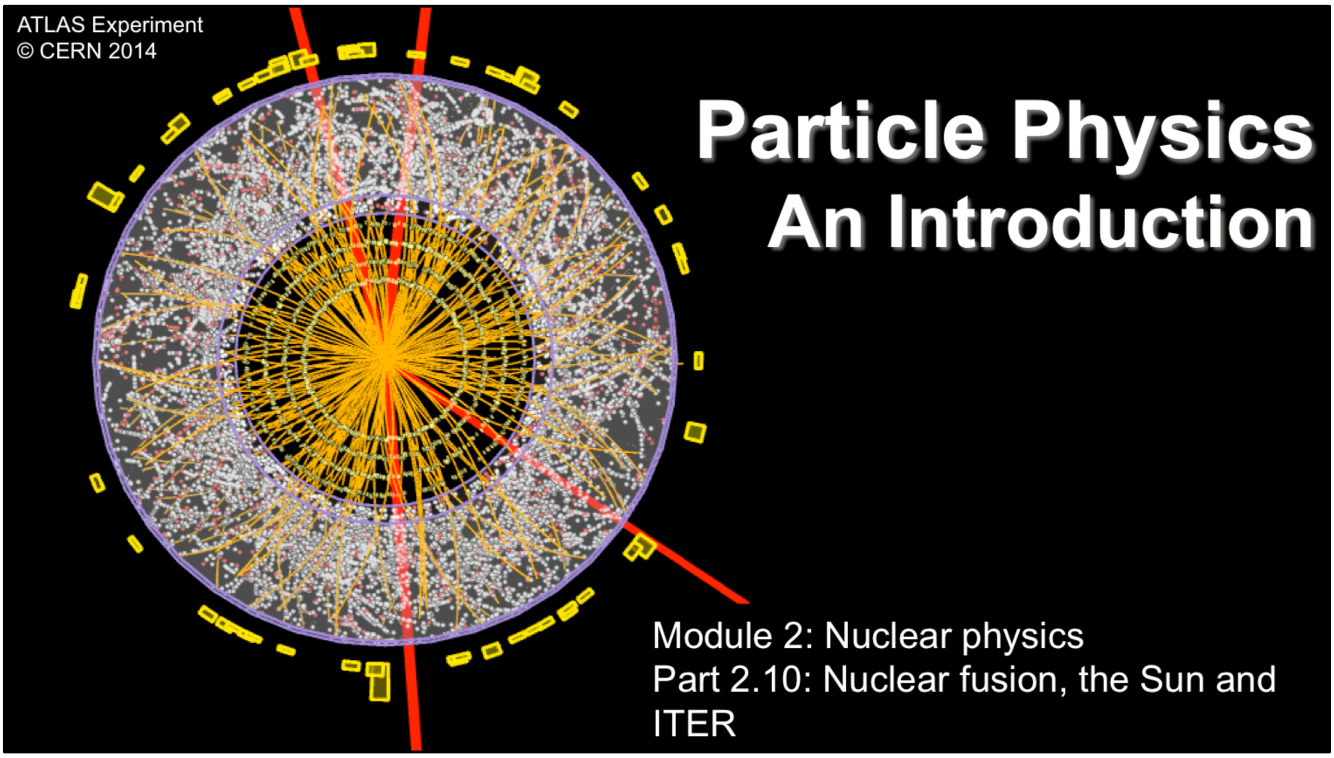
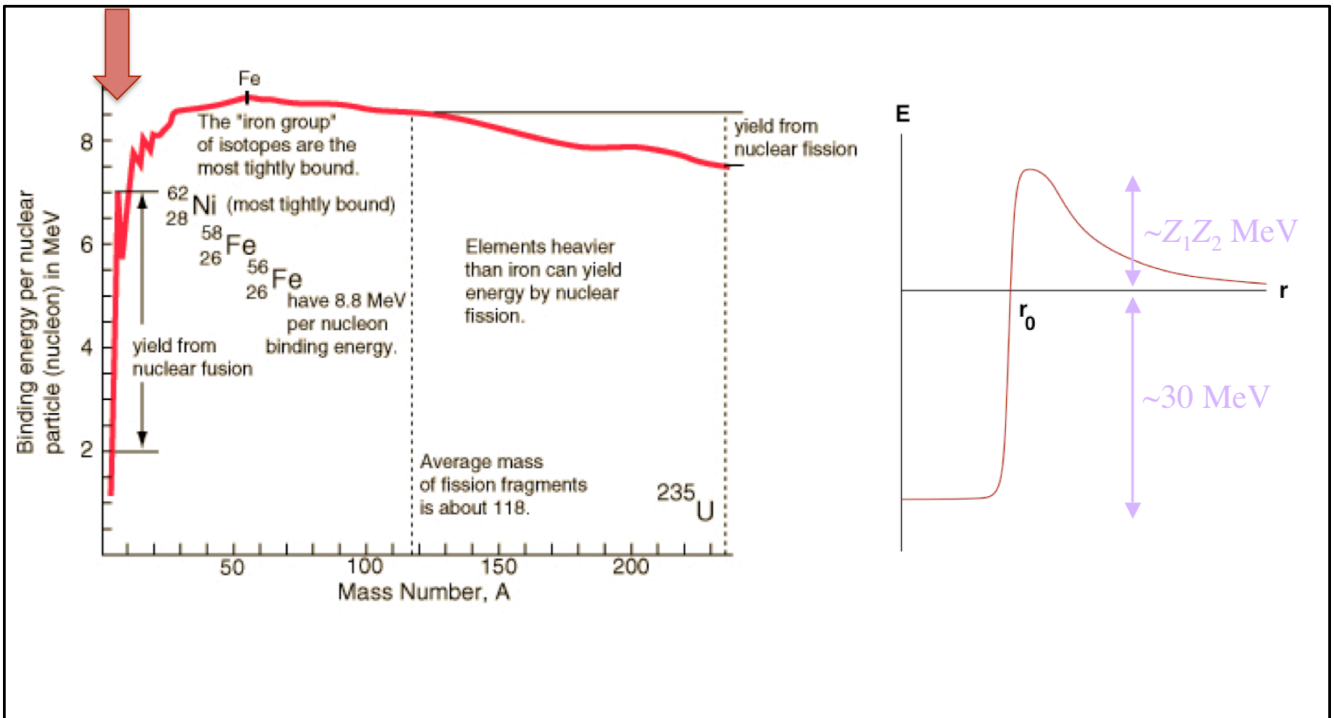


During this second module, we deal with nuclear physics and its applications.

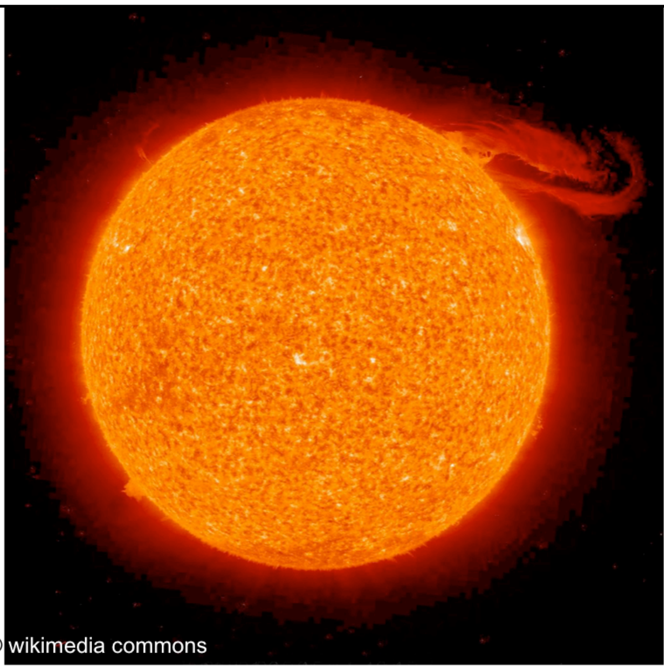
In this 10th video we show how a portion of the nuclear binding energy can be transformed into heat by fusion.

The goals are:

- To know the principle of energy release by nuclear fusion;
- To know how the stars use fusion to produce energy and heavy elements;
- To know the applications of these principles in future power plants.

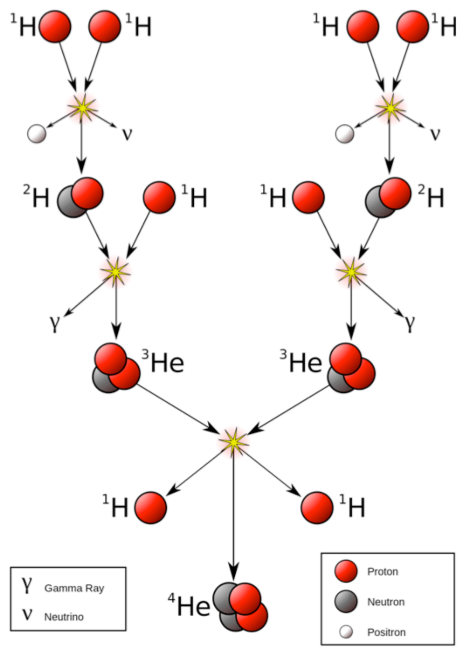


- Let us return to the spectrum of the **binding energy per nucleon** as a function of *A*. We see that there is a maximum for $A \cong 60$, around iron. For lighter nuclei, the dependence of the binding energy on *A* is much stronger than for heavier nuclei. The light nuclei are generally less strongly bound (except for doubly magic nuclei like ^{4}He) and their **binding energy increases fast with *A***.
- One can therefore use the strong *dBE/dA* of light nuclei as a source of energy by fusion. The yield of energy per nucleon is greater than for fission, but the yield per nucleus is smaller due to the low *A*.
- In any case, the **natural abundance of the light elements** makes it an interesting process. In particular, the fusion of light elements is the energy source in stars.
- In principle fusion can occur when two light nuclei are **close enough together** so that they merge. For this they must overcome the **Coulomb barrier**. The maximum potential is reached when the two nuclei just touch. For $A \cong 8$ this maximum potential is of the order of 4 MeV. A kinetic energy of a few MeV overcomes the barrier.



NASA Stereo satellite © wikimedia commons

- One must thus heat nuclei to very high temperatures so that they can overcome the Coulomb barrier. To estimate this temperature, say that each nucleus must have a kinetic energy of 2 MeV, which corresponds to ***T = E/k*** **≅ 10^{10} K**, with the Boltzmann constant k=8.6×10^{-5} eV / K.
- Typical temperatures inside the Sun and other stars are of the order of 15 MK = 1.5×10^{7} K, but the **tail of the Maxwell distribution** of the Sun's spectrum reaches far enough for fusion to take place.
- Currently, in the heart of the Sun, every second about **627 million tons of hydrogen** fuse to produce ±622.7 million tons of helium. The difference in mass of 4.3 million tons of hydrogen (of the order of the mass of the Giza pyramid) is equivalent to the luminous energy produced (4×10^{26} joules).
- The Sun will still burn for **~10^{9} years** before running out of fuel.

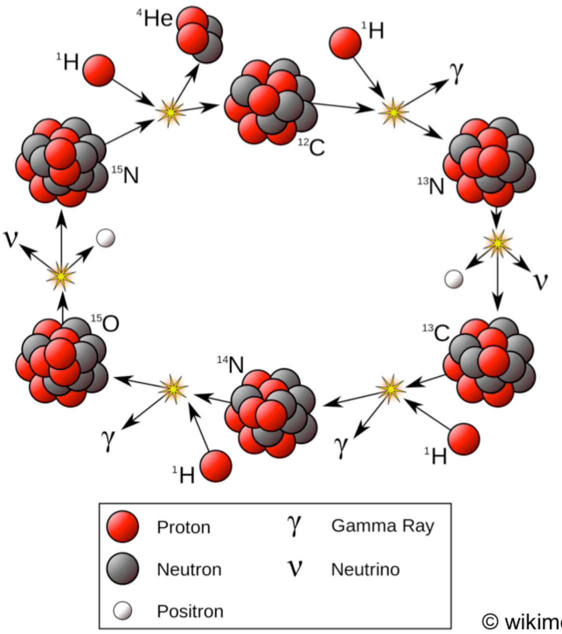


$$^{1}\text{H} + {}^{1}\text{H} \rightarrow {}^{2}\text{H} + e^{+} + \nu_e + 0.42\text{MeV}$$
$$^{1}\text{H} + {}^{2}\text{H} \rightarrow {}^{3}\text{He} + \gamma + 5.49\text{MeV}$$
$$^{3}\text{He} + {}^{3}\text{He} \rightarrow {}^{4}\text{He} + 2\,{}^{1}\text{H} + 12.86\text{MeV}$$

$$4\,{}^{1}\text{H} \rightarrow {}^{4}\text{He} + 2e^{+} + 2\nu_e + 2\gamma + 24.68\text{MeV}$$

$$3\,{}^{4}\text{He} \rightarrow {}^{12}\text{C} + 7.27\text{MeV}$$

- Ideal conditions for nuclear fusion prevail **within stars**. An example is the Sun: weight ~ 10^{30} kg, mainly in the form of ionized hydrogen.
- The main source of the Sun's energy is the **hydrogen combustion**, the p-p cycle, shown in this schematic.
- The large energy release in the 3rd stage is due to the fact that the **helium nucleus is doubly magic** and extremely tightly bound. In total a cycle fuses 4 hydrogen nuclei to produce two positrons, two neutrinos, two photons and 24.68 MeV of kinetic energy.
- **Positrons** annihilate with ambient electrons and contribute to the total energy released. **Photons** can also interact with stellar matter and deposit their energy. **Neutrinos** escape.
- **Helium** produced in the p-p cycle can then produce **carbon** through a double fusion.



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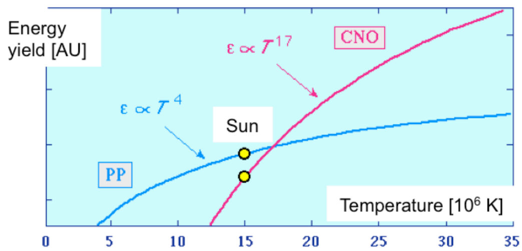
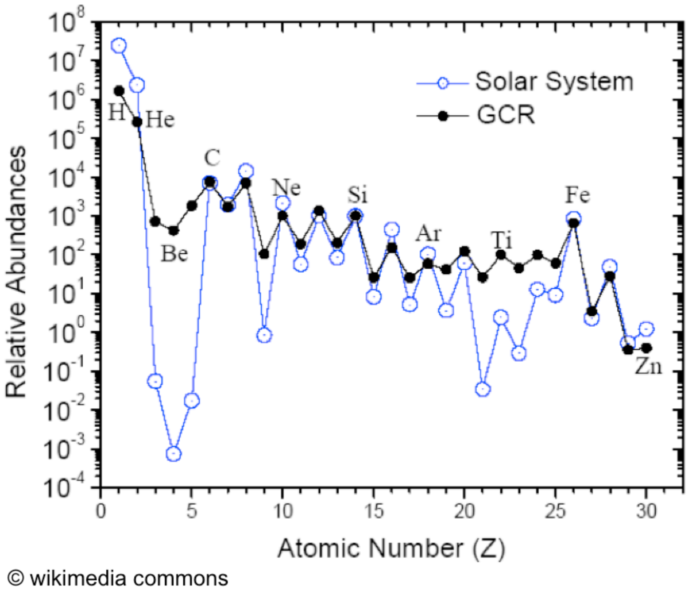
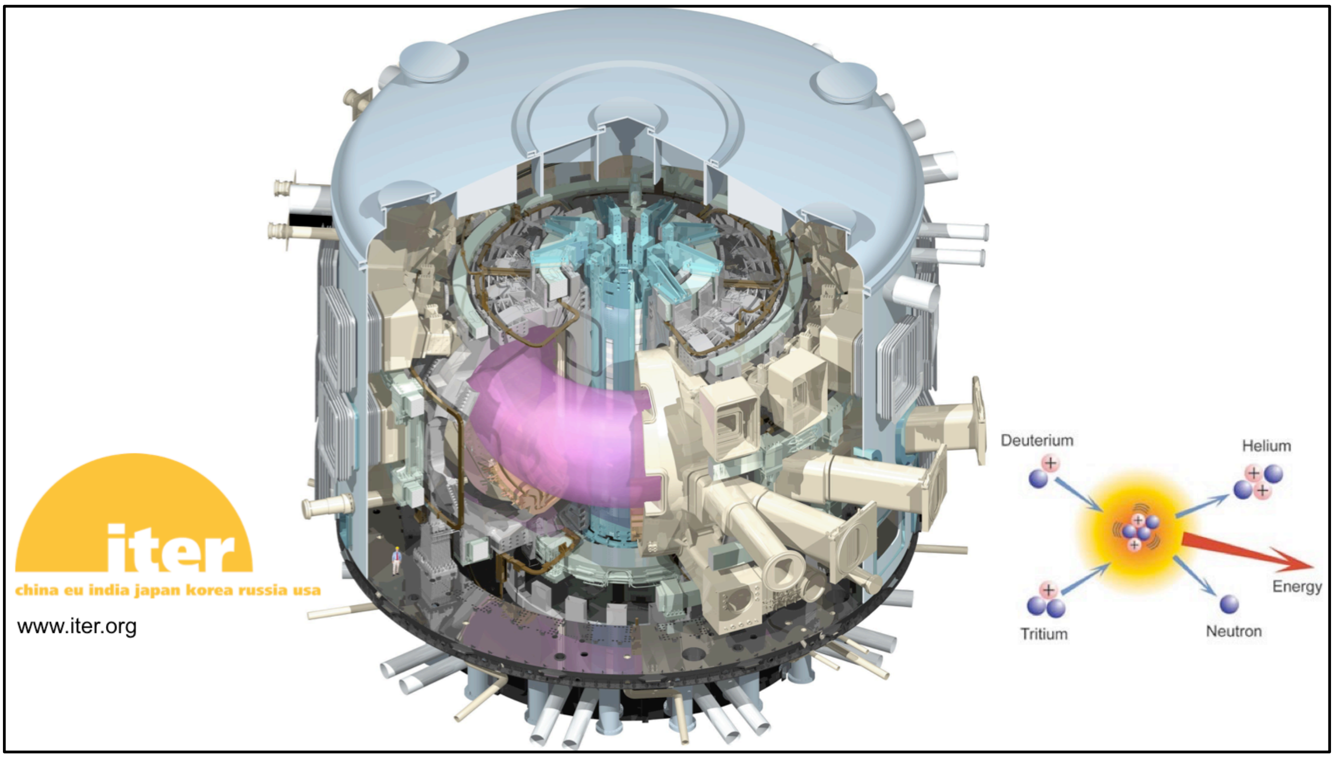
$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{1}\mathrm{H} &\rightarrow {}^{13}\mathrm{N} + \gamma + 1.95\mathrm{MeV}\\
{}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu_e + 1.20\mathrm{MeV}\\
{}^{13}\mathrm{C} + {}^{1}\mathrm{H} &\rightarrow {}^{14}\mathrm{N} + \gamma + 7.55\mathrm{MeV}\\
{}^{14}\mathrm{N} + {}^{1}\mathrm{H} &\rightarrow {}^{15}\mathrm{O} + \gamma + 7.34\mathrm{MeV}\\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu_e + 1.68\mathrm{MeV}\\
{}^{15}\mathrm{N} + {}^{1}\mathrm{H} &\rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He} + 4.96\mathrm{MeV}
\end{aligned}
$$



- For the synthesis of **heavy elements** in stars, the **CNO cycle** (also called carbon cycle) is fundamental. For stars heavier than the sun, it is also a dominant energy source.
- **Nitrogen and oxygen** are produced in this cyclic exothermal reaction.
- In addition, positrons and photons are emitted by the process. The neutrinos escape from the star, often without interacting.



- **Elements up to iron** are abundantly cooked inside stars following similar cycles.
- Even beyond, the chain does not stop, **all stable and unstable elements** can be produced under favorable conditions.
- One finds elements up to iron and beyond in **cosmic rays** from stars exploding in supernovae.
- Their **chemical composition** is however modified by interaction with the interstellar medium. For example, the Li-Be-B group is enriched by the spallation of heavier nuclei. In general, the abundance of **odd nuclei** is more important in cosmic rays that inside stars.
- Our **experiment AMS**, a large spectrometer which takes data on the International Space Station for several years now, measures the chemical composition of cosmic rays as a function of their energy with high precision. This will enrich our knowledge on the origin and propagation of these particles.



- There is a substantial global effort to achieve man-made **nuclear fusion under controlled conditions**.
- Various **fusion processes between deuterium and tritium** have been observed in laboratory conditions. The most important one is ${}^{2}H + {}^{3}H \rightarrow {}^{4}He + n + 17.6$ MeV.
- The main difficulty for a fusion reactor is to maintain the fuel long enough at sufficiently high temperature so that it can penetrate the Coulomb barrier often enough. One can contain hot plasma in two ways:
  - By magnetic confinement where the plasma flows in a helical orbit;
  - Or by inertial confinement, where electromagnetic energy (via lasers or heavy ions) is injected into a small area that contains the fuel.
- **ITER**, the International Thermonuclear Experimental Reactor, is the largest current project, with the aim of demonstrating fusion energy production. The reactor is being built in the south of France.

- In the next two videos we will take you to visit the experimental Tokamak reactor at EPF Lausanne and the world's oldest working nuclear power plant in Beznau.