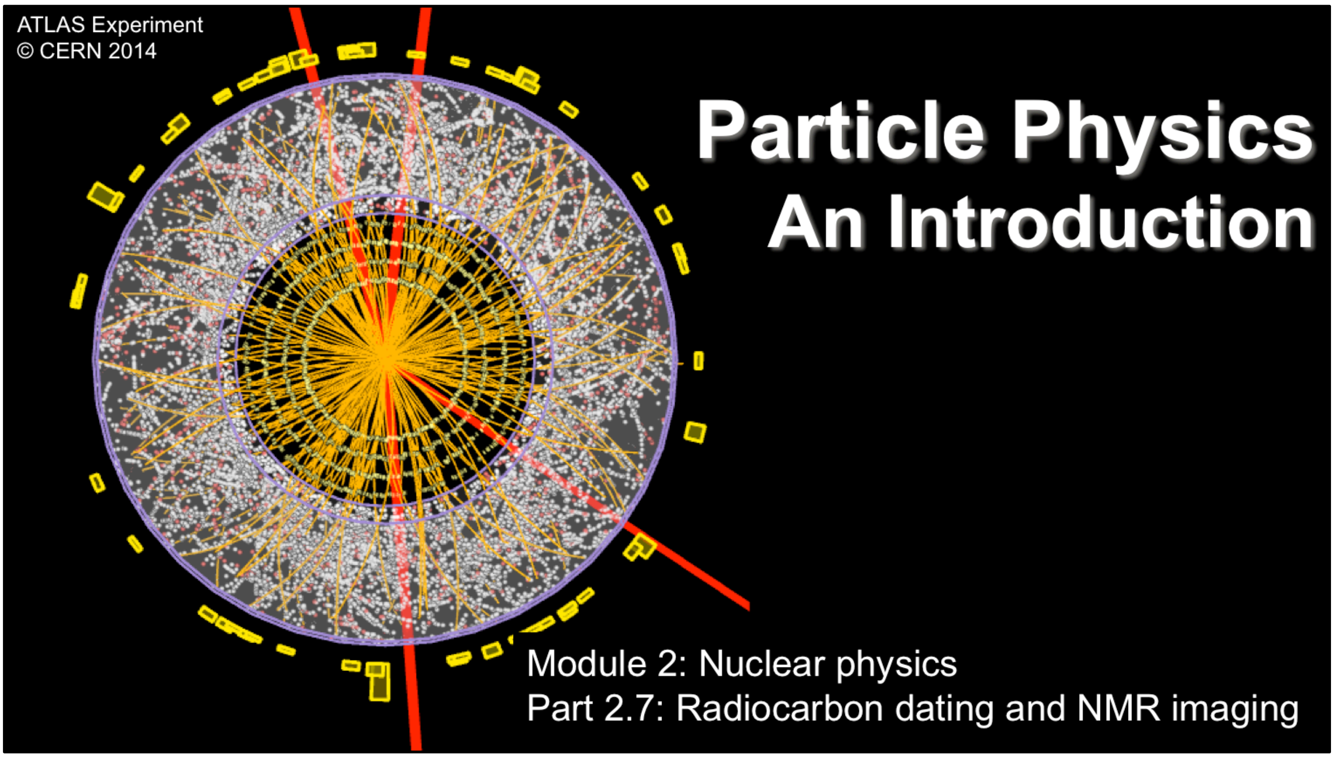


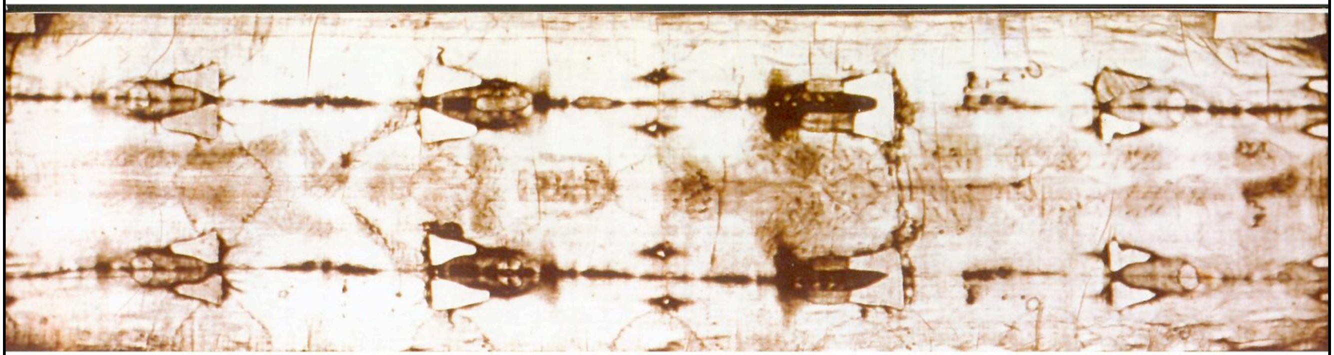
During this second module, we deal with nuclear physics. We now turn to a few examples of its applications.

In this seventh video we very briefly discuss two applications, which are radiocarbon dating and imaging by nuclear magnetic resonance.

After watching this video you will be able to:

- Describe how one determines the age of organic substances based on their contents of ^{14}C;
- Describe the principles of imaging using nuclear magnetic resonance.

Torino linen, XII- XIIIth century



- On of the important applications of natural radioactivity is the dating of organic materials by the radiocarbon method – up to several thousand years and with good accuracy.
- An example is the very controversial dating of the Torino linen, which some believe to show the body of Jesus after his death.

- Production of ^{14}C by cosmic rays:

$$^{14}\mathrm{N} + \mathrm{n} \rightarrow \ ^{14}\mathrm{C} + \mathrm{p}$$

- Today, atmosphere has $^{14}\mathrm{C}/^{12}\mathrm{C} \sim 0.67 \times 10^{-12}$

- β day of ^{14}C, life time $\tau = 8'267$ y:

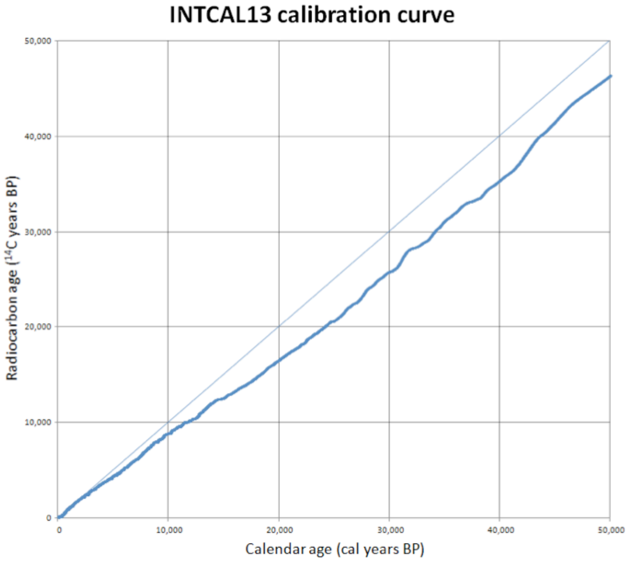
$$\begin{aligned} ^{14}\mathrm{C} &\rightarrow \ ^{14}\mathrm{N} + \mathrm{e}^- + \bar{\nu}_e \\ N_{14}(t) &= N_{14}(0)e^{-t/\tau} \quad \text{while} \quad N_{12} = \text{const} \end{aligned}$$

- Age of the sample as a function of the relative concentration $C(t) = N_{14}(t)/N_{12}$:

$$t = 8267 \cdot \ln\left(C(0)/C(t)\right) \mathrm{y}$$

Attention: $C(0)$ is the concentration of ^{14}C at $t = 0$, which varies with time.

- Our **atmosphere** contains a lot of stable ^{14}N and ^{12}C which play an important role in organic processes.
- The atmosphere is constantly hit by **Cosmic rays** of very high energy; they consist mainly of protons and helium nuclei, but also electrons, photons and neutrinos. Cosmic rays interact with atmospheric nuclei. The slow neutrons they produce among other particles can interact with ^{14}N to produce **the radioactive carbon isotope ^{14}C** in a charge exchange reaction.
- ^{14}C is a **beta emitter** with a life time of a bit more than 8'000 years.
- At any moment, our atmosphere thus contains a **majority of ^{12}C and a small quantity of ^{14}C**, both of them can form CO_2 molecules.
- Living organisms like plants consume CO_2 for their **photosynthesis** and will integrate both carbon isotopes alike. When the organism dies, the CO_2 ingestion stops.
- From then on, the ^{14}C component slowly decays, but the level of ^{12}C will stay constant. One thus uses the **relative concentration** of the two isotopes to estimate the age of fossils.



Reimer, Paula J. et al. (2013). "IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP". *Radiocarbon* **55**: 1869–1887. doi:10.2458/azu_js_rc.55.16947

- Since the concentration of ^{14}C in the atmosphere is not constant, this dating methods needs a **calibration**. The curve gives an example of the deviation from linearity of the method.

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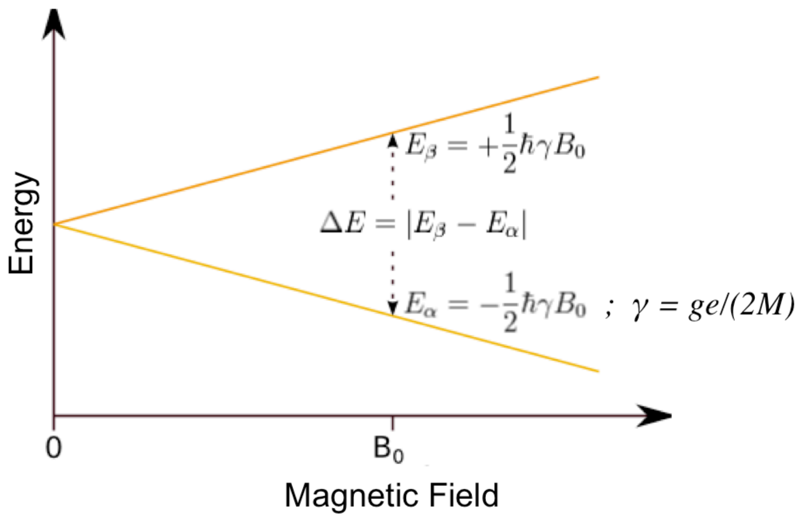

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- Let us now turn to a non-invasive **medical imaging technique** that uses nuclear spin.
- Imaging by **nuclear magnetic resonance NMR** is based on the absorption and re-emission of electromagnetic radiation via the nuclear magnetic moment.
- The sample is immersed in a **magnetic field B_0** to establish an external quantization axis. The component of the nuclear magnetic moment along this axis will be proportional to the quantum number $m_s = \pm 1/2$, the sign depending on the spin orientation.
- The associated energy is proportional to both m and B_0. The transition energy between the two orientations of the spin is $\Delta E = \hbar\gamma B_0$ with $\gamma = g\, e/2M$.
- The spin vector rotates around the magnetic axis with the **Larmor frequency** $\nu_0 = \gamma B_0/2\pi$. A photon can be absorbed by the nucleus if its frequency corresponds to this resonance, in the range of **radio frequencies** if B_0 is a few Tesla.
- This resonance can thus be used to do **nuclear spectroscopy.**

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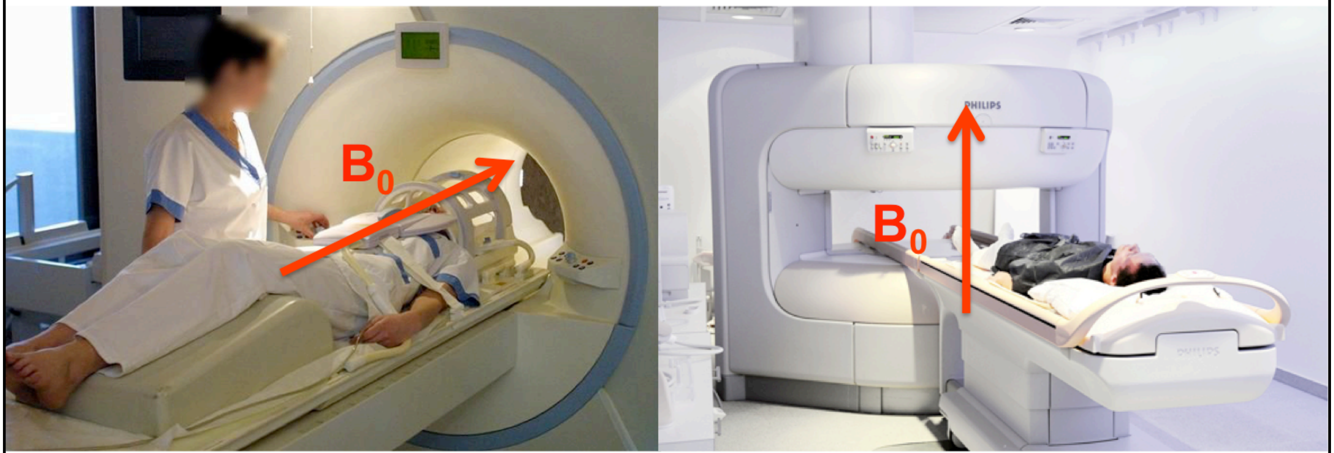
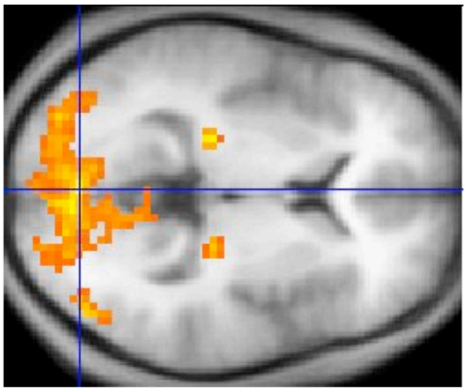


- By **varying the magnetic field** around B_0 with gradients in the *x*, *y* and *z* direction, one can correlate the resonance frequency with the position of a certain type of nucleus. The intensity of the signal is then proportional to the local density of the element. This is the principle of **nuclear magnetic resonance imaging NMR.**
- One uses the resonance frequencies of ^{1}H, ^{23}Na or ^{31}P to obtain an image of the internal structure of the body. Most often hydrogen is used to obtain access to the density distribution of liquids and soft tissue, which are difficult to render by classical tomography.
- The patient is introduced into a **solenoidal magnet** or **between two Helmholtz coils**, which provide the field B_0 of typically a few Tesla. Additional coils adapted to the body region under examination provide the **magnetic field gradient**.
- A **pulsed radiofrequency signal** is then applied and its absorption by the tissue is analyzed by Fourier analysis. The height of the Fourier peak at the resonance frequency measures the **local density** of the chosen nucleus.
- After a characteristic **relaxation time**, between millisecond and second, the RF signal is restored. This time delay can reveal additional tissue properties.

- One obtains an image with a **typical resolution of order millimeters** and a very good contrast.
- In addition, the image shows the **soft tissue**, difficult to visualize by classical X-ray radiography.



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- The mechanism of nuclear magnetic resonance even allows for a **functional imaging** of organs. This is due to the magnetic properties of **hemoglobin**, which transports the oxygen in our blood. Hemoglobin is found in two different forms:
    - The red blood cells which are **oxygenized** by lungs contain oxyhemoglobin, a molecule **inactive** in NMR.
    - The red blood cells which have **delivered their oxygen** to the tissue contain deoxyhemoglobin, which is a paramagnetic molecule. This means that under the influence of the external magnetic field it will acquire a magnetization **detectable** by NMR.
- **Brain activity** for example causes characteristic dynamics in blood flow and composition. In active brain zones, where the neurons are stimulated, one observes simultaneously a higher oxygen consumption and a higher local blood flow. The increase in blood flow is more important than the local consumption of oxygen. This corresponds to a relative decrease in deoxyhemoglobin, which can be used to localize brain activity.

In the next video, we will present another important application: the physical principle of energy release in nuclear fission, currently furnishing about 10% of the global electrical energy consumption.