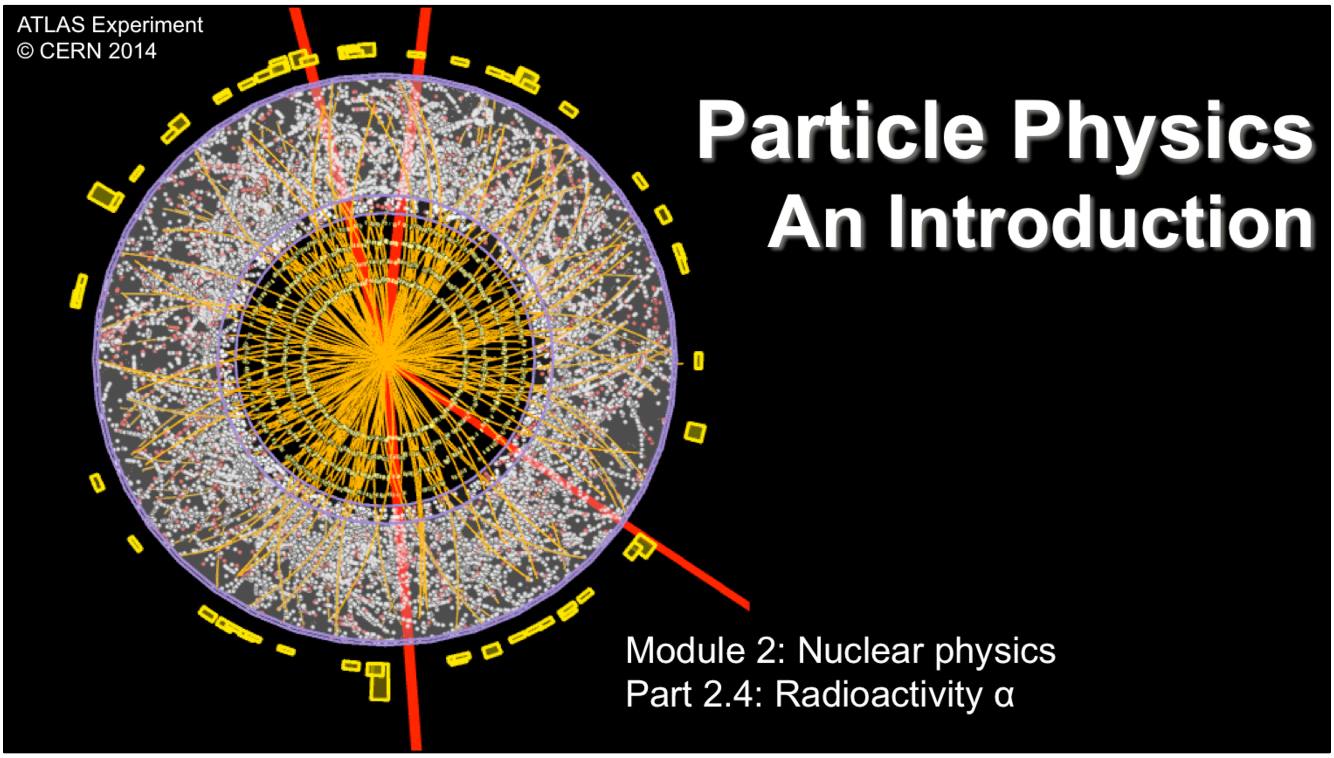


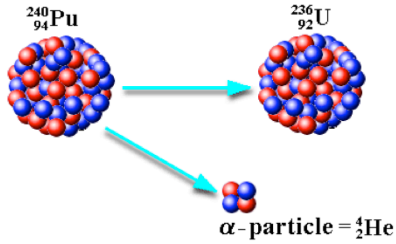
During this second module, we deal with nuclear physics and its applications. We will now discuss radioactivity.

In this 4th video we will talk about nuclear decay in general and alpha decay in particular.

After watching this video you will be able to:
- Describe the valley of stability and its surroundings;
- Know how to locate and characterize nuclei with respect to this valley;
- Characterize alpha decays and their properties.

α decay:

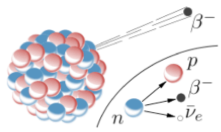
$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\mathrm{He} $$



β decay:

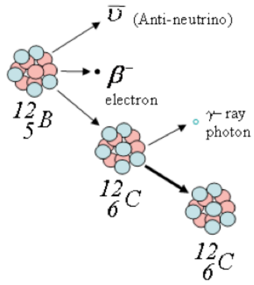
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \mathrm{e}^{-} + \bar{\nu}_e \quad ; \quad {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \mathrm{e}^{+} + \nu_e $$

$$ \mathrm{n} \rightarrow \mathrm{p\,e^{-}}\,\bar{\nu}_e \quad ; \quad \mathrm{p} \rightarrow \mathrm{n\,e^{+}}\,\nu_e $$



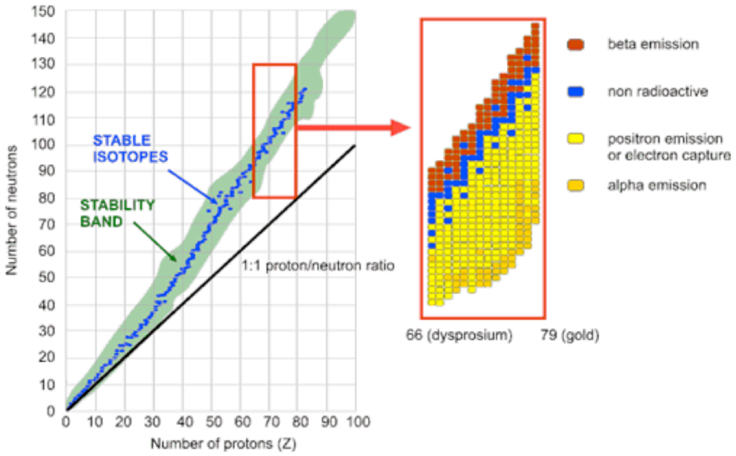
γ decay:

$$ {}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma $$



An unstable nucleus can transform itself into a more stable one through **radioactive decay**. We distinguish three types, historically labeled **alpha, beta and gamma** decays:

- **Alpha decay** is the spontaneous fission of a heavy nucleus into a less heavy one and a nucleus of ^{4}He, also called an alpha particle.
- The **beta decays** are transformations of a nuclear neutron into a proton or vice versa, by respectively emitting an electron and its antineutrino or a positron and its neutrino. This way both baryon number and lepton number are conserved.
- These decays often leave the daughter nucleus in an excited state. The **gamma decays** allow it to return to its ground state by emitting one or more photons.



α decay:

- Heavy nuclei:

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

β decay:

- Neutron-rich nuclei:

$$^{A}_{Z}X \rightarrow \, ^{A}_{Z+1}Y + \mathrm{e}^{-} + \bar{\nu}_e$$
$$\mathrm{n} \rightarrow \mathrm{p}\,\mathrm{e}^{-}\,\bar{\nu}_e$$

- Proton-rich nuclei:

$$^{A}_{Z}X \rightarrow \, ^{A}_{Z-1}Y + \mathrm{e}^{+} + \nu_e$$
$$\mathrm{p} \rightarrow \mathrm{n}\,\mathrm{e}^{+}\,\nu_e$$

γ decay:

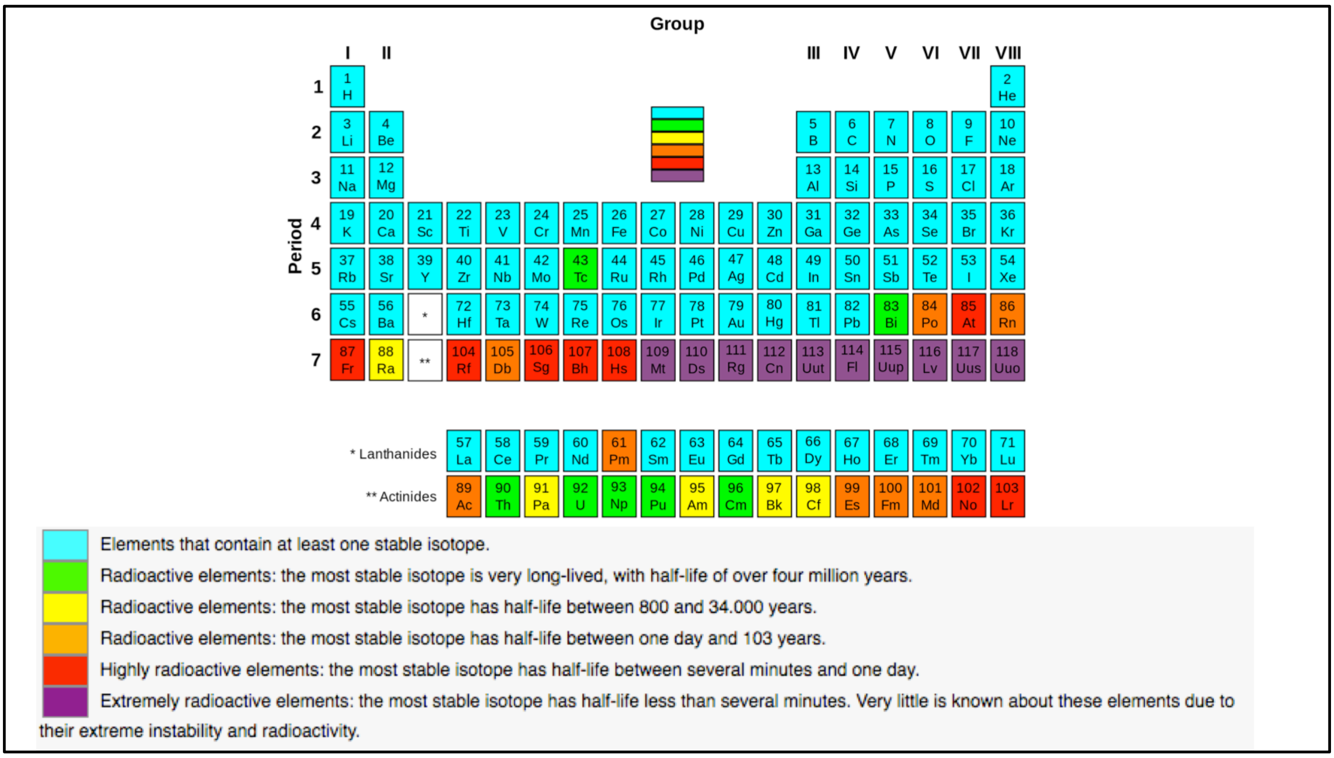
- Excited nuclei:

$$^{A}_{Z}X^{*} \rightarrow \, ^{A}_{Z}X + \gamma$$

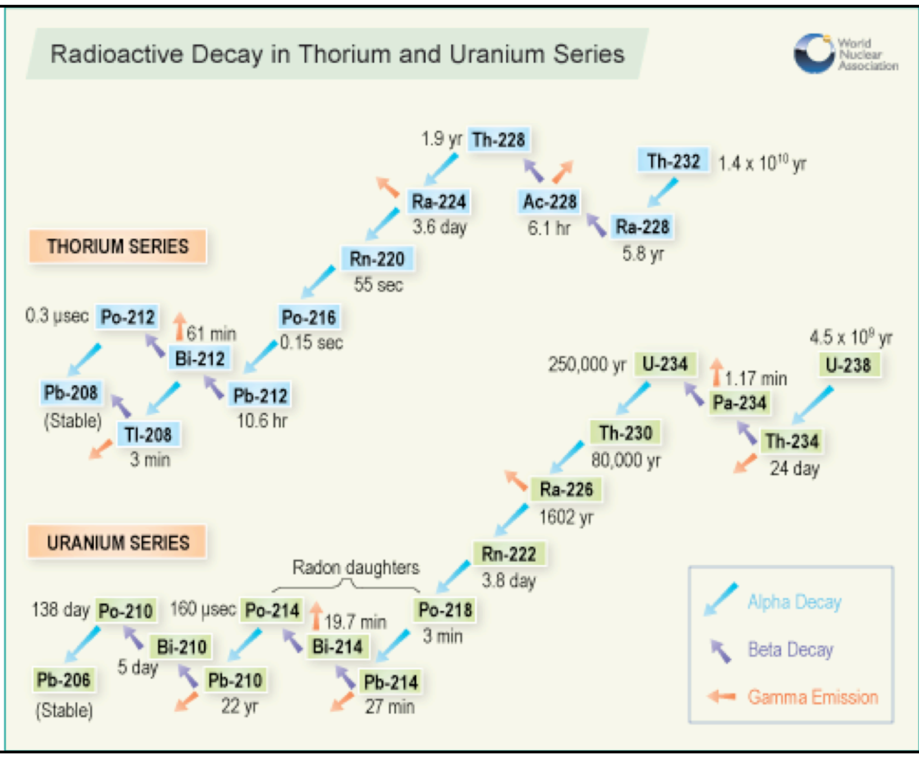
Decays are spontaneous processes. They happen if they **tighten the binding** of a nucleus:

- This way, **heavy nuclei** can reduce their mass and increase their binding energy by emitting a tightly bound **^{4}He nucleus**.
- Nuclei which are **rich in neutrons** can gain a more symmetric state by transforming one of them into a proton via β^{-} decay.
- Nuclei which are **rich in protons** can correct this asymmetry by a β^{+} decay.
- And **excited daughter nuclei** can reach their ground state by emitting one or more photons.

All these reactions take a nucleus closer to the so-called **valley of stability.**



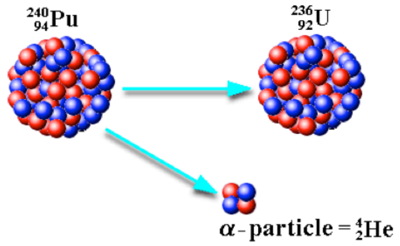
- This table shows the distribution of **nuclei with stable isotopes** over the periodic system.
- About **60 radioactive nuclei are naturally present** on Earth, compared to about **1000 radioactive isotopes** thus far produced in the laboratory. When our planet was formed, we can assume that all these nuclei were roughly equally abundant.
- The absence of certain radioactive nuclei today can give us an idea of the **age of the solar system**. This estimate gives an age of roughly **10^{10} years for the Sun**, all nuclei with a shorter lifetime have completely disappeared.
- The naturally present radioactive nuclei have a nuclear charge ***Z* between 81 and 92**, they are characterized by an excess of neutrons. Since they are heavy, they first undergo **an alpha decay**, leading to an even larger relative excess of neutrons. This is then fixed by a **subsequent beta decay**. The grand-daughters are often themselves unstable and undergo alpha decay, and so on.
- This chain of alpha and beta decays will continue until the **valley of stability** in the *N*-*Z* plane is reached.



This results in **four series of alpha emitters**, where the daughters progressively differ by a multiple of *4* nucleons:

- the Thorium series with ***A = 4n***
- the Neptunium series with ***A = 4n + 1***
- the Uranium-Radium series with ***A = 4n + 2***
- and the Uranium-Actinium series with ***A = 4n + 3***

One of the important applications of radioactivity is the **dating of organic materials**, which can work up to several thousand years. We will go into more details about radioisotope dating in video 2.7.



α decay:

$$^{A}_{Z}P \rightarrow \,^{A-4}_{Z-2}D + \,^{4}_{2}\mathrm{He}$$

Energy balance:

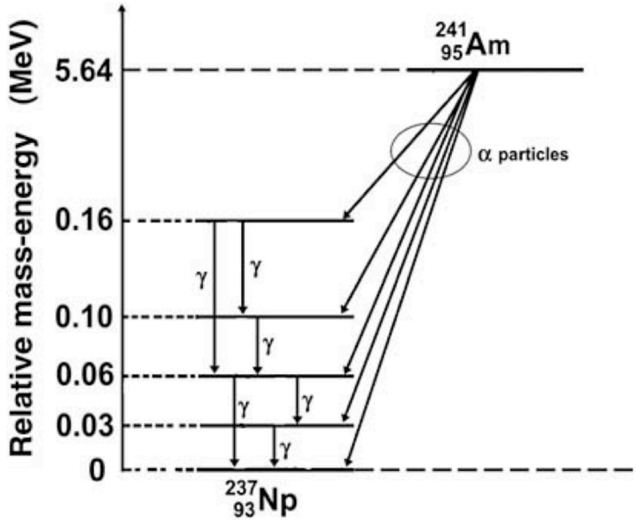
$$M_P = M_D + T_D + M_\alpha + T_\alpha$$

Gain in energy Q-value:

$$Q \equiv \Delta M = M_P - M_D - M_\alpha = T_D + T_\alpha$$

Let us now discuss the physics of alpha decay in more detail:

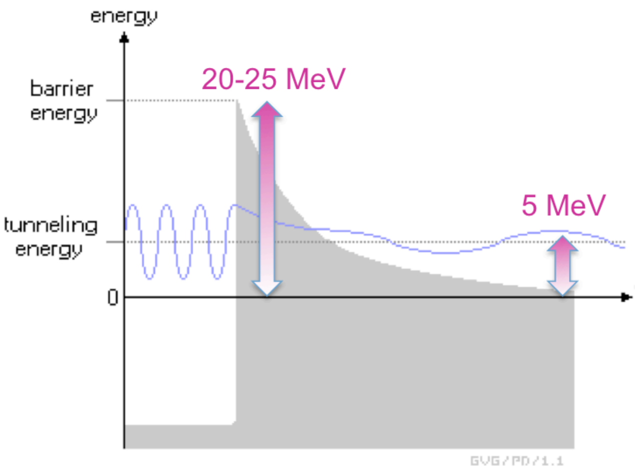
- A **parent nucleus *P*** decays into a **daughter nucleus *D*** via the emission of a ^{4}He nucleus.
- This corresponds to a **spontaneous fission** into daughter nuclei of very asymmetric mass, since the nucleus *D* is much heavier than ^{4}He. For more details on other fission processes, see video 2.8.
- If we consider the **parent nucleus** to be **at rest**, energy conservation gives us a relation between masses and energies. Since the number of electrons is unchanged in the reaction, we can directly use **atomic mass** for our calculation.
- $T_{\alpha/D}$ are the kinetic energies of the alpha particle and the daughter nucleus.
- The gain in binding energy that drives the decay is called the **Q-value**. It is converted into the kinetic energy of the decay products.
- An example of the calculation of T_α et T_D is given in **video 2.4a**. Because of the asymmetry in the masses, the alpha particle takes most of the kinetic energy.



$$^{A}_{Z}P \rightarrow \,^{A-4}_{Z-2}D^{*} + \,^{4}_{2}\mathrm{He}$$

$$^{A-4}_{Z-2}D^{*} \rightarrow \,^{A-4}_{Z-2}D + \gamma$$

- The **spectra of alpha particles** coming from the decay of the same isotope can reveal **intermediate metastable states**. One then observes α particles with slightly different, but of course quantized energies.
- One also observes **gamma ray emission** which comes from the decay cascade towards the ground state.
- The parent nucleus can of course also decay **directly to the ground state**, without passing by the intermediate ones. This direct decay results in the most energetic α particle.
- An example is shown here for the decay chain of **^{241}Am, a radioactive source often used in the laboratory**.



Tunneling effect:

$$
\begin{aligned}
T_\alpha &\simeq V_0 + E \simeq 44\text{MeV} \\
v_\alpha &\simeq \sqrt{2T_\alpha/M_\alpha} \simeq 0.15c \\
R &\simeq 10^{-12}\text{cm} \quad \rightarrow \quad f = v_\alpha/R \simeq 4.5 \times 10^{21}/\text{s} \\
P &\equiv \lambda = 1/\tau \simeq v_\alpha p/R \simeq 0.5 \times 10^{-18}/\text{s} \\
N(t) &= N_0 e^{-\lambda t} = N_0 e^{-t/\tau}
\end{aligned}
$$

- The **kinetic energy of α particles** from nuclear decay is typically of the order of 5 MeV.
- When such a low energy particle approaches a heavy nucleus from outside, it cannot penetrate the **Coulomb barrier**. For a nucleus of $A \cong 200$, it has a typical height of 20 to 25 MeV.
- So why does the process work in the **opposite direction**? How can a alpha particle traverse the Coulomb barrier from the inside?
- The answer is given by the quantum process of **tunneling.**
- The **probability** that an alpha particle traverses the Coulomb barrier is of the order of $p \cong 10^{-40}$. But this is the probability of traversing on a single trial. This is why a low energy alpha particle scattered from the outside cannot penetrate.
- The **velocity of an alpha particle** bound to a nucleus with $T_\alpha \cong V_0 + E \cong 44$ MeV is non-relativistic, but still impressive: $v_\alpha \cong 0.15\ c$.
- Confined to a region with radius $R \cong 10^{-12}$cm, the particle bounces off the barrier with a frequency $v_\alpha/R \cong 4.5 \times 10^{21}$/s. The probability of penetration per second is thus $P \cong v_\alpha\ p/R \cong 0.5 \times 10^{-18}$/s.
- This quantity is called the **decay constant λ**. It is the inverse of the lifetime $\tau = 1/\lambda$. For a typical nucleus we find $\tau \cong 10^{10}$ years, which is representative for nuclei with alpha decay.
- The number of nuclei $N(t)$ remaining after an elapsed time t starting from an initial sample of N_0 nuclei diminishes exponentially according to the **decay law**. This law is examined more closely in the optional video 2.5a.

In the next video, we will talk about the two other types of radioactivity, namely beta and gamma decays.