SOLAR FUSION

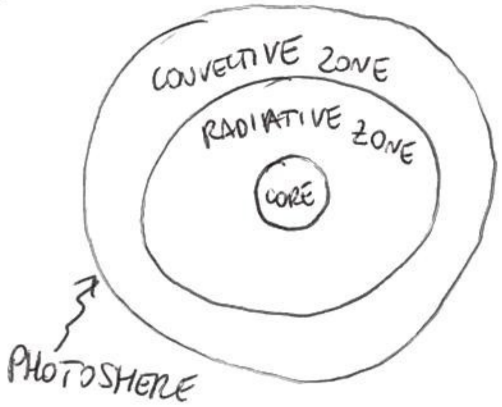
According to fossil records the sun output has been nearly constant over a timescale of more than 10^9 years

The basic process in the sun (and other stars) is H+H → He fusion process.

H is the most abundant material in the Universe ($\simeq$ 90% is made of H, 9% is He, 1% all the other nuclei). (Helium was formed during early stages of the evolution of the Universe and not as a result of later stellar processes).

All reactions in fusion MUST BE two-body reactions, because the simultaneous collisions of 3 is too improbable.

The fusion takes place in the CORE of the sun:



R = Radius of the Sun

$R_{core} \lesssim 0{,}25\,R$

$0{,}25 \lesssim R_{RAD} < 0{,}75\ R$

$0{,}5 \lesssim R_{CONV} < R$

$R_{PHOTOSPHERE} \equiv R$

The temperature of the core of the Sun is $T_{CORE} \simeq 10^7\,K$, ($T_{core} \ll 150\,keV$), but $Pressure \simeq 200 \cdot 10^9$ atm ⇒ Fusion is rather probable. After, the created energy moves throught the surface. The whole process can last 1000 years...

Let's see what happens insdide the core.

The first step is p+p fusion to create a stable nucleus

$$^1H + {^1H} \rightarrow {^2H} + e^+ + \nu \qquad (Q = 1{,}44\ MeV)$$

The lightest "stable" nucleus is deuteron ⇒ 1 p should transform into a n ⇒ β process simultaneous to the creation of d. Two processes have to happen simultaneously. the cross-section of the process is $\simeq 10^{-33}$ b at keV energy and 10^{-23} b at MeV energy.

$T_{core} \cong 1{,}5 \cdot 10^7$ K $\Rightarrow E_{K,p} \doteq 1$ keV

The reaction rate of the reaction is 5×10^{-18} /s/proton

But in the core of the Sun there are $\simeq 10^{56}$ protons $\Rightarrow$ The reaction rate is $\simeq 10^{38}$/sec. This step of solar fusion cycle is called "Bottle neck", because is the slowest and lost probable step.

But, once d are formed it becomes very likely that the following reaction occur:

$$^2H + {}^1H \rightarrow {}^3He + \gamma \qquad Q = 5{,}49\ MeV$$

a $^2H + {}^2H$ reaction at this point is very unlikely because a deuteron is formed every $\simeq 10^{18}$ protons, thus this process is 10^{18} times more likely. Deuterons are thus cooked to ^3He nearly as rapidly as they are formed.

The following reaction:

$$^3He + {}^1H \rightarrow {}^4Li \rightarrow {}^3He + {}^1H$$

is not possible, since ^4Li does not exists as bound state and breaks up as soon it is created. Also the reaction $^3He + {}^2H$ is unlikely since ^2H are converted rapidly into ^3He.

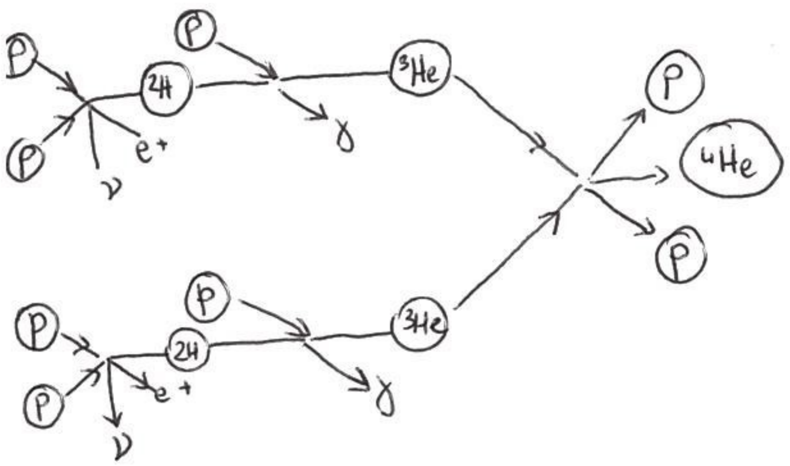
Thus the fate of ^3He is to wait for an other ^3He:

$$^3He + {}^3He \rightarrow {}^4He + 2p + \gamma \qquad Q = 12{,}86\ MeV$$

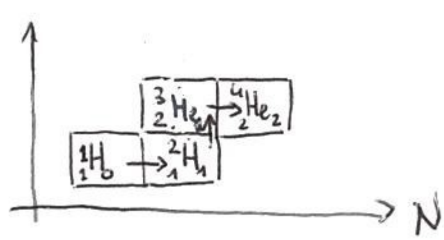
This process happens in the 85% of cases.

The complete process is called "proton-proton cycle". The net reaction is the conversion of 4 protons into an Helium

$$4 \cdot {}^1H \rightarrow {}^4He + 2\nu + 2e^+ \quad (+2p)$$



pp 1 chain



To find the Q-value we must keep in mind that we have also electrons from γ annihilation, so the Q value = 26,7 MeV.

An alternative fate for ^3He is to encounter one α ptc (15%)

$$^3He + {^4He} \rightarrow {^7Be} + \gamma$$

In the 14,9% of the time the reaction is followed by:

$$^7_4Be + e^- \rightarrow {^7_3Li} + \nu_e$$

$$^7_3Li + p \rightarrow {^8_4Be} + \gamma$$

$$^8_4Be \rightarrow 2\,{^4He}$$

This process is called pp-II chain

Alternatively

$$^7_4Be + p \rightarrow {^8_5B} + \gamma \qquad \text{pp-III chain}$$

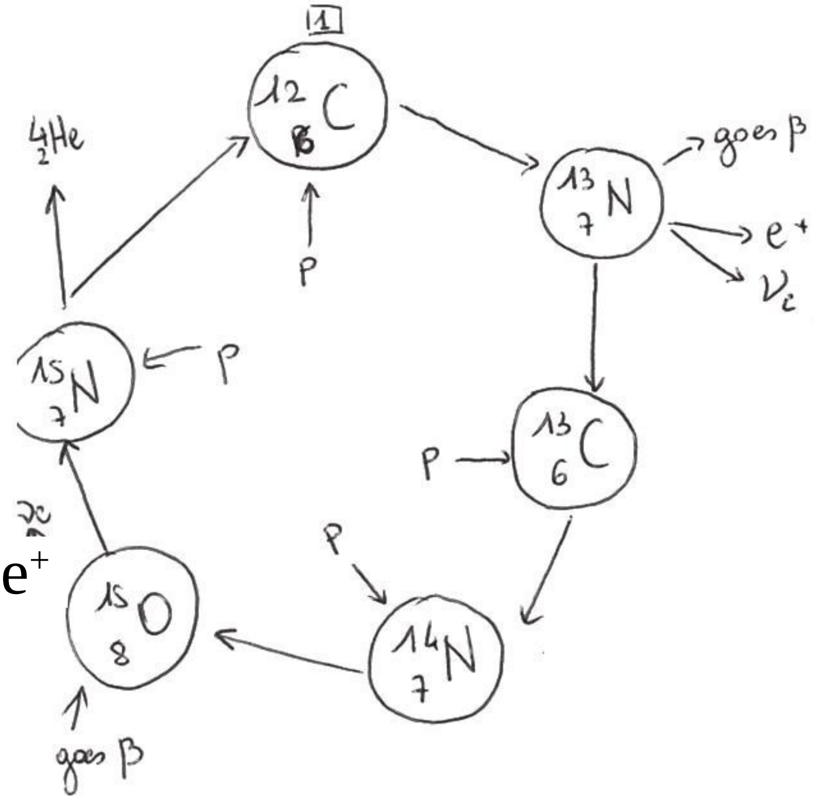
$$^8_5B + e^- \rightarrow 2\,{^4He} + \nu_e$$

The Q value also in these cases is the same, because initial state are 4 protons and final state a ^4He.

An interesting fact about these reactions, is that in each reaction some ν are produced, and they are used to "monitor" the health of the Sun (Let's suppose it suddenly stops to burn ^1H: we won't note any difference for at least 10^4 y on the "visible" effect, but 8 minute after that happens we will notice that no ν are produced anymore and we can understand that something is going on..)

If in addition to H and He the star has heavier elements, a different chain can take place. *

This is called C-N-O or carbon cycle



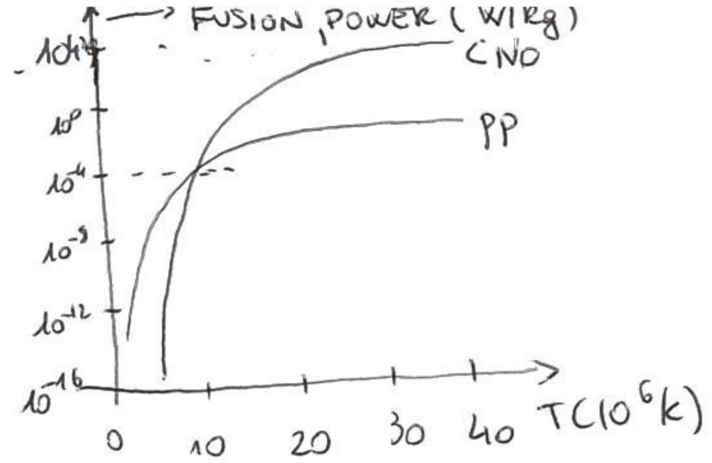
In this core the $^{12}_{6}C$ is neither created nor destroyed, but acts as a catalyst to aid in the fusion process. The net process is

$$4\,^{1}H \rightarrow {}^{4}He + 2\nu_e + 2e^+$$

exactly as in p-p chain => Q value is the same.

The carbon cycle is "faster" since no deuteron-bottleneck is present. However, the Coulomb barrier is 6-7 times higher for protons reactions with $^{12}_{6}C$ an $^{13}_{7}N$ than for a pp reaction.

CNO cycle dominates at higher temperature, where additional thermal energy is needed to penetrate Coulomb barrier.



The mean solar radiation reaching the Earth is $\simeq 1{,}4 \times 10^3$ W/m^2

$\Rightarrow$ Total sun output $= 4 \times 10^{26}$ W.

Each fusion releases $\simeq 25$ MeV $\Rightarrow 10^{38}$ fusion × second must be present

This implies that 4×10^{38} protons are needed each second.

At this rate, the sun can still burn his hydrogen fuel for another 10^{10} y.

Once a star has exhausted its hydrogen fuel, Helium fusion reaction can take place, with $3\ {}^4He \to {}^{12}C$ at the higher temperature needed to penetrate the Coulomb barrier.

Other reactions involving fusion of light nuclei and α-ptc capture can continue to release energy, until the process ends near ^{56}Fe, beyond which there is no gain of energy in combining nuclei.

This simple recipe helps to explain there exists many categories of stars, and also the relative abundances of various atomic species:

- light even-Z atoms made throught a successive capture of α on ^{12}C are far more abundant than the neighboring odd-Z nuclei
- Nearly everything above Fe is less abundant than almost everything below Fe.

SLIDES ON BBN (Big Bang Nucleosynthesis)

RADIO ACTIVE TRACERS

Radioactive isotopes such as Carbon 14 can be used ~~to~~ as tracers in medicine, chemestry and biology.

For example, some type of molecules (i.e. amminoacid) can be created using radioactive atoms.

This molecule can then be injected into a biological cell and be used as amino acid in protein synthesis.

Since the amino acid is composed by unstable atoms, they can give off radiation and this can be detected by a special device.

In this way it is possible to study things like when the amino-acid end up and where the proteins are syntisided inside the cell.

Radioactive tracers form the basis of a variety of imaging systems, such as SPECT scans, PET scans and techetium scans.

Radiocarbon dating uses the naturally occurring carbon-14 isotope as an isotropic label.

SINGLE PHOTON EMISSION TOMOGRAPHY (SPECT)

It is a nuclear medicine tomographic imaging technique using gamma rays.

It is very similar to conventional nuclear medicine planar imaging using gamma camera (→ scintigraphy), but it is able to provide ~~true~~ 3D information

The technique needs delivery ~~of~~ of gamma-emitting radioisotope (a radionuclide) into a patient, normally through injection into the bloodstream.

The gamma are then detected and the image reconstructed.

Applications: Myocardial perfusion imaging
Functional brain imaging
" outside medicine: radioisotope distributions in irradiated nuclear fuels. Due to irradiation of nuclear fuel with neutrons in a nuclear reactor, a wide range of γ-emitting radionuclides are naturally produced in the field

such as fission products and activation products. These can be imaged using SPECT in order to verify the presence of fuel rods assembly, to validate predictions or to study the behaviour of the nuclear fuel in normal operation or in accident scenario

γ-emitter employed: ^{99}Tc, $E_\gamma = 140 keV$, Time x projection ≃ 25-30 for body scan

POSITRON EMISSION TOMOGRAPHY (PET)

PET is an imaging tecnique that uses radioactive substance to visualize and measure metabolic processes in the body.

PET is mainly used in the area of medical imaging for detecting or measuring changes in the physiological activities like metabolism blood flow, regional chemical composition and absorption.

In these tecnique tracers molecules are synthesized and injected into

a patient. These tracers molecules then travel the region of interest. (127)

The radioactive atoms of the tracer molecules undergo position emission (β^+ decay) and then e^+ collide with electrons in the nearby atoms (for atomic shells) producing gamma rays.

E.g. $^{11}_{6}C \rightarrow ^{11}_{5}B + e^+ + \nu$

$e^+ + e^- \longrightarrow 2\gamma$ → Which by conservation of momentum moves in opposite direction.

(Headon collision)

The 2 γ are then detected by γ-detector (≡ colorimeter)

PET scanning is non-invasive, but it does involve exposure to ionizing radiation. Fludeoxyglucose ^{18}F-FDG is the standard for PET neuroimaging and has an effective radiation dose of 14 mSi. The amount of radiation is similar to the dose of spending one year in the city of Denver (Colorado) (12 mSv/year). For comparison, radiation dosage for other medical procendure ranges from 0,02 mSv for chest x-ray and 6,5 ÷ 8 mSv for a CT scan of the chest.

Average civil aircrews are exposed to 3 mSv/years.

=> A PET-CT scan hence implys a substantial radiation dose.

SPECT and PET create imanines that descibe the biochemistry of the region of interest. They point a better picture of what is taking place in the region in term of functionality.

Radionuclides used for PET

	$t_{1/2}$
^{11}C	20 h
^{13}N	10 h
^{15}O	2 h
^{18}F	110 m
^{68}Ga	67 m
^{89}Zi	78 h
^{82}Ru	1,27 minutes

→ Not possible to ship such nuclide, but there exsist some portable generator which uses the electron capture reaction:

$$^{82}Sr + e^- \rightarrow {}^{82}Ru + \nu$$