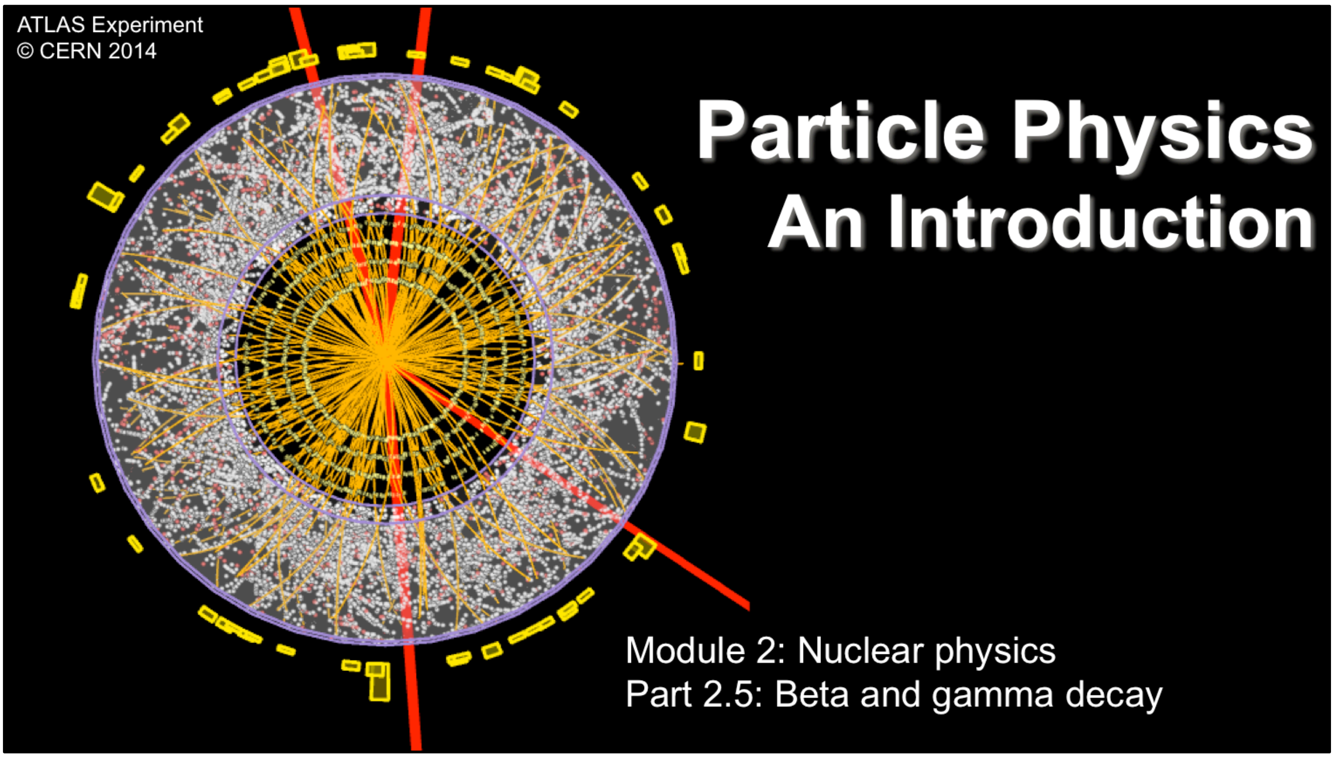
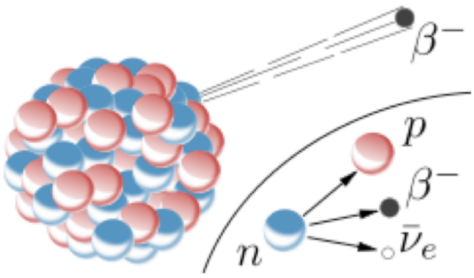


During this second module, we deal with nuclear physics and its applications.

In this fifth video we go into more details on the two other types of radioactivity, i.e. beta and gamma decay.

The goals for you are:
- To be able to characterize β decays of nuclei and their properties;
- To relate these properties to those of the underlying weak interactions;
- To be able to characterize the γ decays of excited nuclei.



β^- decay:

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

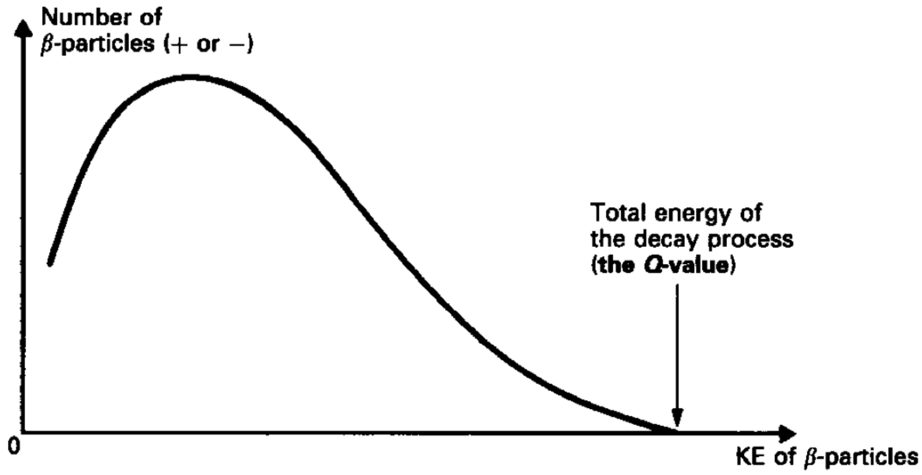
β^+ decay:

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

Electron capture from the K-shell:

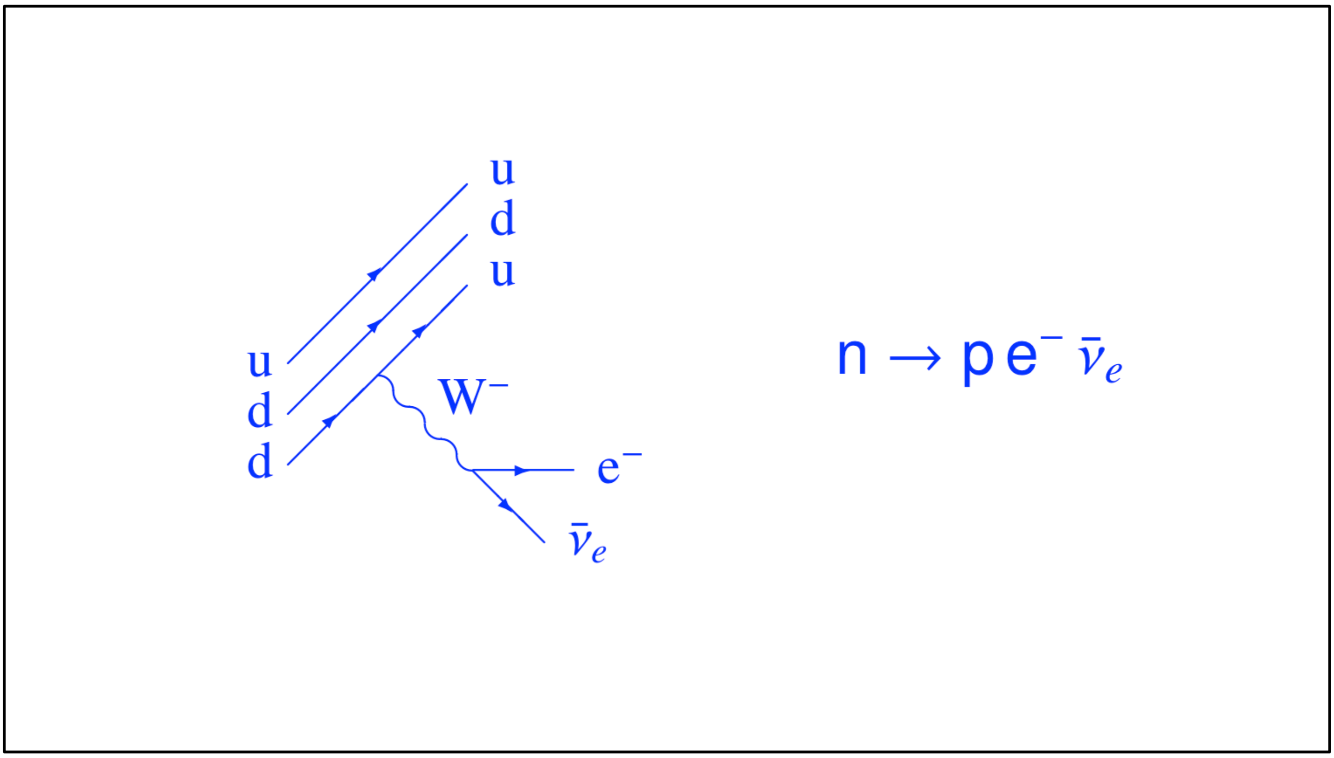
$$ {}^{A}_{Z}X + \mathrm{e}^- \rightarrow {}^{A}_{Z-1}Y + \nu_e \quad ; \quad \mathrm{e}^-\,\mathrm{p} \rightarrow \mathrm{n}\,\nu_e $$

- A neutron-rich nucleus, i.e. with *N/Z* larger than what stability requires, can transform into a more stable nucleus by emitting an electron and transforming one of its neutrons into a proton, in a **β^- decay**. To conserve lepton number, this emission must be accompanied by the emission of an **antineutrino**.
- In the contrary case, proton-rich nuclei, which have too many protons to be stable, can reach stability by **β^+ decay** accompanied by **neutrino emission**. Since the proton is lighter than the neutron, this is only possible for **bound protons**, when the Q-value is turned positive by the **gain in binding energy**.
- A nucleus with a surplus of protons can also **capture an electron from the internal K shell**. The other electrons of the atom will then cascade down to fill the gap. Since a lepton disappears in the capture, a neutrino must be emitted to conserve lepton number.
- All these decays are isobar, with ***ΔA* = 0 and *|ΔZ|* = 1**.

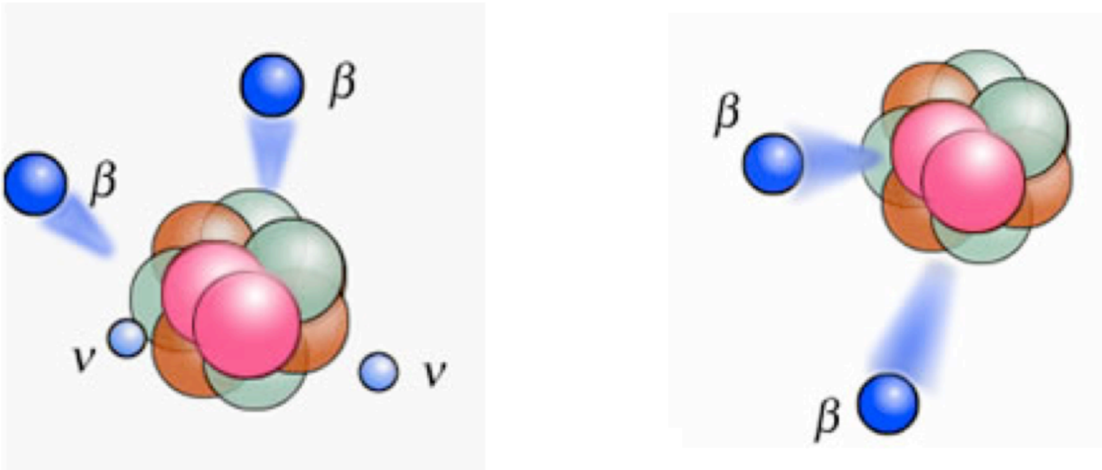


- Since beta decays are **three-body processes**, the spectrum of the emitted electron or positron is continuous. It has the shape sketched here.
- The **neutrino interacts only very weakly** with matter, it will thus normally escape undetected. This is also the reason why the neutrino has taken so long to be discovered.
- Neutrinos and antineutrinos are fermions with zero electric charge and a **very small mass**.
- The **maximum electron energy** is obtained when the neutrino is produced almost at rest. Its maximum value then approaches the Q-value, like it would in a two-body decay. When one measures this energy, one can establish an upper limit on the neutrino mass by energy conservation.

- The video 2.5a introduces the **exponential decay law** which describes the time evolution of this and other decay processes.



- At the quark level, beta decay proceeds via the **exchange of a $W^\pm$**, which is the gauge boson mediating the weak force.
- The large mass of this boson is responsible for the **short range** of the weak force and its **weakness at low energies**.
- **Neutrinos** are very peculiar particles. Their generations can mix with each other, their mass is the lightest among all particles, probably of the order of meV.
- It is not even clear if **neutrinos and antineutrinos** are really different particles. Their charge is the same and they have no magnetic dipole moment, contrary to other neutral particles like the neutron for example.



See: W. Rodejohann, Neutrino-less Double Beta Decay and Particle Physics,
Int. J. Mod. Phys. E20 (2011) 1833

The definitive answer will come from experiments searching for what is called **double-beta decay**:

- They deal with nuclei where **two beta decays happen simultaneously** to reach the valley of stability.
- If neutrino and antineutrino are really the **same particle**, one of them can arrange the lepton number of the other one, such that there are no neutrinos emitted in the process.
- If they are **not identical**, two neutrinos must always be emitted in the process of double beta decay.
- For a **recent review** of the experimental situation, please see the article by W. Rodejohann.

Weakly interacting states:

Family	Generation 1	2	3
Neutrinos	ν_e	ν_μ	ν_τ
Leptons	e	μ	τ
Quarks Up	u	c	t
Quarks Down	d'	s'	b'

Attention: ν_e, ν_μ are ν_τ mixtures of the real particles ν_L, ν_M, ν_H.
d', s', b' are mixtures of the real particles d, s, b.

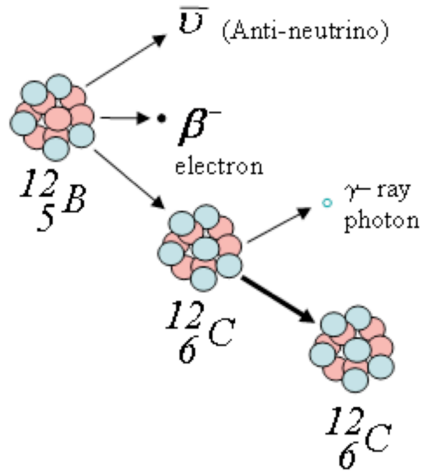
Weak interactions have two more particularities:

- Only the **left-handed part of quark and lepton fields** participate in the interaction. What we mean by that is that only matter particles with spin antiparallel to the direction of motion interact via the weak force. The opposite is true for matter antiparticles: only **right-handed antiparticles**, which have their spin parallel to the direction of motion, can interact.
- Neutrinos and down-type quarks with charge -1/3 which participate in weak interactions are **mixtures** of the corresponding real particles. One denotes the neutrino mixtures with ν_e, ν_μ and ν_τ according to their generation; they are mixtures of the real particles ν_L, ν_M and ν_H. The quark mixtures are denoted d', s' and b' for the three generations, mixtures of the real quarks d, s and b.

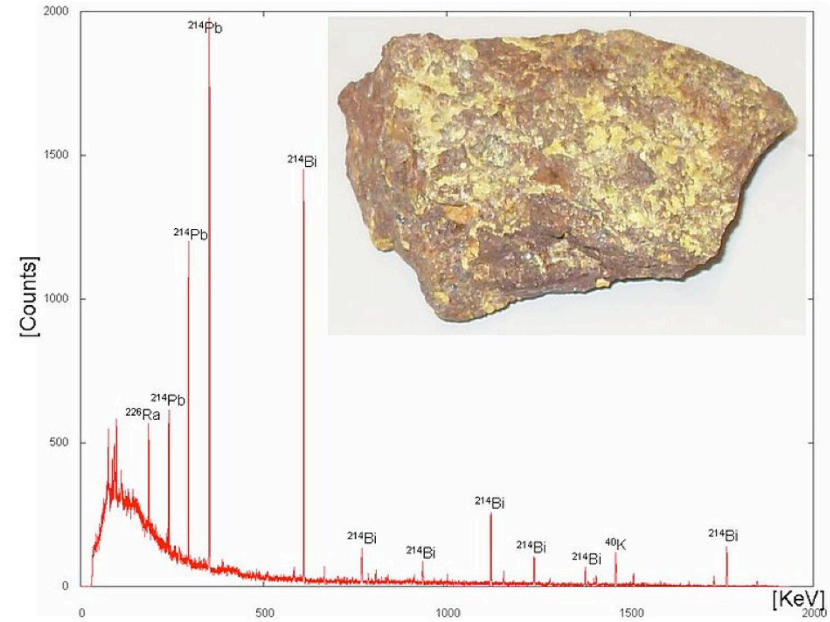
We will come back to these astonishing properties in Module 6.

What I mean by **participating in weak interactions** is that only the left-handed mixtures are able to emit or absorb weak bosons.

What I mean by **real particles** are quantum eigenstates of the mass operator. These states propagate with a specific velocity, when their energy-momentum is known. This is not the case for the ν_e and the d', for example. It is the ν_L and the d quark, which have a mass which is a constant of motion.



Let us now come to the last type of radioactivity, the **gamma decays**. They often follow another previous decay which leaves the daughter nucleus in an excited state. It can then fall back into its ground state by emitting a photon of a quantized energy. The energy of the photon will correspond to the energy difference between excited and ground state.



- The study of the emission and absorption of nuclear gamma rays thus constitutes **nuclear spectroscopy**, in analogy to atomic spectroscopy. With one remarkable difference: one cannot neglect the **recoil of the daughter nucleus** in gamma decay.
- The more massive the system, the less important will be the recoil energy. One can thus freeze the nucleus into a crystal structure, which has a much larger total mass and will recoil as a whole. This is called **Mössbauer effect**.
- It allows to reduce the line width of iron gamma decays to the order of 10^{-7} eV, which in turn allows to measure the relative line separation to an accuracy of the order of 10^{-12}. One can thus study **nuclear energy levels** with great precision.
- This can also be used to measure the **composition of materials**. We show here an example of the gamma spectrum of natural uranium mineral. It allows to identify and quantify the presence of radionuclides like ^{226}Ra, ^{214}Pb, ^{214}Bi coming from the decay chain of ^{238}U, which itself is not a gamma emitter.

In the next video we are invited to visit the laboratory of the nuclear physics course at University of Geneva to see experiments on radioactivity.