Nuclear Astrophysics

II. Solar hydrogen burning and neutrinos

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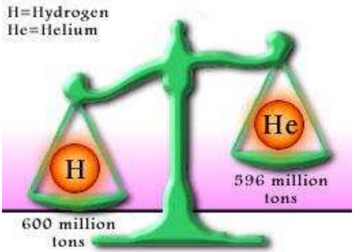
Stellar energy source

Energy comes from nuclear reactions in the core.

$$4\,{}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{neutrinos} + 26.7\mathrm{MeV}$$

$$E = mc^2$$



The Sun converts 600 million tons of hydrogen into 596 million tons of helium every second. The difference in mass is converted into energy. The Sun will continue burning hydrogen during 5 billions years.
Energy relieased by H-burning:
6.45×10^{18} erg g^{-1}
Solar Luminosity: 3.846×10^{33} erg s^{-1}

Coulomb barrier dominates stellar burning

As a star forms, density and temperature increase in the center. Fusion of hydrogen is the first long-term energy source that can ignite as it has the smallest Coulomb barrier:

- For first-generation stars (Population III) the ppI chain is the only possible sequence of reactions.
- 3 or 4 body reactions are very unlikely. Chain has to proceed by 2-body reactions or decays.

The ppI chain

Step 1: $p + p \rightarrow {}^2$He (not possible)
$p + p \rightarrow d + e^+ + \nu_e$
Step 2: $d + p \rightarrow {}^3$He
$d + d \rightarrow {}^4$He (d abundance too low)

Step 3: ${}^3He + p \rightarrow {}^4$Li (${}^4Li$ is unbound)
${}^3He + d \rightarrow {}^4\ He + n$ (d abundance too low)
${}^3He + {}^3\ He \rightarrow {}^4\ He + 2p$

$d + d$ is not going, because Y_d is extremely small and $d + p$ leads to rapid destruction.
${}^3He + {}^3\ He$ works, because Y_{3He} increases as nothing destroys it.

The relevant S-factors

$p(p, e^+\nu_e)d$: $S_{11}(0) = (4.00 \pm 0.05) \times 10^{-25}\ \mathrm{MeVb}$

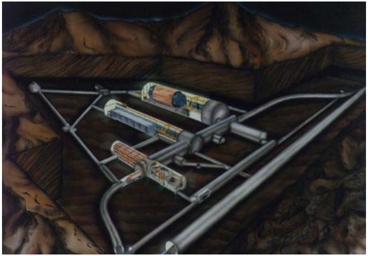
calculated

$p(d,\gamma)^3\mathrm{He}$: $S_{12}(0) = 2.5 \times 10^{-7}\ \mathrm{MeVb}$

measured at LUNA

$^3\mathrm{He}(^3\mathrm{He},2p)^4\mathrm{He}$: $S_{33}(0) = 5.4\ \mathrm{MeVb}$

measured at LUNA



Laboratory Underground for Nuclear Astrophysics (Gran Sasso)

Burning of Deuterium

Deuterons are burnt by the reaction $d(p,\gamma)^3$He:

$$\begin{aligned} \frac{dD}{dt} &= r_{11} - r_{12} \\ &= \frac{H^2}{2}\langle\sigma v\rangle_{11} - HD\langle\sigma v\rangle_{12} \end{aligned}$$

In equilibrium ($\frac{dD}{dt} = 0$) one has

$$\left(\frac{D}{H}\right)_e = \frac{\langle\sigma v\rangle_{11}}{2\langle\sigma v\rangle_{12}}$$

$$(D/H)_e = 5.6 \times 10^{-18} \text{ for } \mathrm{T}_6 = 5$$

Lifetimes of protons and deuterons in the Sun

Consider the reaction $1 + 2 \rightarrow 3 + 4$, then the lifetime of the nucleus a against destruction by b in some environment is given by

$$\tau_b(a) = \frac{1}{N_b \langle \sigma v \rangle_{ab}}$$

If we assume a density $\rho = 100$ g/cm^3 and an equal mixture by mass of hydrogen and helium ($X_H = X_{He} = 0.5$), one finds

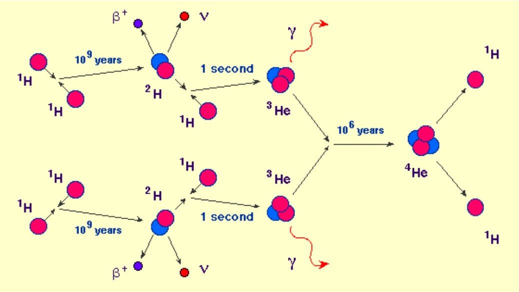
$$\tau_p(p) = 0.9 \times 10^{10}\ y\ ;\ \tau_p(d) = 1.6\ s$$

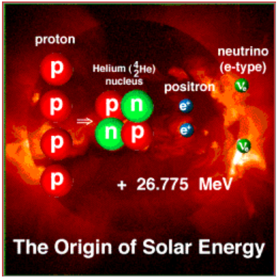
If one assumes a constant H abundance, one finds for the time evolution of D/H

$$D = \frac{H^2}{2}\langle \sigma v \rangle_{11} + e^{-t/\tau_p(d)}\left(Y_{\mathrm{D,initial}} - \frac{H^2}{2}\langle \sigma v \rangle_{11}\right)$$

Equilibrium is reached in about $\tau_p(d) = 1.6$ s!

The ppI chain





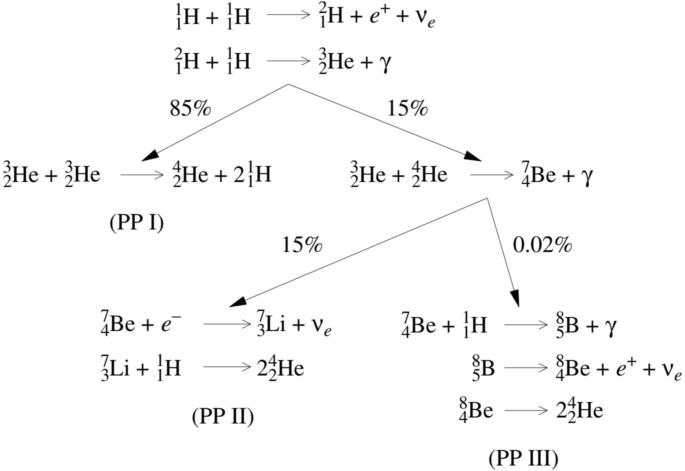
^{4}He as catalyst

^{4}He can act as catalyst initializing the ppII and ppIII chains.
With which nucleus will ^{4}He fuse?

- protons:
  the fusion of ^{4}He and protons lead to ^{5}Li which is unbound.
- deuterons:
  the fusion of deuterons with ^{4}He can make stable ^{6}Li; however, the deuteron abundance is too low for this reaction to be significant
- ^{3}He:
  ^{3}He and ^{4}He can fuse to ^{7}Be. This is indeed the break-out reaction from the ppI chain.

Once ^{7}Be is produced, it can either decay by electron capture or fuse with a proton. Thus, the reaction sequence branches at ^{7}Be into the ppII and ppIII chains.

The solar pp chains



$${}^1_1\mathrm{H} + {}^1_1\mathrm{H} \longrightarrow {}^2_1\mathrm{H} + e^+ + \nu_e$$

$${}^2_1\mathrm{H} + {}^1_1\mathrm{H} \longrightarrow {}^3_2\mathrm{He} + \gamma$$

85%

15%

$${}^3_2\mathrm{He} + {}^3_2\mathrm{He} \longrightarrow {}^4_2\mathrm{He} + 2\,{}^1_1\mathrm{H}$$

(PP I)

$${}^3_2\mathrm{He} + {}^4_2\mathrm{He} \longrightarrow {}^7_4\mathrm{Be} + \gamma$$

15%

0.02%

$${}^7_4\mathrm{Be} + e^- \longrightarrow {}^7_3\mathrm{Li} + \nu_e$$

$${}^7_3\mathrm{Li} + {}^1_1\mathrm{H} \longrightarrow 2\,{}^4_2\mathrm{He}$$

(PP II)

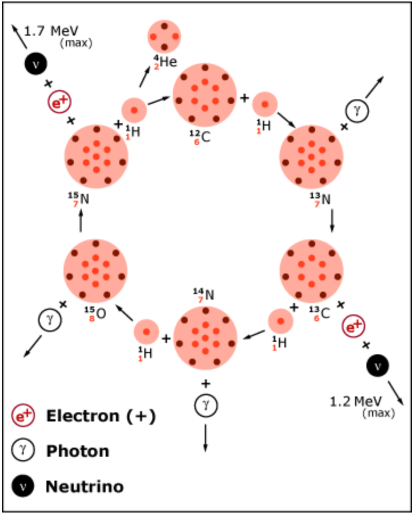
$${}^7_4\mathrm{Be} + {}^1_1\mathrm{H} \longrightarrow {}^8_5\mathrm{B} + \gamma$$

$${}^8_5\mathrm{B} \longrightarrow {}^8_4\mathrm{Be} + e^+ + \nu_e$$

$${}^8_4\mathrm{Be} \longrightarrow 2\,{}^4_2\mathrm{He}$$

(PP III)

The other hydrogen burning: CNO cycle



requires presence of ^{12}C as catalyst

Hydrogen burning: pp-chains vs CNO cycle

Slowest reaction determines efficiency (energy production) of chain:

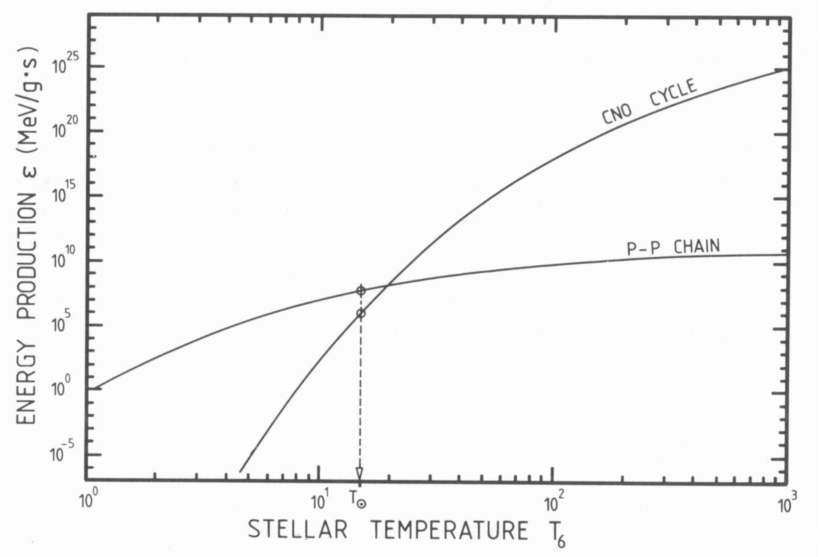
pp-chains:
p+p fusion, mediated by weak interaction

CNO cycle:
^{14}N+p, largest Coulomb barrier, mediated by electromagnetic interaction (in contrast to strong interaction in ^{15}N+p)

Temperature dependence quite different:
$\langle \sigma v \rangle \sim T^{(\tau-2)/3}$
with $\tau = \frac{3E_0}{kT}$; $E_0 = 1.22[keV](Z_1^2 Z_2^2 \mu T_6^2)^{1/3}$

At $T_6 = 15$ (solar core): $\langle \sigma v \rangle \sim T^{3.9}$ (pp); $\langle \sigma v \rangle \sim T^{20}$ (CNO)

Energy generation: CNO cycle vs pp-chains



Consequences

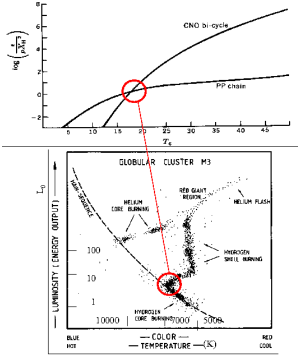
- stars slightly heavier than the Sun burn hydrogen via CNO cycle
- this goes significantly faster; such stars have much shorter lifetimes

mass [$M_\odot$]	timescale [y]
0.4	2×10^{11}
0.8	1.4×10^{10}
1.0	1×10^{10}
1.1	9×10^{9}
1.7	2.7×10^{9}
3.0	2.2×10^{8}
5.0	6×10^{7}
9.0	2×10^{7}
16.0	1×10^{7}
25.0	7×10^{6}
40.0	1×10^{6}

hydrogen burning timescales depend strongly on mass. Stars slightly heavier than the Sun burn hydrogen by CNO cycle.

Future Sun will burn hydrogen by CNO cycle

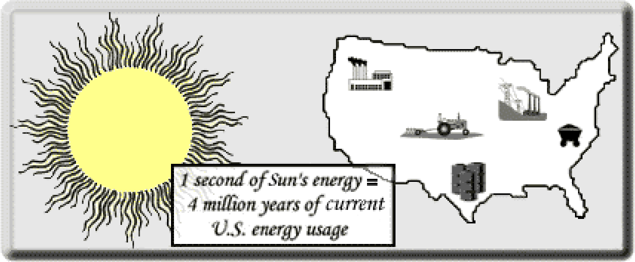
- by continuous hydrogen burning, the Sun reduces its hydrogen reservoir in the core
- at some point in the future energy production by the pp-chains will not suffice to balance the solar energy household
- to gain sufficient energy the solar core will gravitationally contract and thereby increase the temperature
- hydrogen core burning in the Sun then switches from pp-chains to CNO cycle



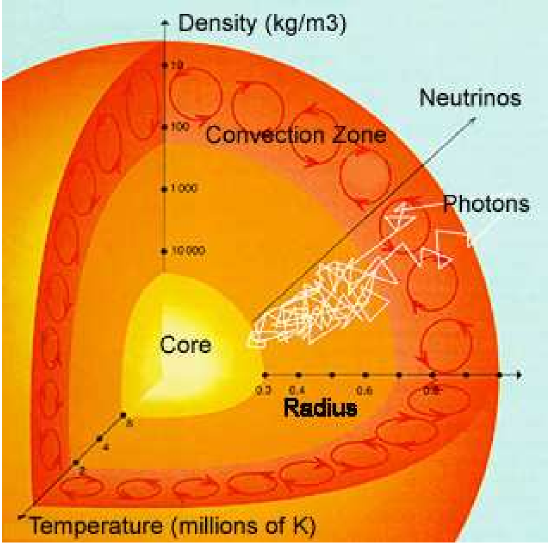
when a star changes from core pp-burning to CNO cycle, its evolutionary track leaves main sequence in HR-diagram

Main properties

Radius	700,000 km
Mass	2.0×10^{30} kg
Surface Temperature	5770 K
Central Temperature	15.7×10^{6} K (1.35 keV)
Central density	160 g cm^{-3}
Current Age	4.5 billions years



Cut through the Sun



Observational tests of Standard Solar Model

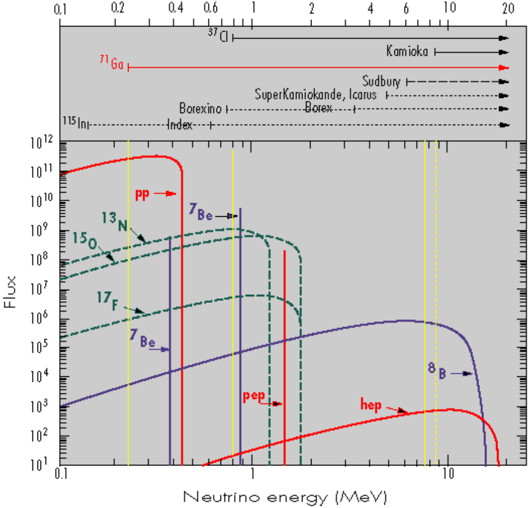
By construction, the solar models reproduce important observables like luminosity, age, radius, mass.

Stringent tests of models by two different tools:

1. earthbound observation of neutrinos produced by nuclear reactions in the Sun
2. observation of solar eigenmodes (helioseismology)

Solar neutrino fluxes and detector thresholds

Solar hydrogen burning produces neutrinos (Bahcall)

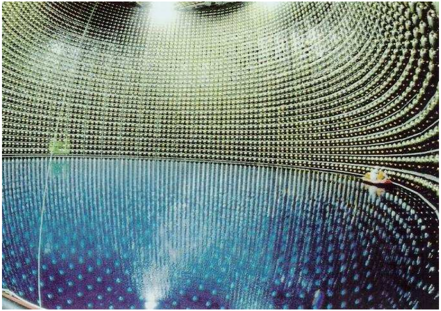


Depending on material, the detectors are blind for neutrinos with energies smaller than a threshold.

Neutrino astronomy

- In the 1950s, Ray Davis (2002 Nobel Prize Laureate) decided to measure the solar neutrinos. (Every second, 10 billion neutrinos pass through every square cm on Earth).
- In 1967, the detector (615 tons of C_2Cl_4) was installed at Homestake Gold Mine, South Dakota (1,500 m depth).
- In 1968, the first measurement was a factor 3 smaller than predictions. Similar results by other experiments.

Super-Kamiokande, Japan (50,000 tons pure water)

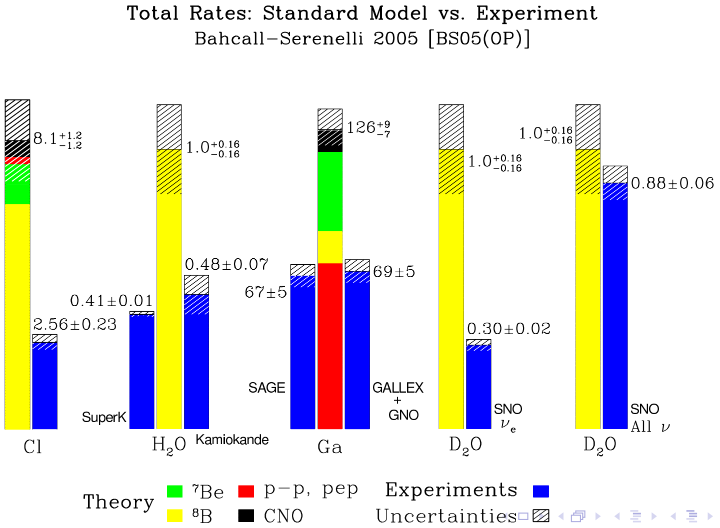


Sudbury Neutrino Observatory, Canada (1,000 tons heavy water)

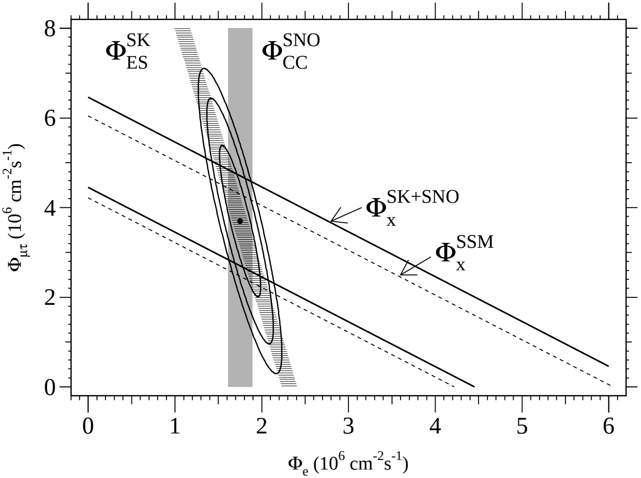
Detecting solar neutrinos

- Homestake:
  - first observation of solar neutrinos
  - detection $\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$
  - blind for $E_\nu < 814$ keV
- Kamiokande, Super-Kamiokande:
  - proof that neutrinos are from Sun
  - detection $\nu_e + e^- \rightarrow \nu_e + e^{-\prime}$ (Cerenkov)
  - blind for $E_\nu < 5000$ keV
- GALLEX:
  - observation of pp neutrinos, in agreement with luminosity
  - detection $\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$
  - blind for $E_\nu < 233$ keV
- Sudbury SNO:
  - proof of solar neutrino oscillations
  - detection $\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + e^-$ (charged current)
  - detection $\nu_x + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x$ (neutral current)
  - neutral current reaction detects all neutrino flavors
  - blind for $E_\nu < 2224$ keV

Observed solar neutrino deficit



The SNO proof of neutrino oscillations



Observed TOTAL neutrino flux agrees with solar model predictions!