MAJOR NUCLEAR BURNING STAGES

The Coulomb barrier is higher for heavier nuclei with high charge: The first reactions to occur are those involving light nuclei -- Starting from hydrogen burning, helium burning and then proceed to more advanced burning.

HYDROGEN BURNING

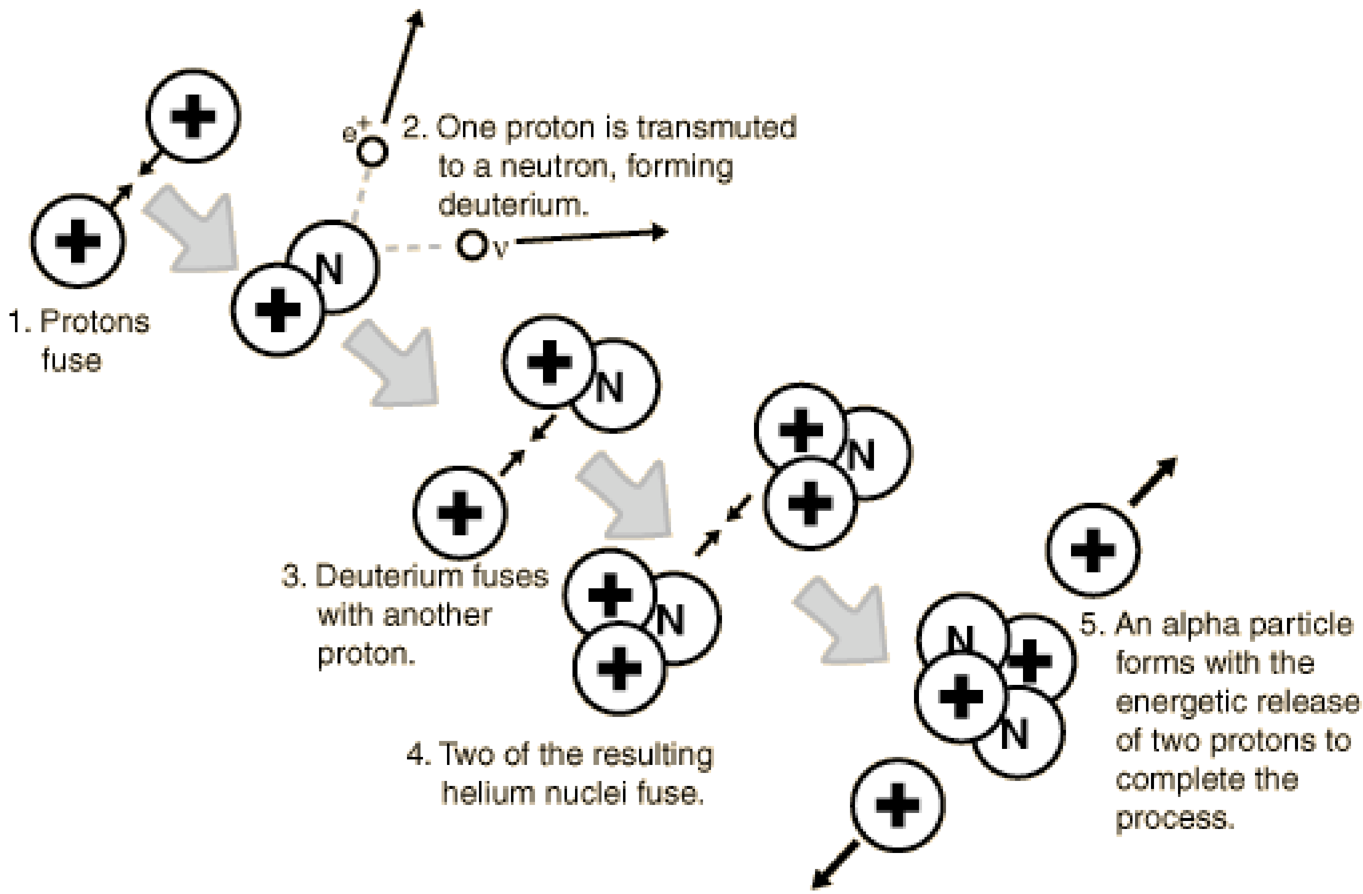
hydrogen is the most abundant element in the universe and has the lowest Coulomb barrier, so hydrogen burning is the first stage. The net- result is four H atom fused in He. The total energy released is Q = 26.73 MeV. This amounts to 0.7% of the rest mass of protons, some of this carried away by neutrinos. There are different chains of reactions by which a nuclear burning processs can occur for H there are 2 main chains: the PP chain (lower MS stars) and the CNO cycle (massive stars)

PP CHAIN

The PP chain divides into three main branches, which are called the PPI, PPII and PPIII chains.

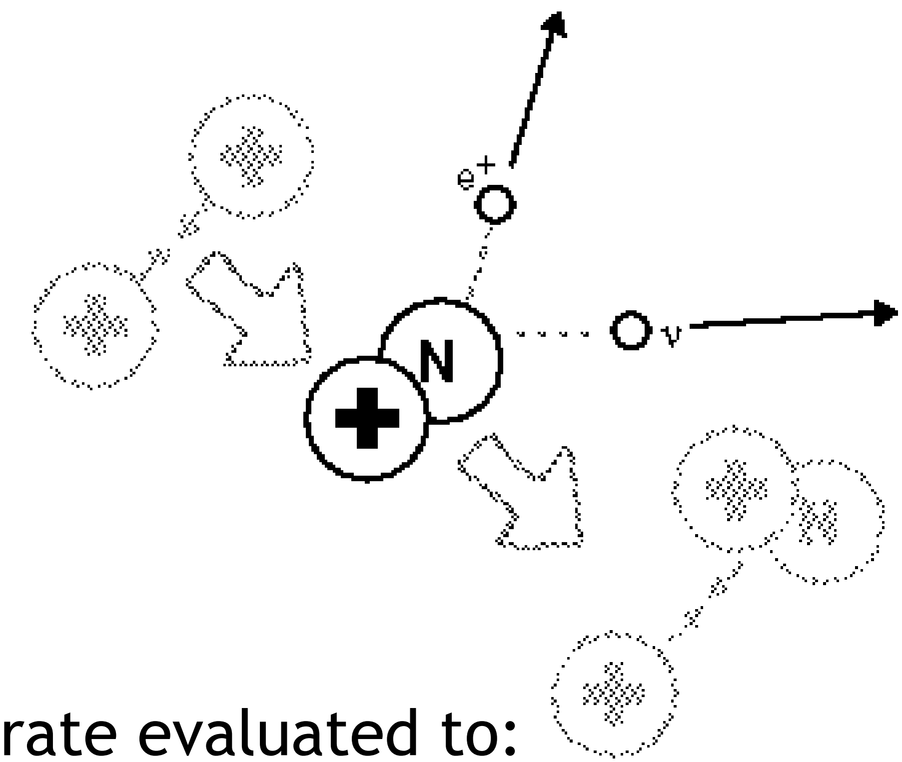
The first reaction is the interaction of two protons (p or ^{1}H) to form a nucleus of heavy hydrogen (deuteron, d, or ^{2}H), consisting of one proton and one neutron, with the emission of a positron (e+) and a neutrino (e). The deuteron then captures another proton and forms the light isotope of helium with the emission of a gamma-ray. The ^{3}He nucleus can then either interact with another ^{3}He nucleus or with a nucleus of ^{4}He (an alpha particle), which has either already been formed or has been present since the birth of the star. The former case is the last reaction of the PPI chain, whereas the latter reaction leads into either the PPII or the PPIII chain.

PPI chain	PPII chain	PPIII chain
	this starts with reactions 1 and 2	this starts with reactions 1 2 and 3'
1 $p + p \rightarrow d + e^+ \nu_e$	3' $^3He + ^4He \rightarrow ^7Be + \gamma$	4'' $^7Be + p \rightarrow ^8B + \gamma$
2 $d + p \rightarrow ^3He + \gamma$	4' $^7Be + e^- \rightarrow ^7Li + \nu_e$	5'' $^8B \rightarrow ^8Be + e^+ + \nu_e$
3 $^3He + ^3He \rightarrow ^4He + p + p$	5' $^7Li + p \rightarrow ^4He + ^4He$	6'' $^8Be \rightarrow 2\,^4He$



e+
2. One proton is transmuted to a neutron, forming deuterium.
N
v
1. Protons fuse
N
3. Deuterium fuses with another proton.
N
N
4. Two of the resulting helium nuclei fuse.
N
N
5. An alpha particle forms with the energetic release of two protons to complete the process.

Step 1: Proton-Proton fusion and deuterium formation



this reaction is slow involves weak interaction. It involved transmutation of 1 proton to a neutron. On order to form d the protons have to undergo a Beta+ decay at the time of closest approach.

the rate evaluated to:

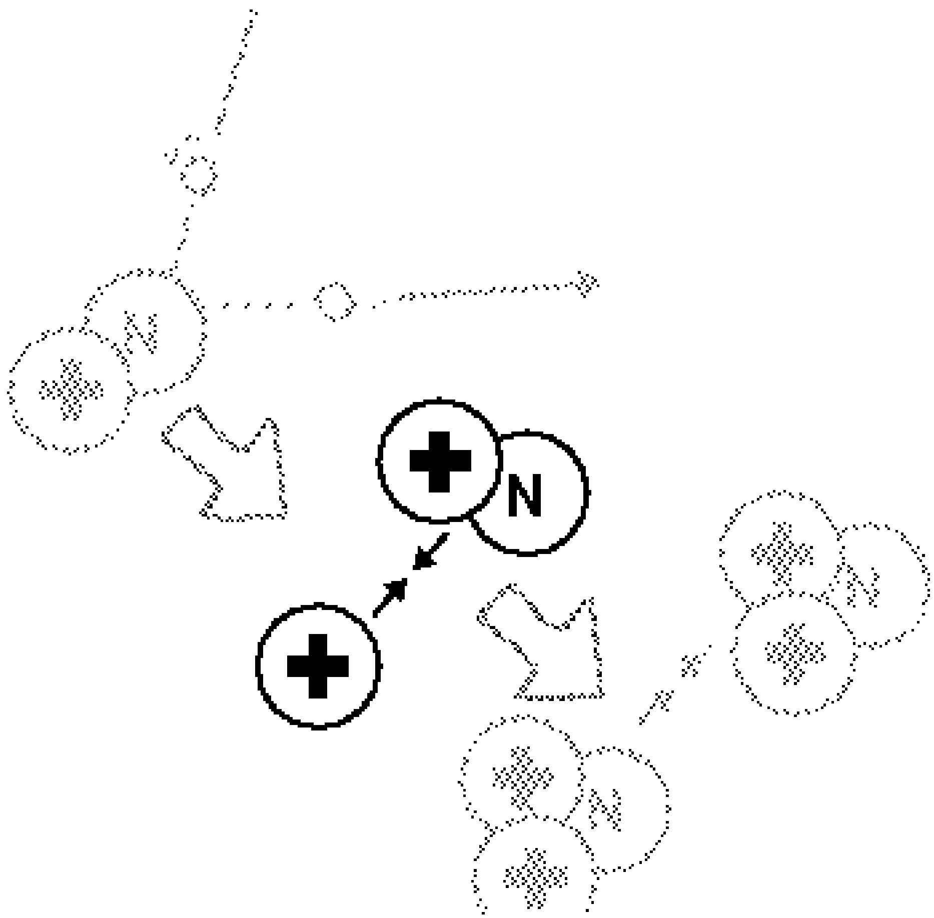
$r_{pp} = 1.15 \times 10^9\ T_9^{-2/3} X^2 \rho^2 \exp(-3.380/\ T_9^{-1/3})\ cm^{-3}\ /s$

where T_9 is the temperature in units of 10^9 K

the lifetime of a proton against destruction is:

$t = n_p/dn_p/dt\ = n_p/2\ r_{pp} = 6 \times 10^9$ yr for Solar central val.

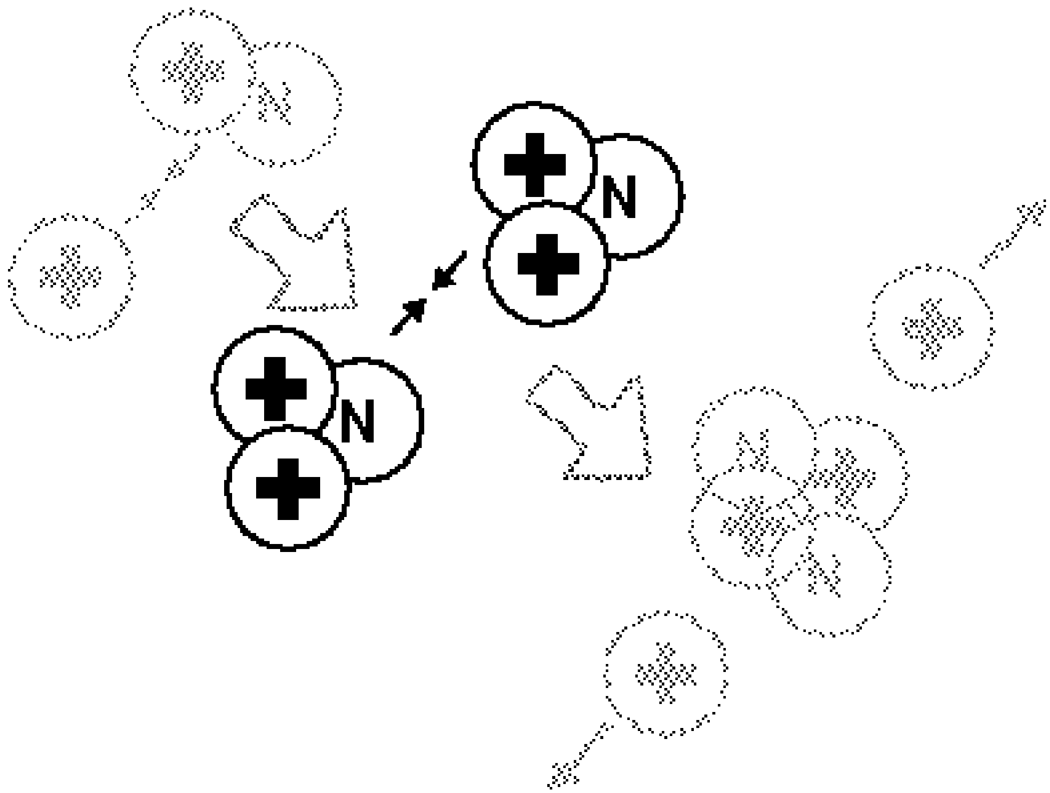
DEUTERIUM - PROTON FUSION



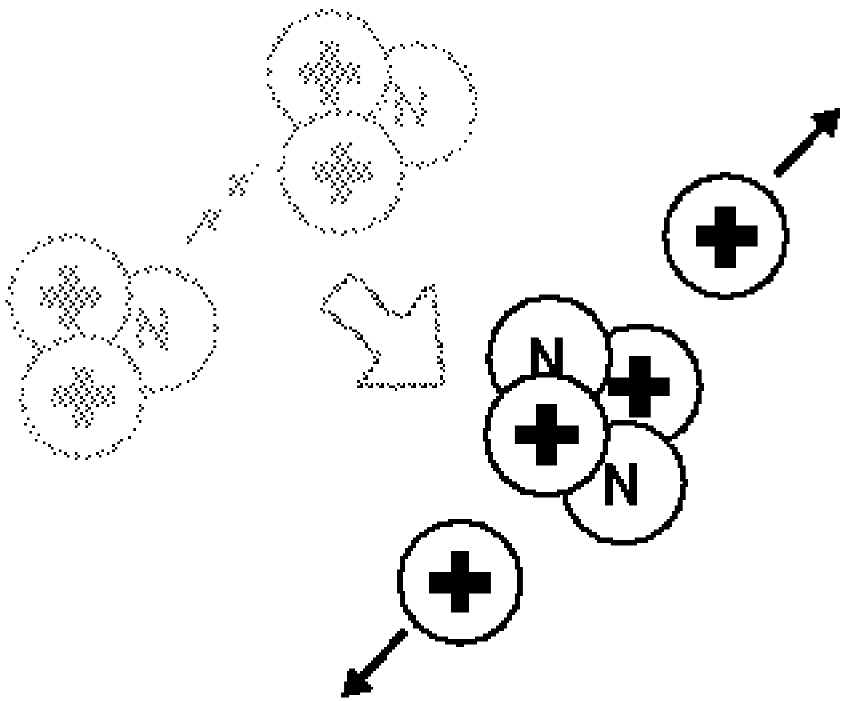
this reaction is very fast
the completion in PPI
is a He nucleus is by
fusion of 2 ^{3}He

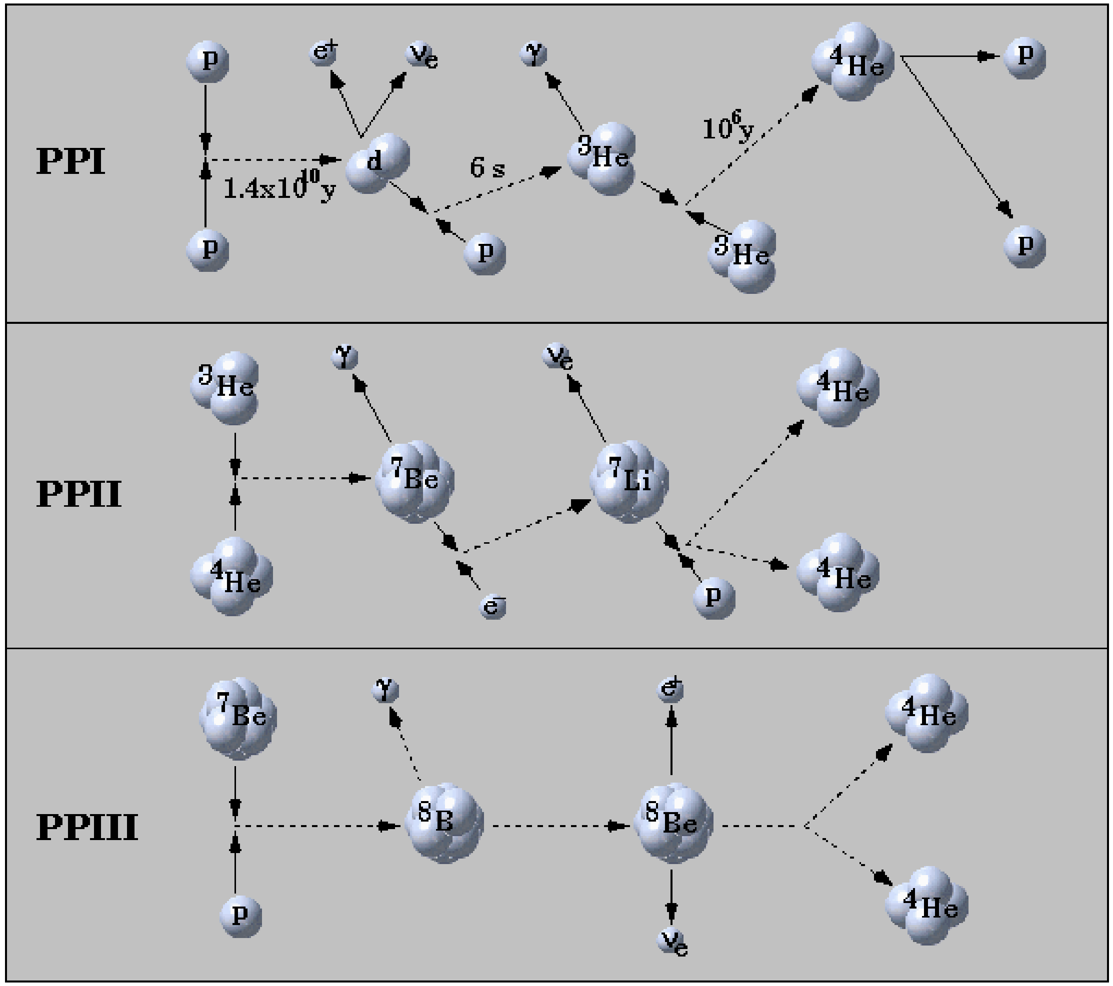
the other alternatives
require pre-existing
^{4}He

HELIUM 3 FUSION:



ALPHA-PARTICLE FORMATION





the PPI is the obvious route but it requires somewhat unlikely collision of 2 rel short lived nuclei. PPII requires splitting of nucleus that is twice as massive as helium. Relative importance of these chains depends on the abundance of He 3. Termination via PPI chain requires 2 of these nuclei to fuse so the rate of the chain varies as the square of their number density.

find:

•As T increased equilibrium abundance of He 3 decreases

•with increasing T, importance of PPI compared to PPII and PPIII decreases

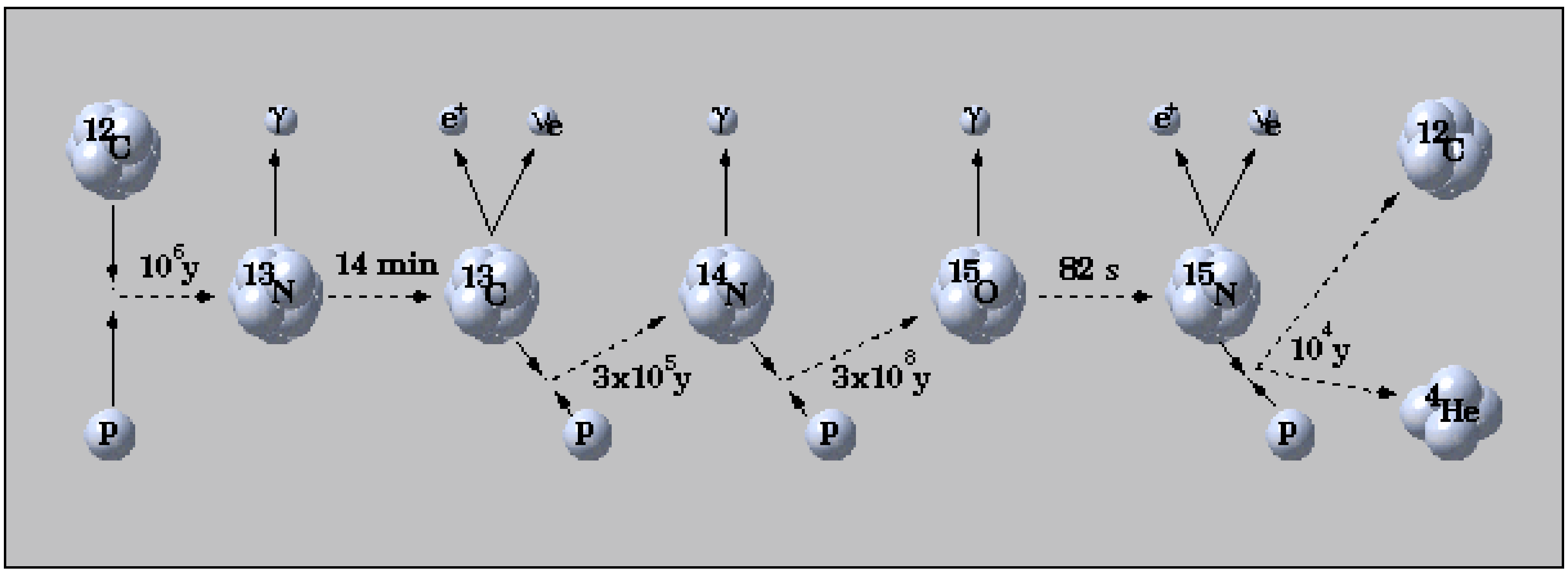
although the rate is determined by the slow initial reaction common to all three chains the exact energy yield depends of the relative importance of PPI, PPII and PPIII (because the fraction of energy lost via neutrinos is different).
The leading term is

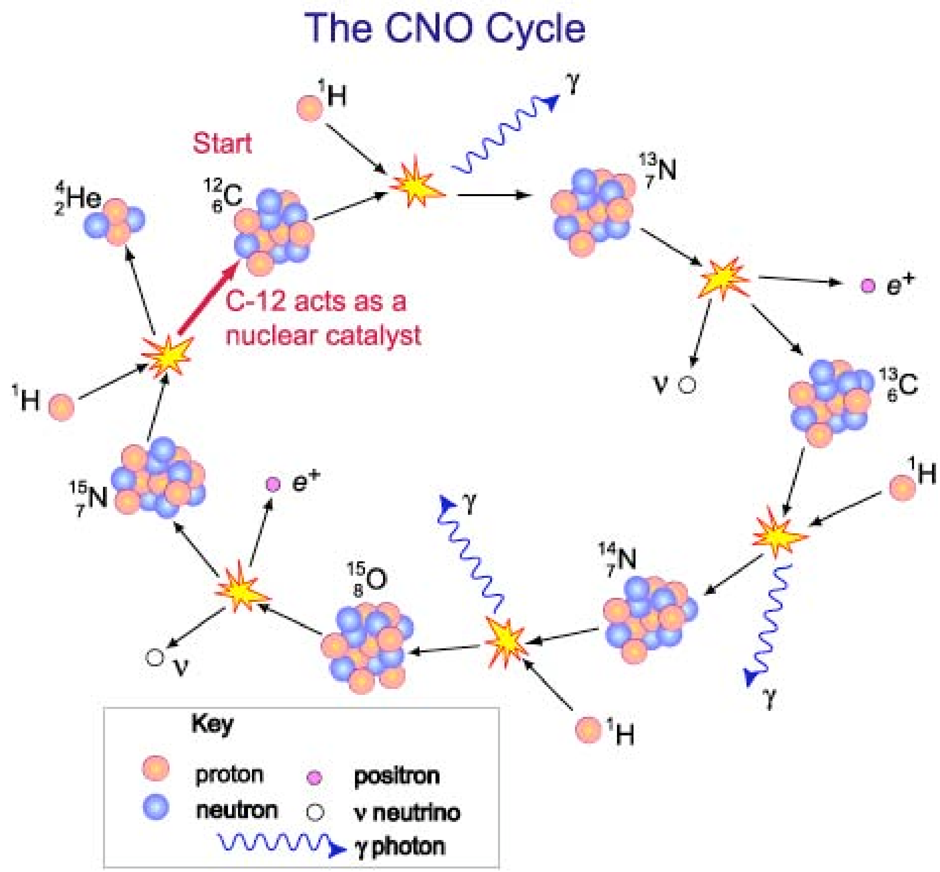
$$E_{pp} \sim 2.4 \times 10^4\, T_9^{-2/3} X^2 \rho \exp(-3.380/\ T_9^{-1/3})\ \mathrm{erg/g/s}$$

dominant temperature dependence id the exponential arising from the cross-section!

THE CNO CYCLE:

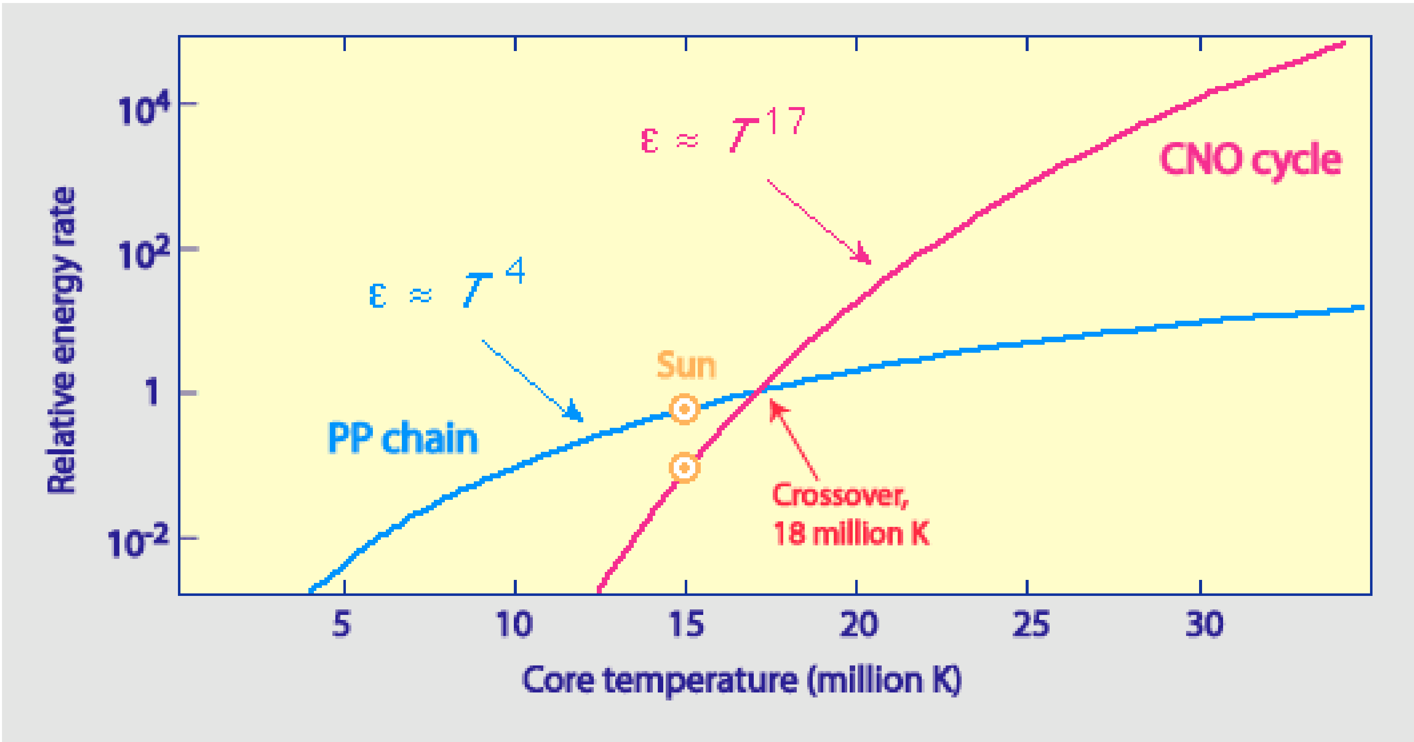
the other main route for hydrogen burning is the CNO cycle. this involves Carbon, nitrogen and oxygen nuclei in a ‘catalytic’ role (elements are not consumed instead they are recylcled and act as catalyst in the reactions).
As with the pp reactions there are several alternative routes
All basically involve a series of proton captures interspersed with positron decays.





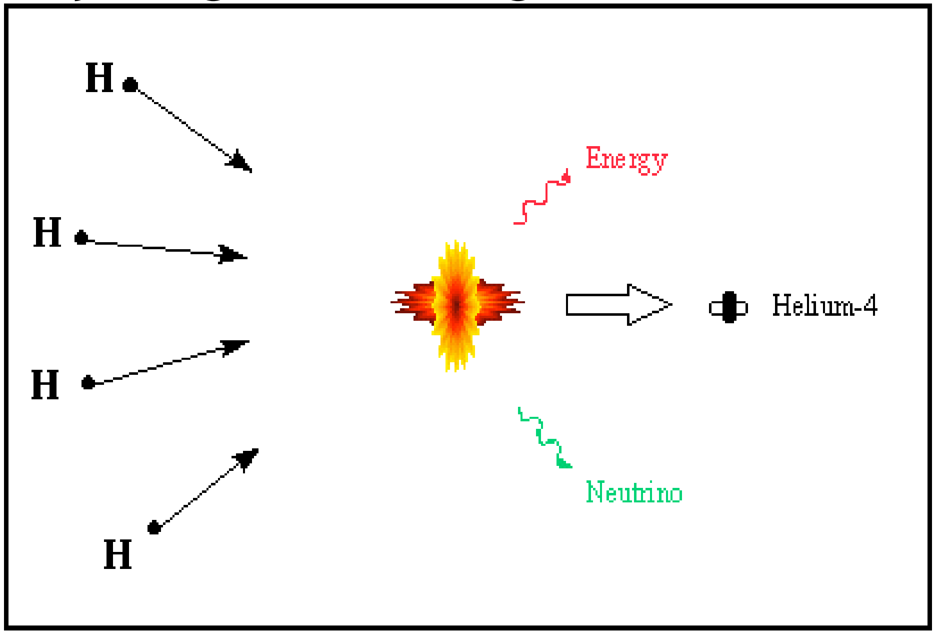
The cycle involves a total of four protons that react one after the other with the heavy nucleus (Carbon first). After the first reaction Carbon is turned into Nitrogen, then Oxygen is produced that finally decays back into Carbon emitting an alpha particle (Helium nucleus). During the cycle two neutrinos, three photons and two antielectrons are also emitted. The antielectrons will annihilate with electrons producing two more photons.

$$E_{pp} \sim 4.45 \times 10^{25}\, T_9^{-2/3}\, X\, Z\, \rho\, \exp(-15.228/\, T_9^{1/3})\ \mathrm{erg/g/s}$$

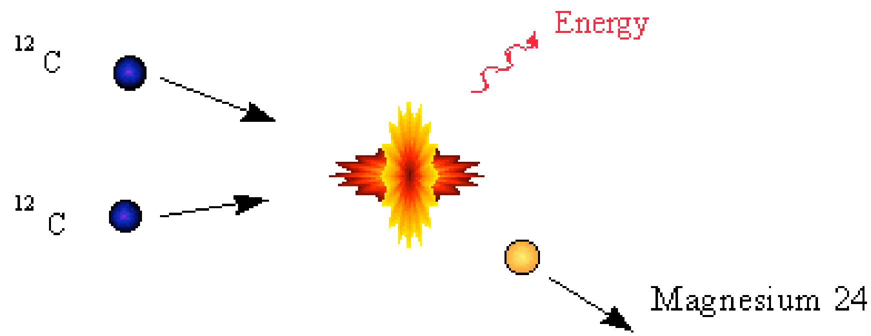


Relative energy production for the pp chain and CNO cycle. Note that at the temperature range typically found in main sequence stars, the contribution due to the pp chain is dependent on T4 whereas that from the CNO cycle is T17. Above 18 million K the CNO cycle contributes most of the energy and any further slight increase in core temperature leads to a greater increase in energy output.

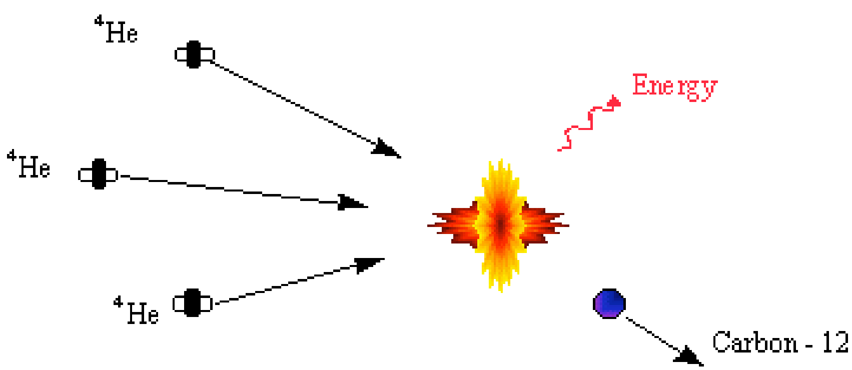
hydrogen burning

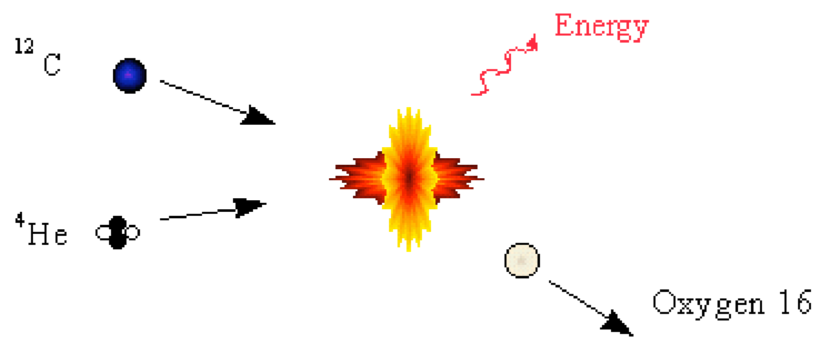


carbon burning



helium burning





HELIUM BURNING

Hydrogen burning takes most the stars active life. In the core hydrogen is converted into helium. when hydrogen is exhausted the core contracts and heats ---> the star leaves the MS.
If the core temperature reaches 10^8 K, He-burning begins
This happens for Mstar > 0.5 Msun. (Lower mass stars have insufficient gravitational potential energy to burn He their contraction is halted by electron degeneracy pressure)

The key reactions are:

$^{4}He + {}^{4}He \longleftrightarrow {}^{8}Be$ (-0.095 MeV)

$^{8}Be + {}^{4}He \longrightarrow {}^{12}C + \gamma + 7.367$ MeV

TRIPLE ALPHA REACTION $3\ {}^{4}He \dashrightarrow {}^{12}C + \gamma$

The ^{8}Be produced in the first step is unstable and decays back into two helium nuclei in 2.6 $\times 10^{-16}$ seconds. This time is short but suffcicient to build up a small equilibrium abundance of ^{8}Be; capture of another alpha particle then leads to ^{12}C. This conversion of three alpha particles to ^{12}C is called the triple-alpha process.

Ordinarily, the probability of this occurring would be extremely small. However, the beryllium-8 ground state has almost exactly the energy of two alpha particles. In the second step, ^{8}Be + ^{4}He has almost exactly the energy of an excited state of ^{12}C. These resonances greatly increase the probability that an incoming alpha particle will combine with beryllium-8 to form carbon. The fact that the existence of carbon depends on an energy level being exactly the right place, has been controversially cited by Fred Hoyle as evidence for the anthropic principle (we are carbon-based human beings!!!) .

As a side effect of the process, some carbon nuclei can fuse with additional helium to produce a stable isotope of oxygen :

$$^{12}C + {}^{4}He \longrightarrow {}^{16}O + \gamma$$

Advanced Nuclear Burning Stages

Following the Triple-alpha process there are a variety of reactions which may occur depending on the mass of the star. Three general principles influence the roles that these nuclear burning stages may play:

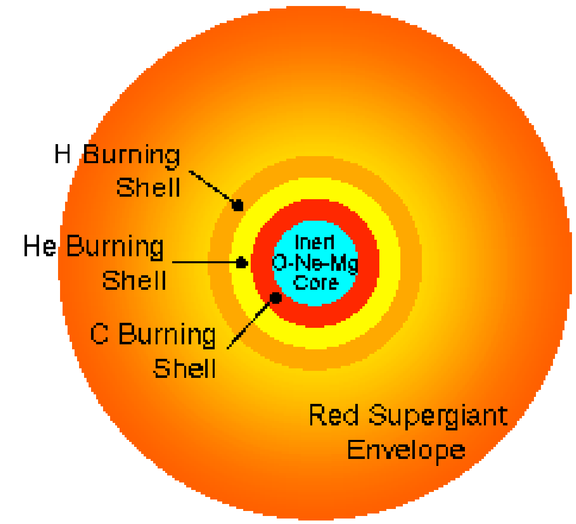
1. Successive nuclear burning stages, involving more massive nuclei with higher charges, will require increasingly high temperatures to overcome the increased electrical repulsion.

2. The amount of energy released by each successive reaction stage decreases so that later nuclear burning stages become shorter and shorter.

3. Once fusion reactions have produced an iron core, further fusion reactions no longer produce energy, but absorb energy from the stellar core. As we shall see this may have a catastrophic effect on the star as it nears the end of its life

Carbon Burning: at T > 5 x 10^8 K. In the order of probability the following reactions can take place:

$$^{12}C + ^{12}C \text{ ----> } ^{23}Na + p$$
$$^{20}Ne + ^{4}He$$
$$^{24}Mg + \gamma$$



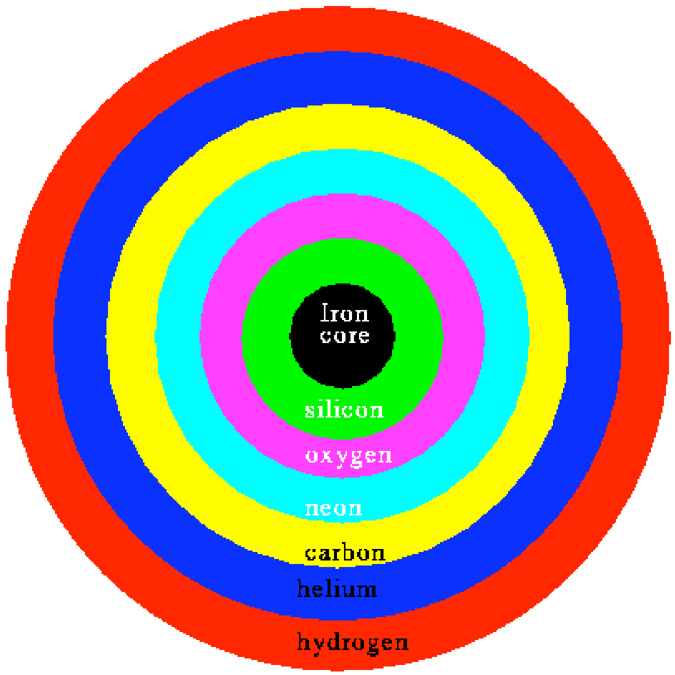
Oxygen Burning: at T > 10^9 K. Oxygen can burn as well

$$^{16}O + ^{16}O \text{ ----> } ^{28}Si + ^{4}He$$
$$S + n$$

… then silicon burning ans so on..

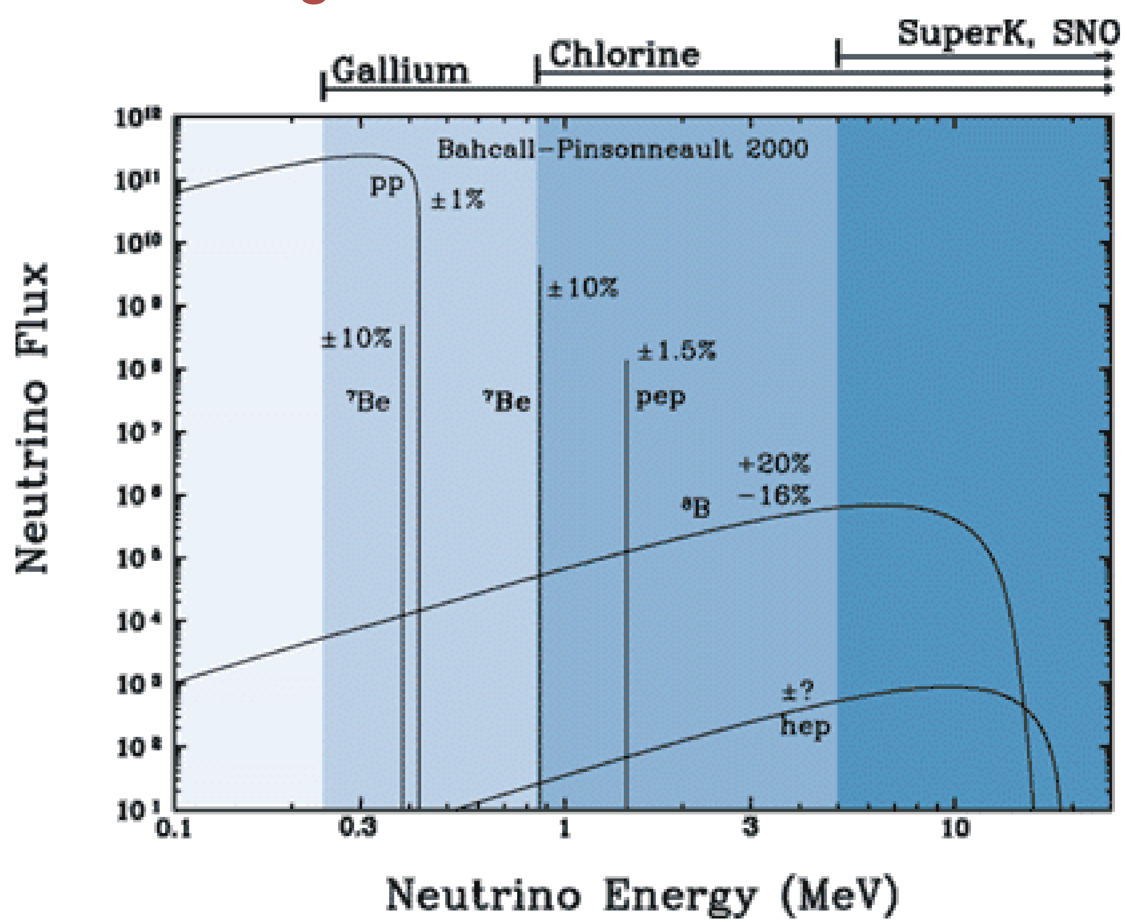
The nuclear burning can proceed all the way to iron - the most stable nucleus. Overall the predictions of stellar nucleusynthesis are in v. good agreement with the abundance of elements in the universe. For a star - of M > 10Msun the star can go through virtually all the nuclear burning structure and develop and 'onion'-like nuclear burning structure.

elements heavier than iron are formed by adding neutrons (have no Coulomb barrier) and subsequent radiative decays ($\beta-$decay, $\beta+$decay, $\alpha-$ decay) via the so-called s-process or r-process (s= slow, r=rapid). s-process occurs in AGB stars r-process in supernovae



In the core of the star, burning of different nuclei takes place in shells around the iron core, at successively lower temperatures.

At the end of the 60's the radiochemical **Homestake** experiment began the observation of solar neutrinos the through charged current reaction $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ with a energy threshold E = 0.814 MeV, which allows to observe mainly ^{7}Be and ^{8}B neutrinos from the sun. The Homestake experiment detected solar neutrinos for about 30 years, measuring a flux which is about one third of the one predicted.



Experiment	reaction	threshold	location
Kamiokande	$\nu_e e \rightarrow \nu_e e$	7.3 MeV	Japan
Homestake	$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$	0.8 MeV	United States
SAGE	$\nu_e\,{}^{71}Ga \rightarrow e^+ + {}^{71}Ge$	0.233 MeV	Russia
GALLEX	$\nu_e\,{}^{71}Ga \rightarrow e^+ + {}^{71}Ge$	0.233 MeV	Italy

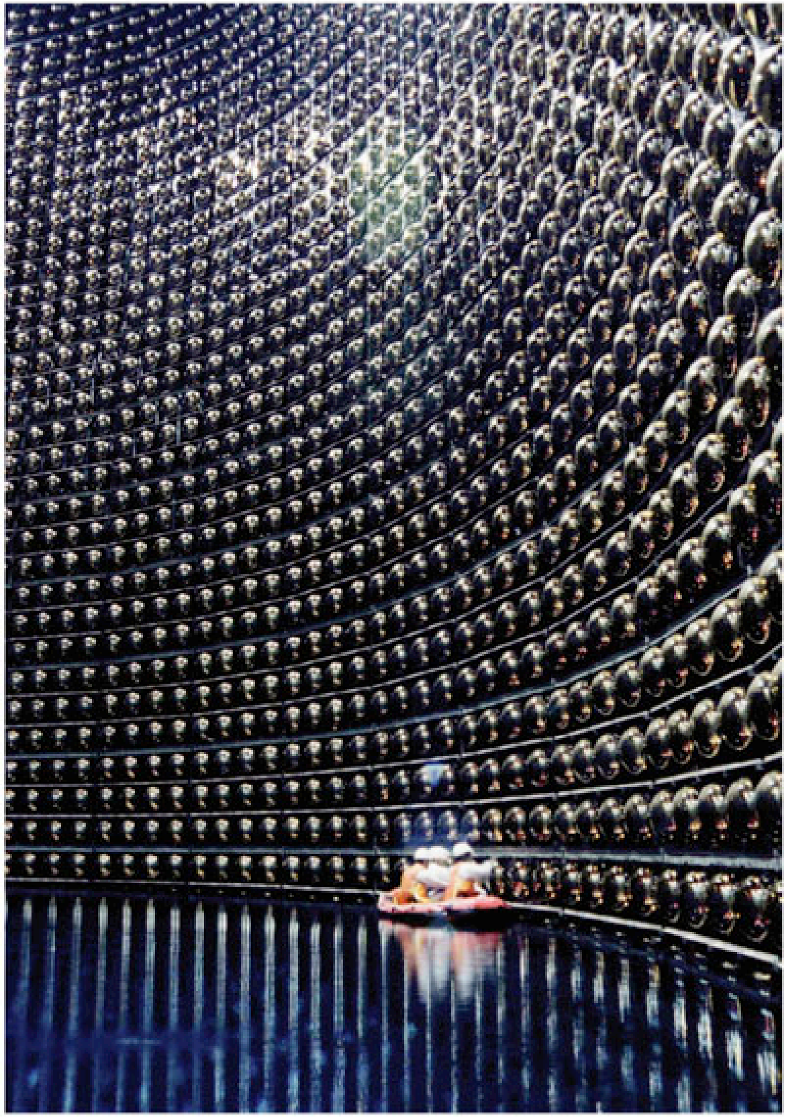
Table 1: Presently operating solar neutrino experiments.

the Homestake mine of South Dakota
(Ray Davis won the Nobel Prize in Physics in 2002)

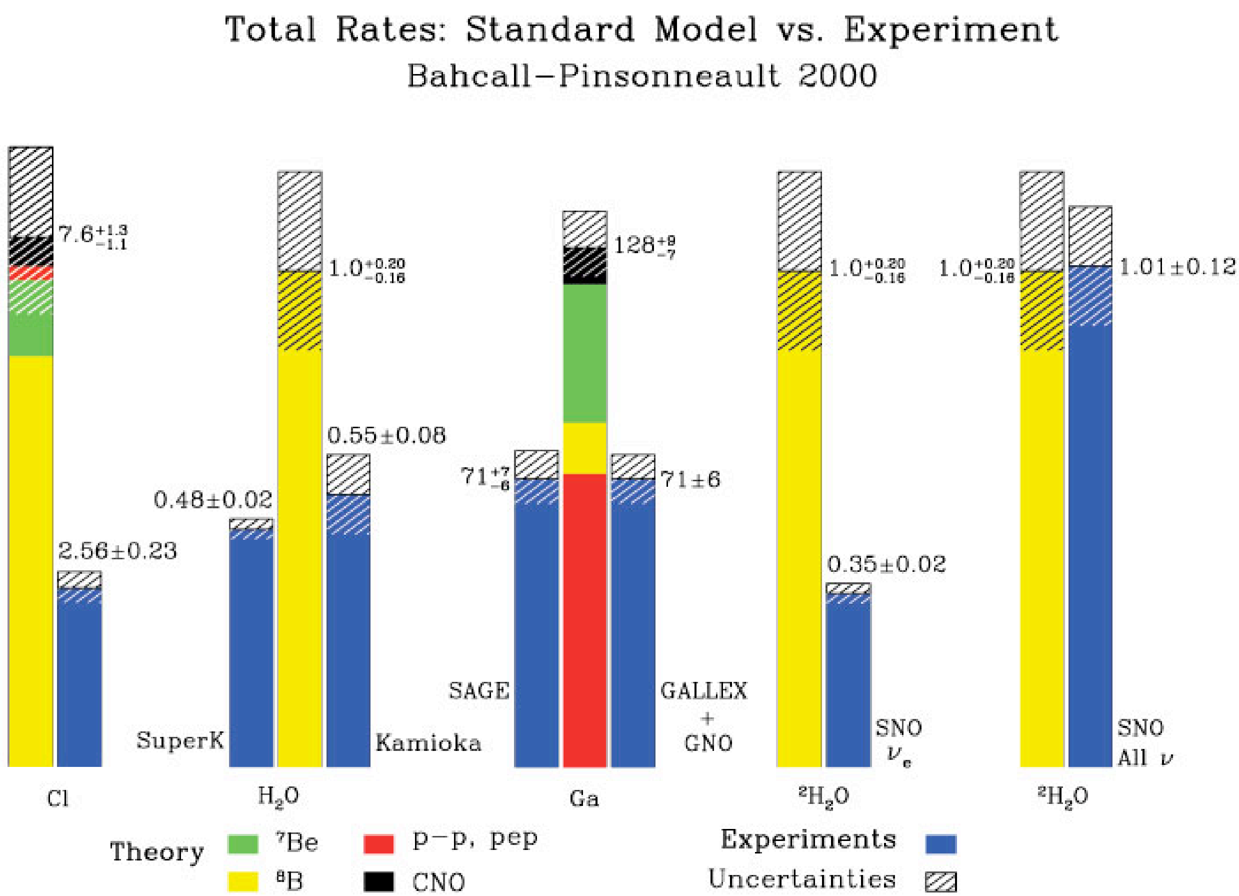
His detector consisted of a tank of 615 tonnes of perchloroethylene - a dry-cleaning fluid. On very rare occasions - about twice every three days - a neutrino would interact with a nucleus of chlorine in the liquid and produce a nucleus of radioactive argon.

argon has a 1/2 life of 35 days

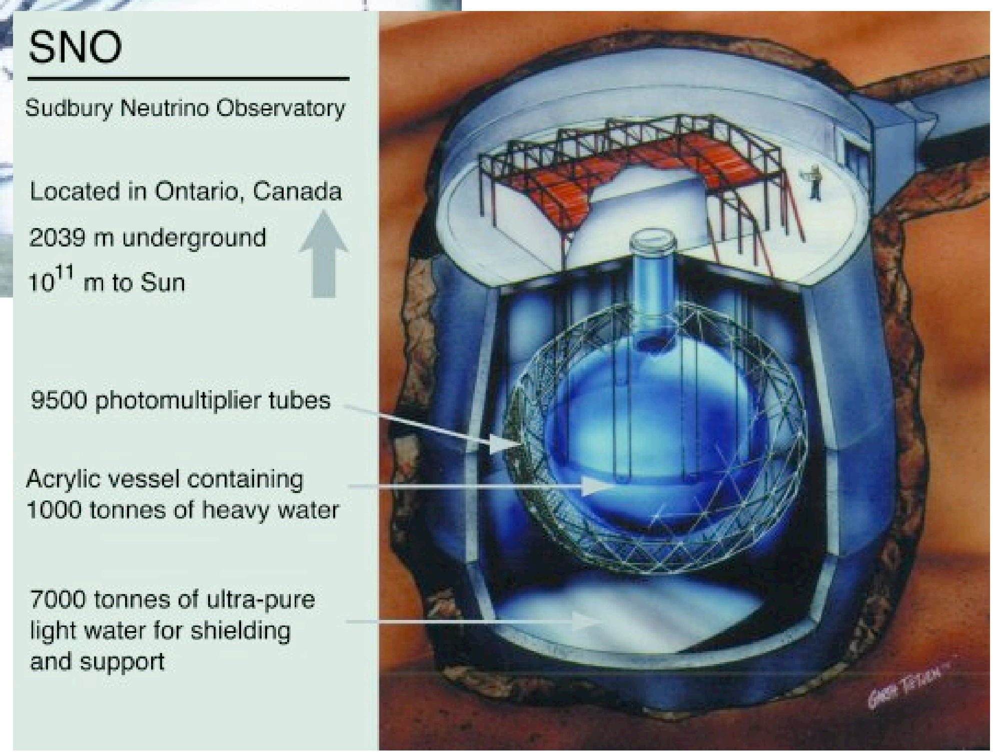
super-kamiokande neutrino telescope (JAPAN)

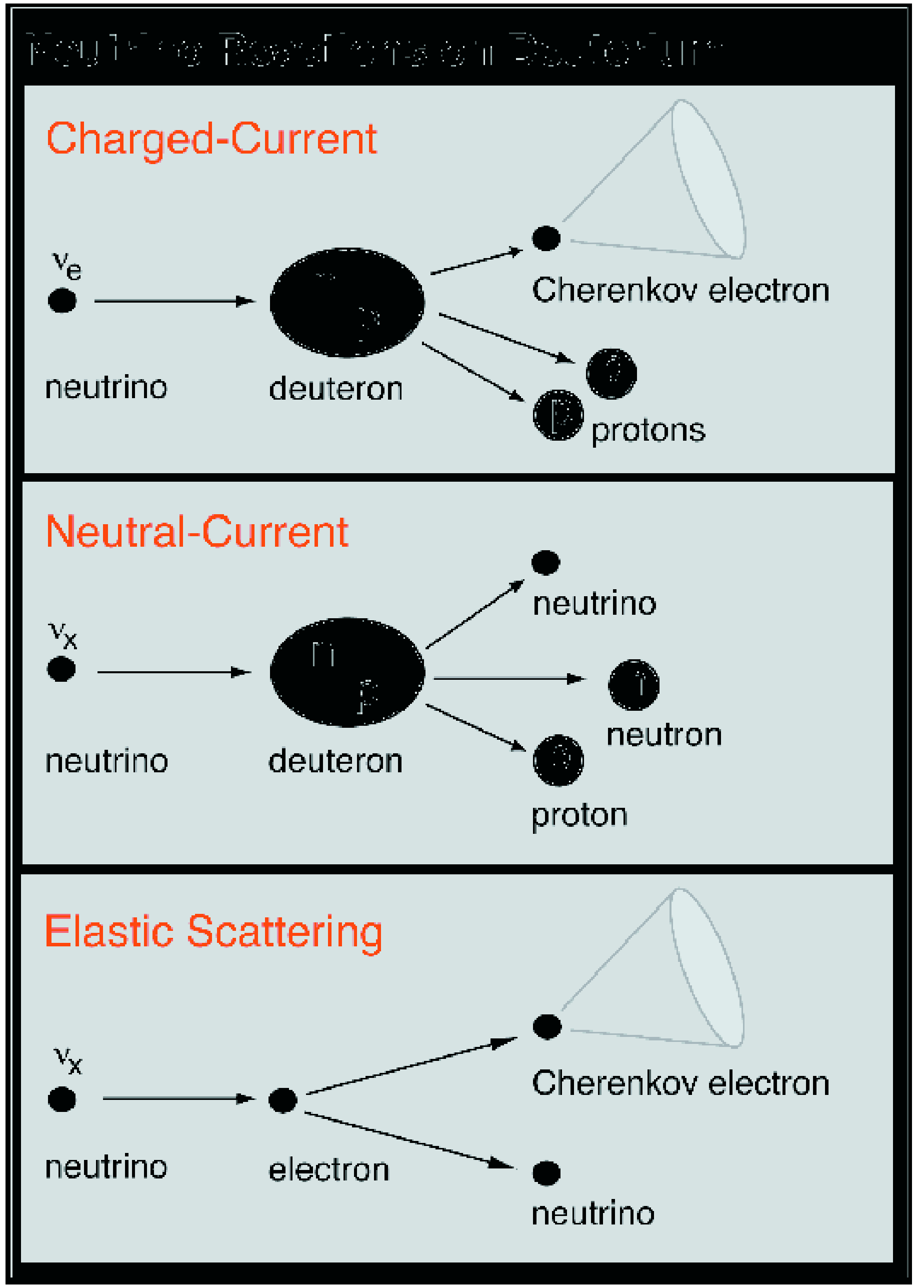


the solar neutrino problem:



Sudbury Neutrino Observatory (SNO)




Charged-Current
ν_e
neutrino
deuteron
Cherenkov electron
protons
Neutral-Current
ν_x
neutrino
deuteron
neutrino
neutron
proton
Elastic Scattering
ν_x
neutrino
electron
Cherenkov electron
neutrino