Reaction rates and network

$$\left(\frac{dN_1}{dt}\right)_2 = -(1+\delta_{12})\, r = -N_1 N_2 \langle\sigma v\rangle$$

$$= -N_1 \rho N_A \frac{X_2}{A_2} \langle\sigma v\rangle = -N_1 \rho N_A Y_2 \langle\sigma v\rangle$$

$$r = \frac{1}{1+\delta_{12}} N_1 N_2 \langle\sigma v\rangle$$

$$N_i = \rho N_A \frac{X_i}{A_i} = \rho N_A Y_i$$

Number density N
Matter density ρ
Avogadro‘s constant N_A
Mass fraction X
Atomic mass A
Mol fraction Y

The solar ppI chain consists of the following reactions:
$p(p,e^+\nu)d$ (11), $d(p,\gamma)^3He$ (12), $^3He(^3He,2p)^4He$ (33)
with $Y_1 = Y_p$, $Y_2 = Y_d$, $Y_3 = Y_{^3He}$, $Y_4 = Y_{^4He}$

$$\begin{aligned}
\dot{Y}_1 &= \rho N_A(-\langle\sigma v\rangle_{11} Y_1^2 - \langle\sigma v\rangle_{12} Y_1 Y_2 + \langle\sigma v\rangle_{33} Y_3^2) \\
\dot{Y}_2 &= \rho N_A(+\frac{1}{2}\langle\sigma v\rangle_{11} Y_1^2 - \langle\sigma v\rangle_{12} Y_1 Y_2) \\
\dot{Y}_3 &= \rho N_A(+\langle\sigma v\rangle_{12} Y_1 Y_2 - \langle\sigma v\rangle_{33} Y_3^2) \\
\dot{Y}_4 &= \rho N_A(+\frac{1}{2}\langle\sigma v\rangle_{33} Y_3^2)
\end{aligned}$$

The factors 1/2 avoid double-counting of identical nuclei.

proton-proton chain

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

$p + d \rightarrow {}^3He + \gamma$

86% | 14%

$^3He + {}^3He \rightarrow {}^4He + 2p$

PP-I

$Q_{eff} = 26.20$ MeV

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

99.7% | 0.3%

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + p \rightarrow 2\,{}^4He$

PP-II

$Q_{eff} = 25.66$ MeV

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$

$\downarrow$

$2\,{}^4He$

PP-III

$Q_{eff} = 19.17$ MeV

result: $4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{eff}$

Q=26,73 MeV, one ^{4}He serves as catalyst,

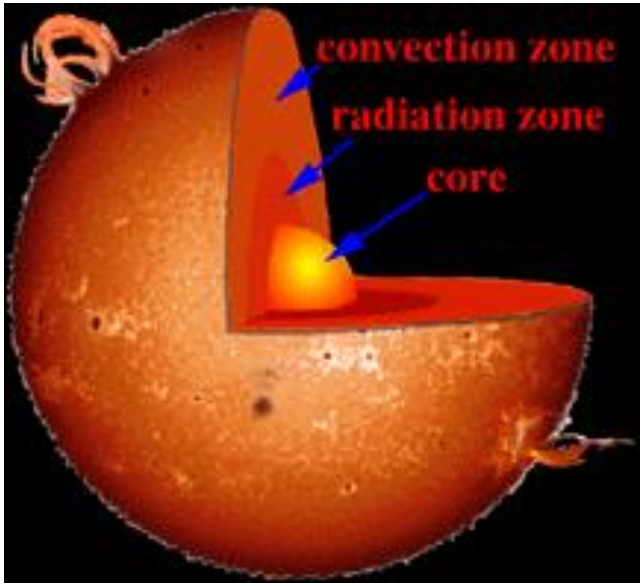
$Q_{eff} = Q - E_\nu$ E_ν energy which is taken away in average by the neutrinos

How to measure the reaction network?

Energy transport inside sun

Energy is produced at centre but radiation is emitted from surface.
How is energy transported inside the sun?

Two mechanism: radiation, convection
for $r > 0.7\ R_{\odot}$ convection for inner radii radiative energy transport.



Radiative energy transport :

- Mean free path length photons: 0.5 cm
- 10^{22} absorptions and re-emissions
- 10^{6} years are needed to transfer the energy to the surface.

Neutrinos allow to observe nuclear processes inside the sun. Most neutrinos from pp fusion leave sun without interaction. However neutrinos have extremely small cross sections for interaction with matter. Experiments to detect the solar neutrinos are very challenging!

Reminder

- Continuos energy spectrum of electrons and positrons after β-decay! Violation of energy conservation?

1930 Pauli postulated existence of neutrino; energy, momentum and angular momentum are conserved!

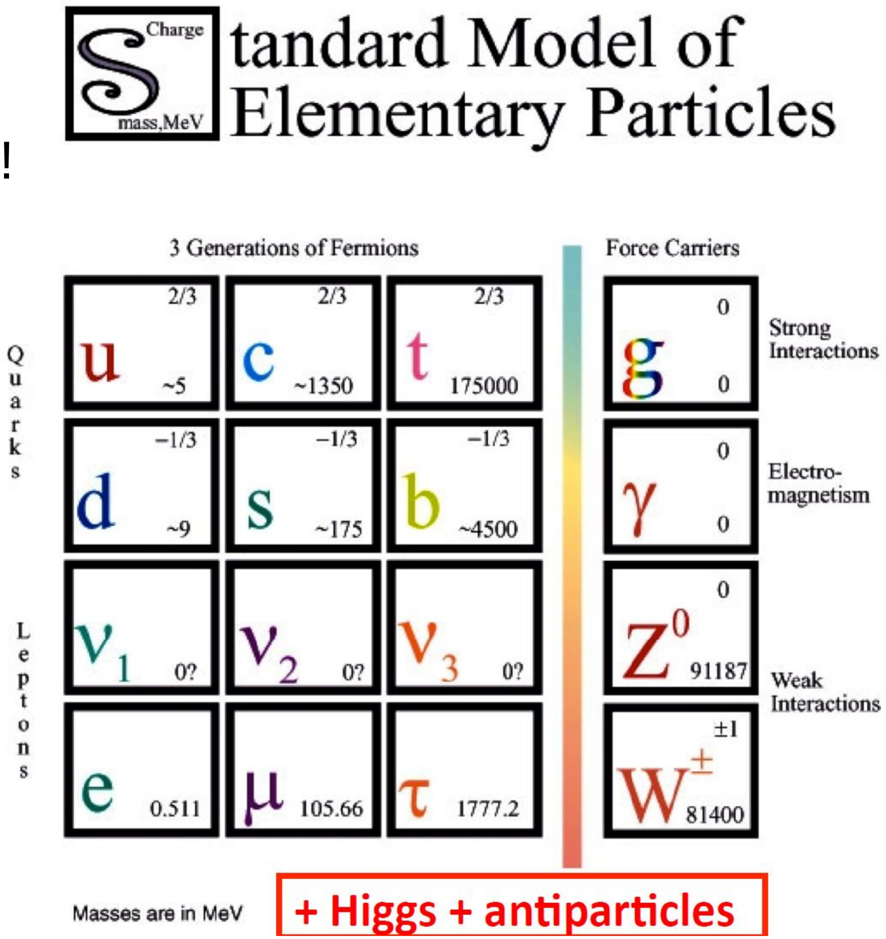
1934 E. Fermi

First theory of β-decay

1956 discovery of ν_e (Cowan,Reines)

1962 discovery of ν_μ (Lederman,Steinberger,Schwartz)

2000 discovery of ν_τ (DONUT collaboration)



Properties of neutrinos

- very abundant elementary particle $N=10^{89}$
- electrical neutral
- spin ½ particle, fermion
- ‘feels’ only weak interaction
- Mean free path length in lead ~10^{3} light years, within human body a flux of 5×10^{14} neutrinos/sec. However, only one interaction during our lifespan.
- helicity
- mass
- lepton number (Dirac or Majorana particle?)

Neutrino detection

- Nachweis von Neutrinos über den inversen β-Zerfall: $\bar{\nu}_e + p \to n + e^+$

- Schwierigkeit: Die Wahrscheinlichkeit oder der Wirkungsquerschnitt für diese Reaktion ist sehr klein und liegt bei $6{,}3 \cdot 10^{-44}\ \mathrm{cm}^2$!

- Grosser Neutrinofluss wird benötigt, Experiment wird in Nähe eines Kernreaktors durchgeführt.

- Experiment: Messe Positron und Neutron aus dem inversen β-Zerfall

- **Positron** vernichtet schnell mit einem Elektron zu zwei Gamma-Quanten mit jeweils 511 keV Energie (Ruheenergie von Positron und Elektron), die diametral (180° korreliert) ausgestrahlt werden.

  Simultaner koinzidenter Nachweis der Gamma-Quanten mit 511 keV Energie und Richtungskorrelation.

- **Neutron** muss zunächst in Wasser abgebremst werden und dann z.B. von Cadmium-Kern eingefangen werden. Insgesamt werden hierbei ~9 MeV Energie frei, die von Cd* in Form von γ-Strahlung emittiert werden. Die Cd-Gammas sind zu den zwei koinzidenten 511 keV γ-Quanten aus der e^-e^+ Vernichtung um einige µs (~3-10) verzögert.

$$n + Cd \to Cd^* \to Cd + \gamma$$

- C. Cowan und F. Reines gelang 1956 die erste Identifikation des Elektronantineutrinos. Cowan verstarb 1974, Nobelpreis für Reines 1995.

Proton-proton-cycle (extended)

pp-Neutrino

$p + p \Rightarrow {}^{2}H + e^{+} + \nu_e$ *(99%)*

pep-Neutrino

$p + e^{-} + p \Rightarrow {}^{2}H + \nu_e$ *(1%)*

${}^{2}H + p \Rightarrow {}^{3}He + \gamma$

${}^{3}He + {}^{3}He \Rightarrow {}^{4}He + 2p$ *(86%)*

${}^{3}He + {}^{4}He \Rightarrow {}^{7}Be + \gamma$ *(14%)*

${}^{3}He + p \Rightarrow {}^{4}He + \nu_e + e^{+}$ *(<<1%)*

hep-Neutrino

${}^{7}Be + p \Rightarrow {}^{8}B + \gamma$

${}^{8}B \Rightarrow {}^{8}Be + e^{+} + \nu_e$

${}^{8}Be \Rightarrow 2\ {}^{4}He$ *(1%)*

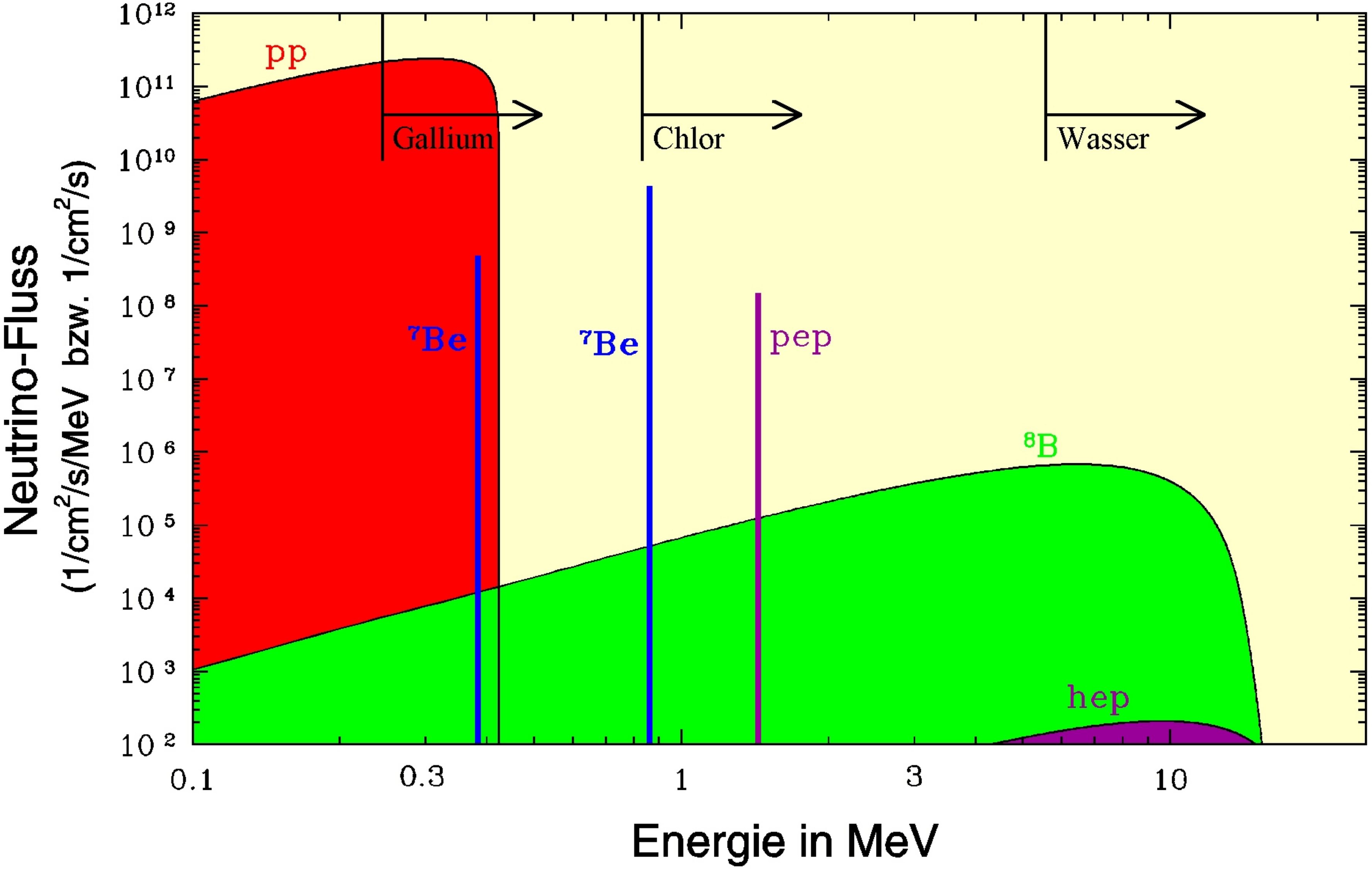
^{8}B-Neutrino

${}^{7}Be + e^{-} \Rightarrow {}^{7}Li + \nu_e$

${}^{7}Li + p \Rightarrow 2\ {}^{4}He$ *(99%)*

^{7}Be-Neutrino

Energiespektrum der Sonnenneutrinos



Radio-chemical method

Neutrino reactions: $\mathbf{n + \nu_e \Rightarrow p + e^-}$

$\mathbf{p + \bar{\nu}_e \Rightarrow n + e^+}$

Radio chemical reaction in nuclei:

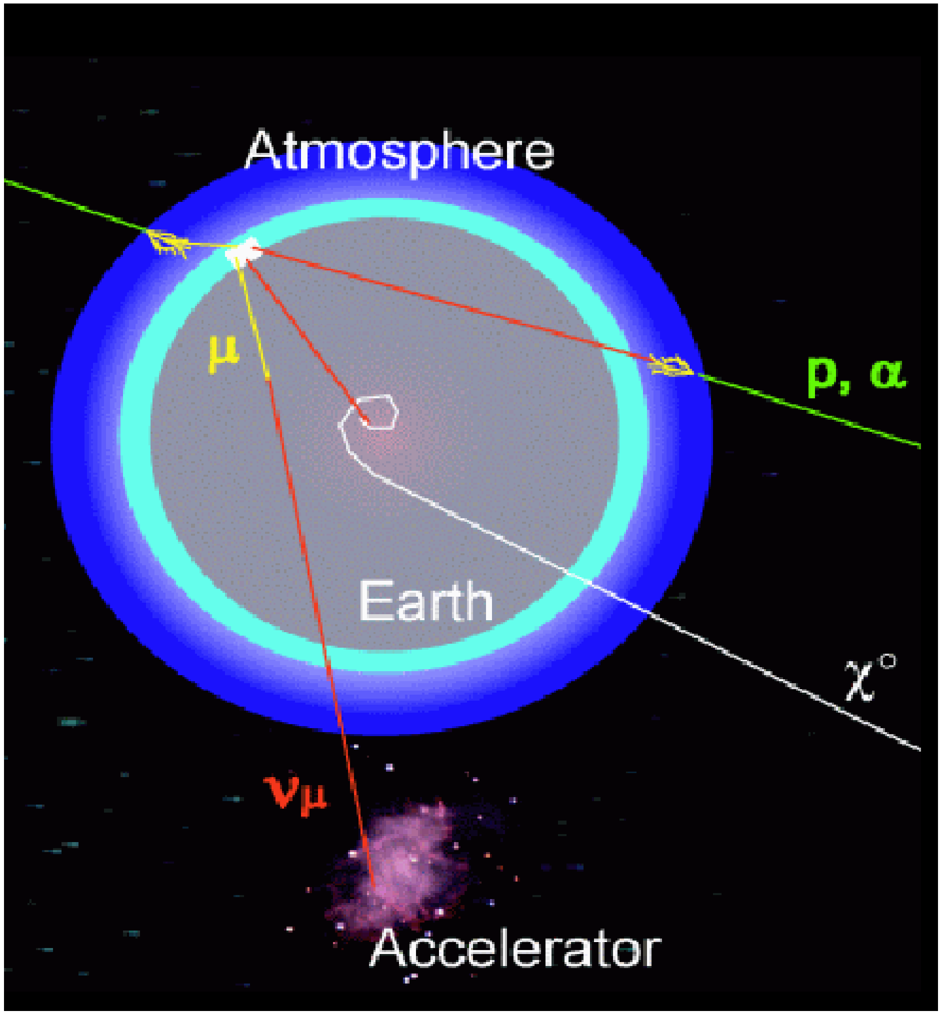
$$\mathbf{{}^{A}_{N}Z + \nu_e \Rightarrow {}^{A}_{N-1}(Z+1) + e^-}$$

- (Z+1) will be extracted, decay products are detected
  (charged particles, γ-transitions, x-rays, 511 keV annihilation radiation)
- Reaction rates are tiny: ~ 10^{30} atoms are needed for one reaction per day
- The very low reaction rate caused a new unit for the solar neutrino flux

  Solar Neutrino Unit SNU

  1 SNU = 10^{-36} neutrino captures per second and per atom

General demands on detection



Measurement of neutrino reactions require:

- very large detector mass (due to tiny cross sections)
- Very high shielding against direct and indirect particles from cosmic radiation, especially muons
- suppression of natural radioactivity

Homestake experiment I

- First experiment which detected solar neutrinos, R. Davis (1968)

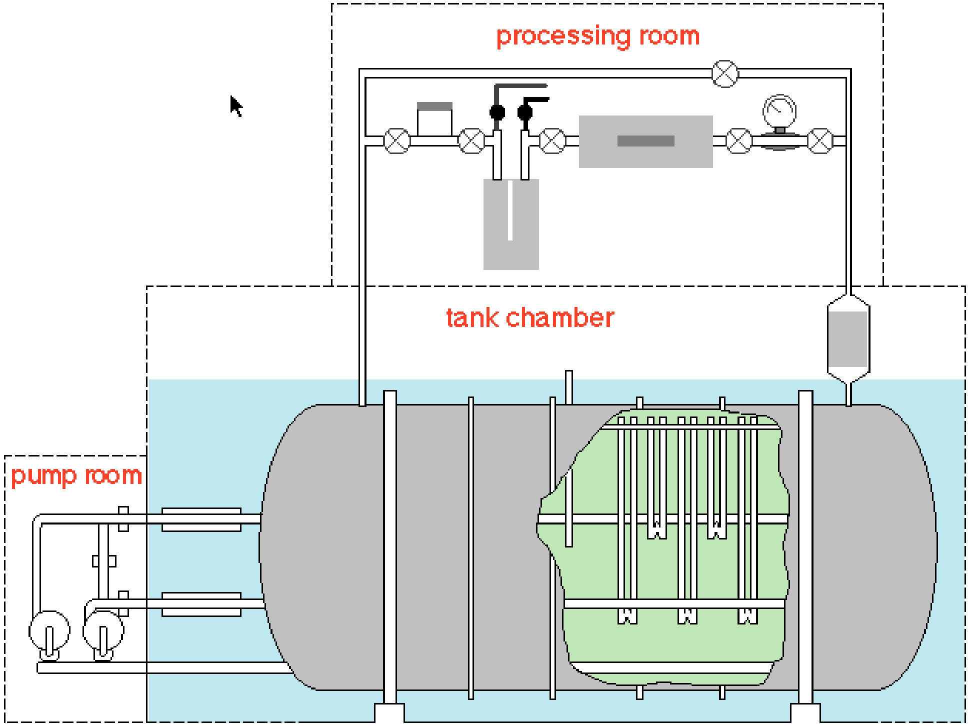
  $380 m^3$:= 615t C_2Cl_4

Nobelpreis für Raymond Davis 2002

- Detection is based on neutrino capture in ^{37}Cl:

  $^{37}Cl + \nu_e \Rightarrow {}^{37}Ar + e^-$

- Chemical separation of ^{37}Ar atoms after 60-70 days



Homestake experiment II

- Detection of ^{37}Ar, decays via K-electon capture:

  $^{37}Ar + e^- \Rightarrow {}^{37}Cl + \nu_e$

  Half live: $t_{1/2} = 35$ d

  Decay products: (i) X-rays (Röntgen radiation)

  (ii) Auger electrons

Typical values:
100 days measurement
60 Ar-decays/10^{31} Cl atoms

- Threshold energy for ν-capture in ^{37}Cl: 814 keV
- => mainly ^{8}B neutrinos
- Final result after 20 years:

  Y = 0.482 ^{37}Ar atoms per day

  R = 2.56+-0.22 SNU

  Standard Sun Model SSM:

  ~ 8.0 SNU
- Solar neutrino deficit problem