Solar neutrino experiments

1970 - 1994 Homestake experiment by R. Davis

Basic source characteristics:

- sun produces ν_e from H fusion

  net reaction: $4p \rightarrow {}^4_2He + 2e^+ + 2\nu_e + \underbrace{26.7\,MeV}_{Q}$

- expected neutrino flux at Earth:

  $$\phi_\nu \approx \frac{S_\odot}{Q} \cdot 2\nu_e \approx 6 \cdot 10^{10}\ \nu_e/cm^2 s$$

  $S_\odot$: solar constant, $1367 \frac{W}{m^2} = 8.5 \cdot 10^{11} \frac{MeV}{cm^2}$

Detection:

- Neutrino reaction:

  $$\nu_e + {}^{37}_{17}Cl \longrightarrow {}^{37}_{18}Ar + e^- \quad ; \; E_{thr} = 814\ keV$$

- Target:

  tank of 615 tons of C_2Cl_4 (natural abundance of ^{37}Cl: 24%)

- Background:

  conversion of $^{37}Cl \rightarrow {}^{37}Ar$ by cosmic rays

  → rock shielding required: Homestake mine, 1478 m depth

- ^{37}Ar extracted from tank by He purging after equilibrium is reached

- count ^{37}Ar re-decays in proportional gas counters

  ↳ $^{37}Cl + e^+ + \nu_e$, $T_{1/2}(^{37}Ar) = 35\,d$

- Result: rate measurement — unit: SNU (solar ν unit)

  $1\ SNU = 10^{-36}$ per atom × sec

  $R_{exp} = 2.32 \pm 0.22$ SNU (0.5 d^{-1})

  $R_{theo} = 7.9$ SNU (SSM) (1.5 d^{-1})

→ deficit, a.k.a. Solar Neutrino Problem

Where does R_{theo} come from?

Standard Solar Model (John Bahcall)

input parameters:

- Mass, age, luminosity

  $M_\odot \approx 2 \cdot 10^{30}$ kg
  Age: 4.5×10^9 yrs
  $S_\odot$: $1367 \frac{W}{m^2}$

  } main sequence star, H-burning

- Elemental composition

  hydrogen $X = 75\%$ (mass percent)
  helium $Y = 24\%$
  metals (Li, Be ...) $Z = 1\%$

- Equations of stellar structure

– Hydrostatic equilibrium: $\frac{dP}{dr} = -\frac{G m \rho}{r^2}$ with $m(r) = \int_0^r m(r')\,dr'$

→ equilibrium pressure-gravity

– Energy equation: $\frac{dL(r)}{dr} = 4\pi r^2 \left(\varepsilon(r) - \varepsilon_\nu(r)\right)$

(L: luminosity; ε: energy created by fusion; ε_ν: energy lost in neutrinos)

– Equation for radiative energy transport ($R < 0.7 R_\odot$)

$$\frac{dT}{dr} = -\frac{3 \kappa \rho L}{64 \pi r^2 k_B T^3}$$ κ: opacity

[convective for $R > 0.7 R_\odot$]

→ Temperature, density in solar core

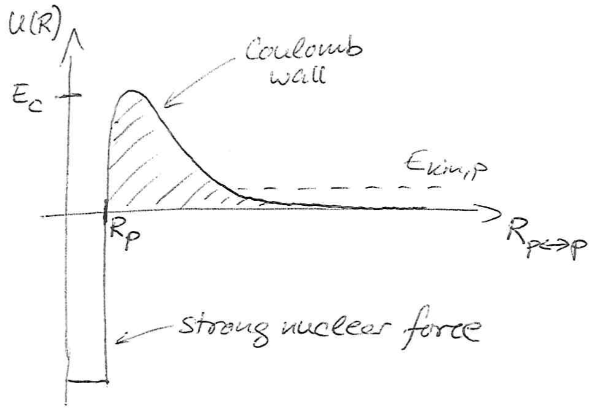
$T_{\odot,c} = 1.5 \times 10^7$ K, $\rho_{\odot,c} = 150 \frac{kg}{\ell}$

Thermonuclear burning

In the Sun: pp-chain is dominant

1st step: $p + p \rightarrow d + e^+ + \nu_e$, $Q \approx 450\,\text{keV}$

$R_{pp} \propto T^4$, $\tau_{pp} \approx 8$ Gyrs. Why?



pp-fusion: $E_C = 1.4\,\text{MeV}$

$T_{\odot,c} = 1.5 \times 10^7\,\text{K}$

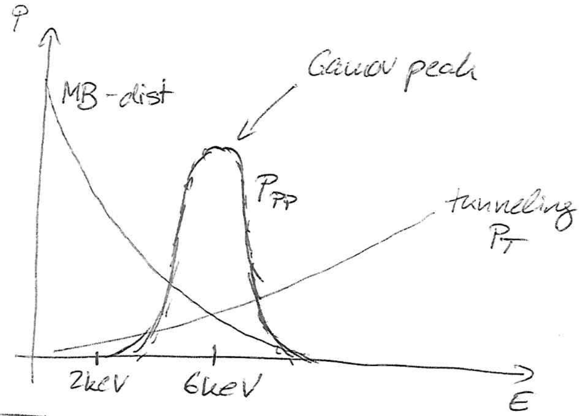
→ Kinetic energy of proton:

$E_p = \frac{3}{2} k_B T_{\odot,c} \approx 2\,\text{keV}$

→ not possible in classic picture

But:

- Quantum mechanics
  → finite tunneling probability
  $P_T \propto e^{-E_g/\sqrt{E}} \sim 10^{-5}$ @ 2keV
- Maxwell-Boltzmann distribution for proton energy
  $n_p(E) \propto e^{-E/k_BT}$



→ Reaction probability:

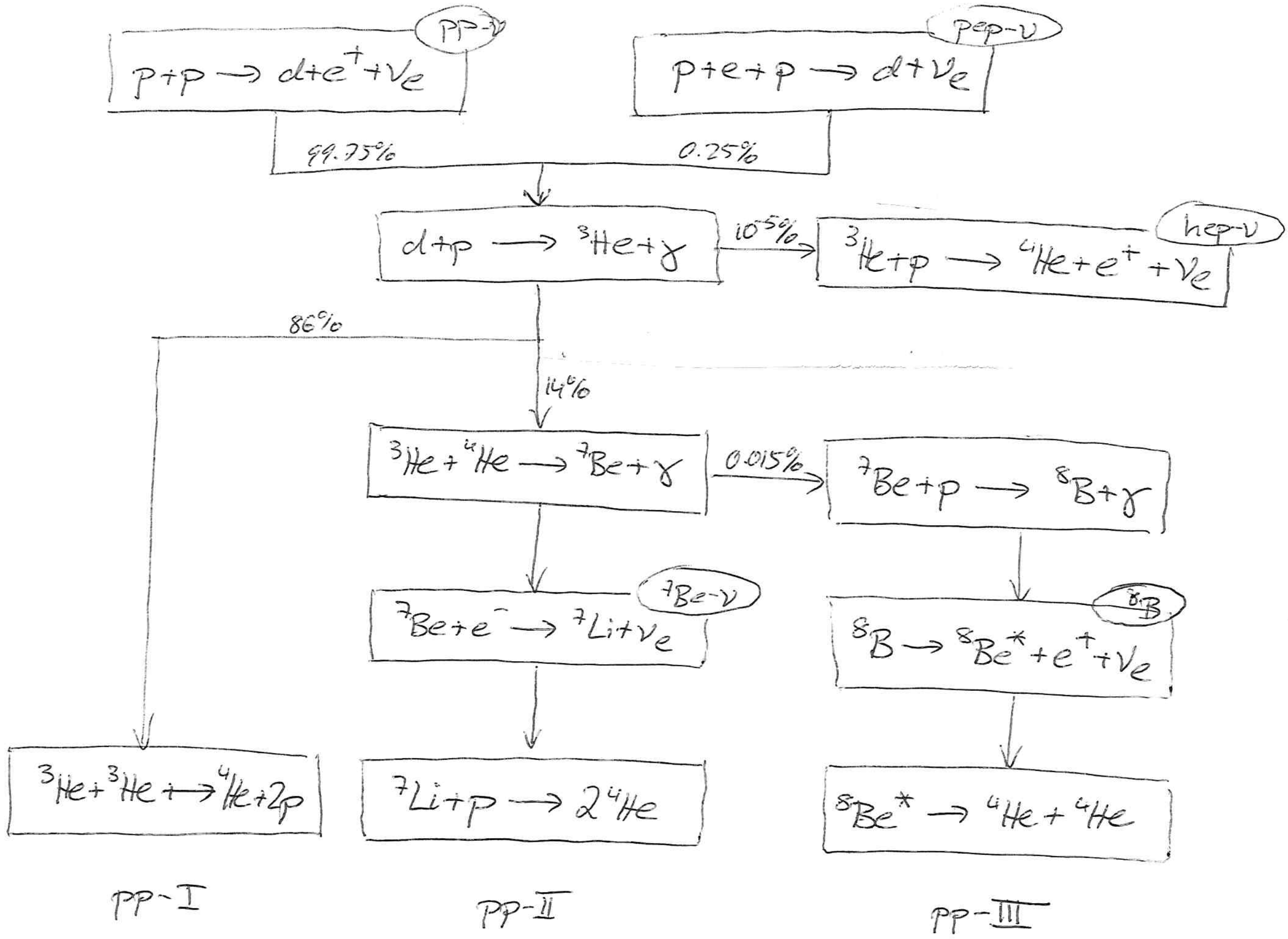
$P_{pp}(E) = \underbrace{P_T(E)\, n_p(E)}\, \sigma_{weak}(E)$

(X) $E_g = \left(\frac{2m}{\hbar^2}\right)\left(\frac{Z_1 Z_2 e^2}{4}\right)^2 \sim 0.5\,\text{MeV}$ for pp is Gamov energy

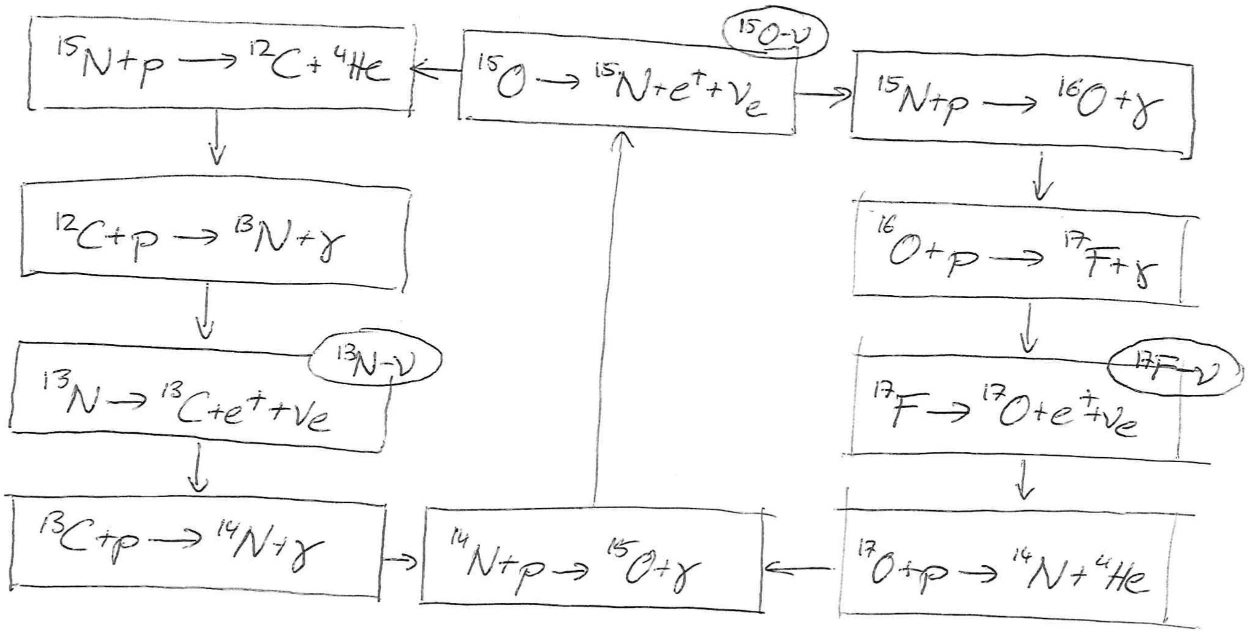
→ steep energy → temperature dependence

→ reactions between partners with high Z suppressed at low T because of $E_g \propto Z_1^2 Z_2^2$

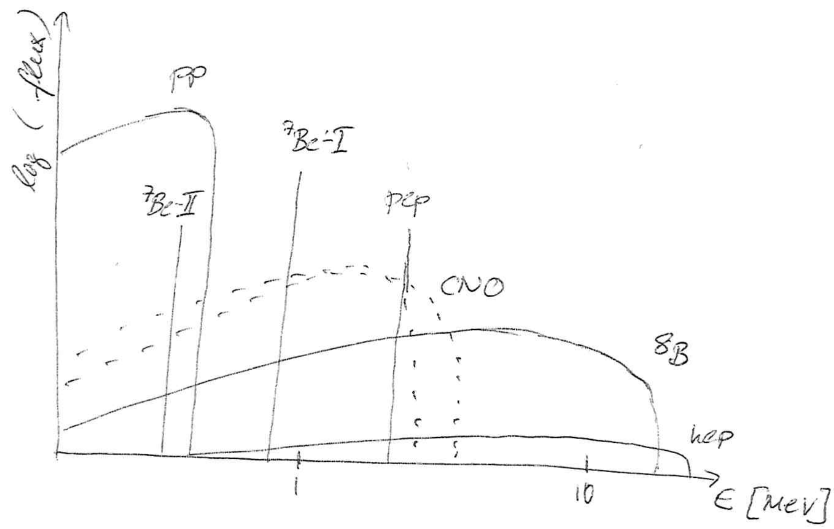
proton-proton-chain (99% in Sun)



CNO cycle (≲1%)



Solar neutrino spectrum



flux uncertainties:

- low for pp: $\sim \pm 0.6\%$ from solar luminosity constraint
- large for reactions with low contribution and difficult-to-measure cross-sections, e.g. ^8B ($\sim 10\%$), CNO ($\sim 30\%$)

Homestake: $E_{thr} = 814\,keV$ → mostly ^7Be, ^8B

→ lower-threshold experiments

⇒ Gallium as target

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^+$$

$E_{thr} = 233\,keV$ → pp-ν included

$T_{1/2}^{71Ge} = 11.4\,d$

1991-2004 GALLEX/GNO @ LNGS

Target: 100t of $GaCl_3$-acid

→ extraction of $GeCl_4$ with N_2

→ reaction with water to GeH_4

→ measure re-decay in gas counters

$$^{71}Ge + e^- \xrightarrow{(EC)} {}^{71}Ga + \nu_e + \text{Auger electrons/X-rays}$$

→ Result: rate $R_{exp} = 70 \pm 6$ SNU ($\hat{=}\, 0.75/d$)

expected $R_{theo} = 120-140$ SNU

SAGE @ Baksan

$R_{exp} = 65 \pm 3_{stat} \pm 3_{syst}$ SNU

→ 50% deficit

→ SSM prediction cannot be the problem (solar luminosity)

Sudbury Neutrino Observatory (SNO)

2000 - 2006, Sudbury mine, 2km rock shielding

Detector concept

Water Cherenkov detector with heavy water target: 1kt of D_2O

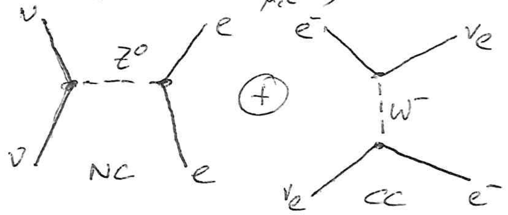
Energy threshold: $E_\nu \sim 5\,MeV$

Detection channels

(CC) $\nu_e + d \xrightarrow{CC} p + p + e^-$ — only ν_e

(NC) $\nu + d \xrightarrow{NC} p + n + \nu$ — all flavors, same cross-sections

(ES) $\nu + e^- \rightarrow e^- + \nu$ — primarily ν_e ($\sigma_{\nu_e e} \approx 5\, \sigma_{\nu_{\mu\tau} e}$)



Result (2002)

$$\left.\begin{aligned} \phi_{CC} &= 1.76 \pm 0.11 \\ \phi_{NC} &= 5.09 \pm 0.62 \\ \phi_{ES} &= 2.39 \pm 0.27 \end{aligned}\right\} \times 10^6 / cm^2 s \quad \text{vs.} \quad \phi_{SSM} = 5.05^{+1.01}_{-0.81} \times 10^6 / cm^2 s$$

→ $\phi_{NC} \approx \phi_{SSM}$, but $\phi_{CC}, \phi_{ES} < \phi_{SSM}$

→ ν_e converted to ν_μ, ν_τ