Nuclear Astrophysics:
The pp-I chain

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Overview

The proton-proton chain

Chain of nuclear reactions that generates most of the energy produced in the Sun

In general it can follow different branches depending on the temperature and can compete with the CNO cycle

The most relevant branch for the Sun can be summarized in :

$$4p \rightarrow {}^4He + 2\ e^+ + 2\ \nu_e$$

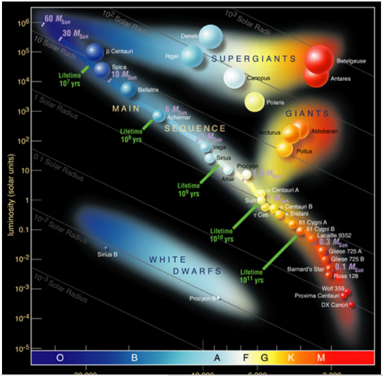
and produces 26.73 MeV of energy per chain, some of which is carried away by the neutrinos.

Relevance in stellar evolution

Relevant during hydrogen burning, the first stage of burning after the star creation

Hydrogen burning is the longest lasting burning stage in the star lifetime and 90% of the visible stars are in this burning stage

The stars undergoing core hydrogen burning belong to the **main sequence** of the Hertzsprung–Russell diagram



pp chain vs CNO cycle: energy production

Depending on the temperature the main contribution to the energy production of a star can come from the pp chain or the CNO cycle [1]

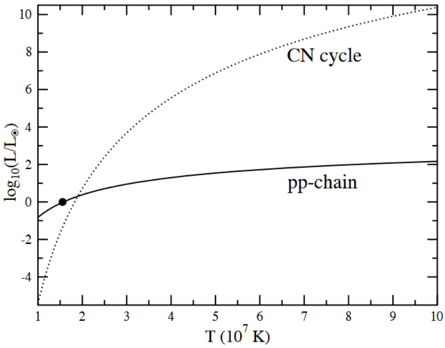


FIG. 1 The stellar energy production as a function of temperature for the pp chain and CN cycle, showing the dominance of the former at solar temperatures. Solar metallicity has been assumed. The dot denotes conditions in the solar core: the Sun is powered dominantly by the pp chain.

pp chain vs CNO cycle: energy transport

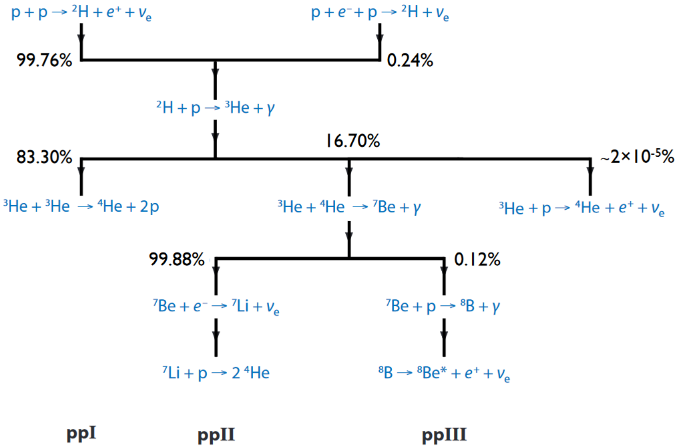
The different energy dependence for the two processes leads to a different internal structure for the star[2]

For masses lower than 1.2 M_{sol} the pp chain dominates, while for higher masses the CNO cycle gives the main contribution

- **pp chain** : convective envelope, radiative core
- **CNO cycle** radiative envelope, convective core

pp-I reaction chain

The different possible branches of the reaction chain with the branching ratios relative to the case of the Sun are



Neutrino measurements

The different branches have characteristics neutrinos with different energies

The branching ratios depend on the temperature

By measuring the neutrino spectra it is possible to determine accurately the temperature of the center of the Sun *if* the cross sections are know accurately[1]

$p + p \rightarrow d + e^+ + \nu_e$

It is a *weak* process $\rightarrow$ allows stars to survive as long as they do

Beyond the reach of experiment but can be estimated theoretically

It is a reaction between very light nuclei $\rightarrow$ can be studied using *ab initio* models

Potential based models and EFT models agree on a S factor value of [1]

$$S(0) = 4.01(1 \pm 0.009)10^{-25} MeV\ \ b$$

$d(p,\gamma)^3He$

Very fast reaction in respect to previous one $\rightarrow$ cross section affects mainly deuterium equilibrium abundance in stars

Fundamental in modelling of slow down in proto star contraction due to deuterium burning and deuterium abundance after BBN

Data taken in the entire Gamow peak region 4-10 keV by the LUNA collaboration $\rightarrow$ only fit required instead of an extrapolation

- Variational Methods $S(0) = 0.219$ ev b
- LUNA $S(0) = (0.216 \pm 0.01)$ ev b
- Fit including previous measurements $S(0) = 0.214^{+0.017}_{-0.016}$ ev b

d(p,γ)^{3}He at LUNA[3]

Large muon flux reduction at LUNA $\rightarrow$ low cross sections are measurable

50 keV accelerator with high beam current, long term stability and precise energy determination

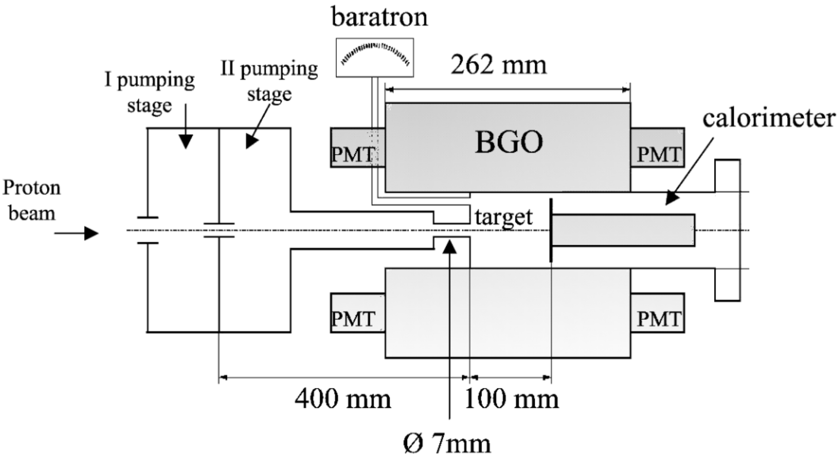
Beam current measured by beam calorimeter

Differentially pumped gas target of deuterium at 0.2 mbar

γ measured by large BGO array with 70% efficiency

No information on the screening potential could be obtained at this precision

LUNA set-up[3]


baratron
262 mm
I pumping stage
II pumping stage
BGO
PMT
PMT
calorimeter
Proton beam
target
PMT
PMT
400 mm
100 mm
Ø 7mm

$^3He(^3He,2p)^4He$

Reaction studied at LUNA in search of a resonance in the Gamow peak that could have explained the solar neutrino problem

Initially measured down to 20.7 keV [4] and after taking only the coincidences between 2 p down to 16.5 keV with a rate of about 2 counts/month [5]

Measured with 50 keV accelerator but with silicon detectors to measure the protons instead of BGO

$S(0) = 5.21 \pm 0.27$ MeV b

Correcting for the electron screening present in laboratory experiments $S^{bare}(0) = 5.11 \pm 0.22$ MeV b

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