total mass of the quarks inside a nucleon is only about 1% of the nucleon mass. It is their binding energy which dominates the nucleon mass.



When one analyses the dependence of the binding energy *B* per nucleon on the mass number *A*, one notices the following:

- $A < 20$: $\Delta M/A$ oscillates, but rises rapidly with increasing A
- $20 < A < 60$: $\Delta M/A$ saturates
- $A \cong 60$: $\Delta M/A$ has a broad maximum for the iron group (Ni, Fe, Co) with about 9 MeV/nucleon
- $A > 60$: $\Delta M/A$ decreases slowly

- The general mean is ≅ 8 MeV/nucleon. The kinetic energy of nucleons inside the nucleus must be relatively small, otherwise they would not stay bound. The velocities of bound nucleons are thus non-relativistic.

Wave length of a non-relativistic nucleon confined inside the nucleus:

$$\lambda\!\!\!^{-} = \frac{\hbar}{p} = \frac{\hbar}{\sqrt{2mT}} \simeq \frac{197 \text{ MeV fm}}{\sqrt{2 \cdot 940 \cdot 8} \text{ MeV}} \simeq 1.6 \text{ fm} = 1.6 \times 10^{-13} \text{ cm}$$

Wave length of a hypothetic electron confined inside the nucleus:

$$\lambda\!\!\!^{-} = \frac{\hbar}{T} \simeq \frac{197 \text{ MeV fm}}{8 \text{ MeV}} \simeq 25 \text{ fm} = 2.5 \times 10^{-12} \text{ cm}$$

- The binding energy corresponds to a **wave length** of nucleons inside the nucleus. This wavelength is **less than 2 fm**, of the order of the nuclear size. It is thus plausible that a nucleus can contain nucleons with a **maximum kinetic energy *T* of 8 MeV**, or a maximum momentum *p* of 120 MeV.

- If, on the other hand, the nucleus would contain **electrons**, they would be relativistic and their wave length would be **2.5 × 10^{-12}cm, much bigger than the nuclear size.** The nucleus thus contains no bound electrons, they need a much larger volume to be contained. This is obviously in agreement with the findings of Geiger and Marsden.

- In the next video we will talk about the size and spin of nuclei.