Solar neutrinos

Overall result of the proton-proton (p-p) chain of reactions:

$$4\,p \rightarrow {}^{4}_{2}\mathrm{He} + 2e^{+} + 2\nu_{e}$$

+28 MeV of energy shared between the reaction products.

Note that this reaction conserves:

- **Charge** (+4 in electron units on both sides)
- **Baryon number** (4 protons / 2 neutrons + 2 protons)
- **Lepton number** (zero on left-hand side / 2 electron neutrinos + 2 positrons `anti-electrons’ on right-hand side)

Electron neutrino produced in this reaction can have a range of energies (E = 0 - 0.42 MeV), but always a small fraction of the total energy release.

Note: experiments at CERN in the 1980s established that there are exactly three families of `electron-like’ particles (leptons):

Particle	Associated neutrino
Electron	ν_e
Muon	ν_μ
Tau lepton	ν_τ

Lepton number is conserved within each family. So if we start with zero electrons, must form pairs of particle + anti-particle (e.g. electron + positron, or positron + neutrino + something else to conserve charge).

In the Sun, energy is too low to create muons or tau leptons. Hence, p-p fusion reactions yield **only** positrons plus electron neutrinos.

What happens to the neutrinos? Cross-section for scattering of ~MeV neutrinos off matter is $\sigma \sim 10^{-44}$ cm^2. Mean free path is:

$$l = \frac{1}{\sigma n}$$

…where n is the density of particles. If we estimate $\rho = 100$ g cm^{-3}, then $n \sim 2\rho / m_H$ which gives $n \sim 10^{26}$ cm^{-3}.

$$\Rightarrow \quad l \sim 10^{18} \text{ cm} \sim \frac{1}{3} \text{ pc}$$

The neutrinos escape the Sun without being scattered or absorbed.

Since we get 2 neutrinos for each 28 MeV of energy, can use observed Solar luminosity to calculate neutrino flux at Earth:

$$\text{Neutrino flux} = \frac{2L_{sun}}{28 \text{ MeV}} \times \frac{1}{4\pi d^2}$$

units of **particles** per second per cm^2

$$\text{Neutrino flux} = \frac{2 \times 3.9 \times 10^{33}\ \text{erg s}^{-1}}{28 \times 1.6 \times 10^{-6}\ \text{erg}} \times \frac{1}{4\pi\left(1.5 \times 10^{13}\ \text{cm}\right)^{2}}$$

$$= 6 \times 10^{10}\ \text{cm}^{-2}\ \text{s}^{-1}$$

Detecting these neutrinos on Earth would:

- confirm or falsify that these reactions were taking place in the Sun
- provide a direct window into the Solar core

But, very difficult: $\text{Interaction rate} = \text{Flux} \times \text{target area}$

Target area = number of particles x cross-section: $\sim \frac{M\sigma}{m_H}$

…where M is the mass of the detector.

Taking M = 1000 kg, $\sigma = 10^{-44}$ cm^2, rate is ~10^{-4} s^{-1} if we can detect 100% of the neutrinos. Need a large volume of detecting medium.

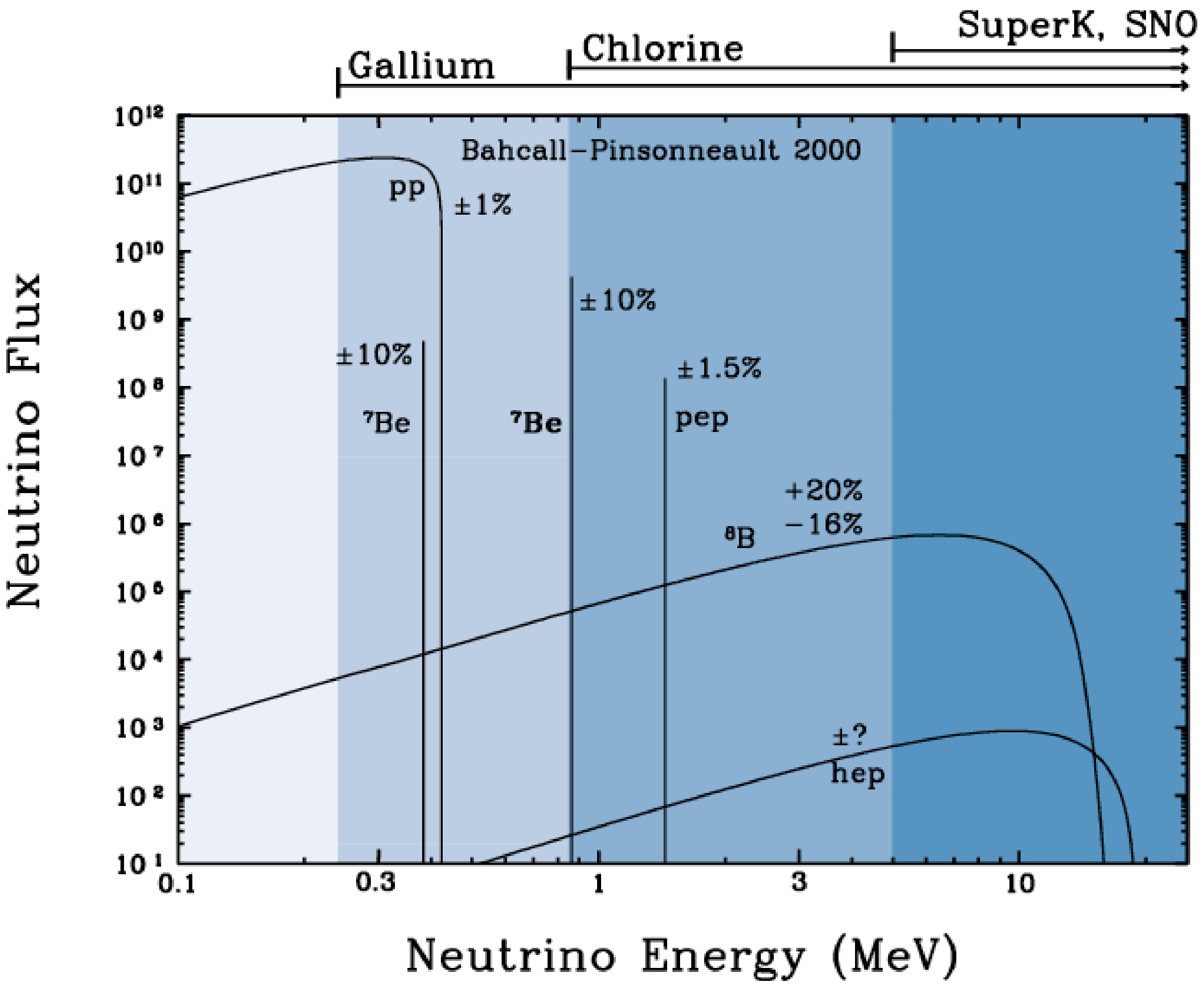
Neutrinos from the main p-p chain are of very low energy. Less important reactions (energetically) yield a smaller flux of higher energy neutrinos:

$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$	`pep' - 1.4 MeV neutrino
${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$	0 - 18.8 MeV
$e^{-} + {}^{7}Be \rightarrow {}^{7}Li + \nu_e$	0.383, 0.861 MeV
${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$	0 - 15 MeV

Can't calculate the flux of these neutrinos just from knowing the Solar luminosity. Relative rates of these reactions (compared to normal p-p chain) depend sensitively on the core temperature.

Can be calculated accurately using a model of the Sun + nuclear physics.

Prediction of the Solar neutrino flux



Two methods for detecting neutrinos:

1) Absorption by a nucleon

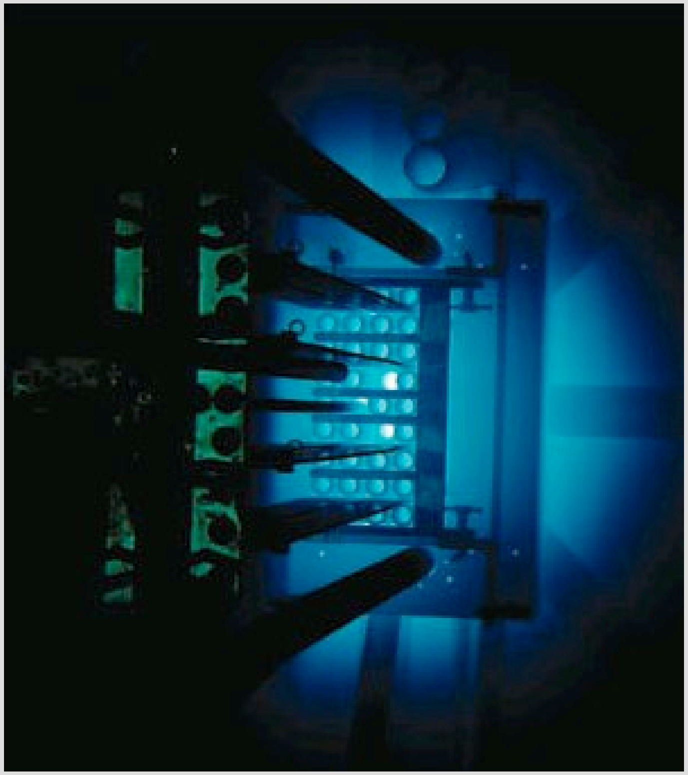
- Reverse process from the nuclear reaction that formed the neutrino in the Sun. Yields a charged lepton, plus a different nucleus from the original one, either of which may be detected.

2) Scattering off an electron

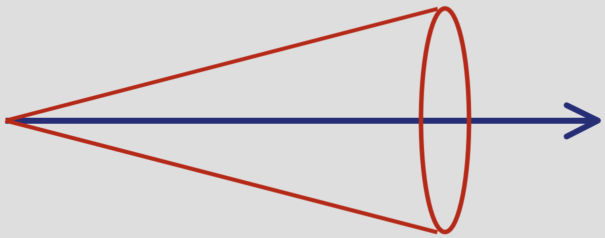
- Neutrino gives up some of its energy to an electron, which is subsequently detected (for these energies, detection is usually via Cherenkov radiation)

Cherenkov radiation

Speed of light in a medium (e.g. water) is less than the speed of light in vacuum - therefore possible for an energetic particle to move at v > speed of light.



Moving charged particle excites molecules, which emit light when they decay back to their ground states. For $v_{particle} > v_{light}$, light is emitted in a cone around the direction of travel:



Visible in nuclear reactors.

Homestake mine detector

First attempt to detect Solar neutrinos began in the 1960s:

Detector is a large tank containing 600 tons of C_2Cl_4, situated at 1500m depth in a mine in South Dakota.

Neutrinos interact with the chlorine to produce a radioactive isotope of argon:

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

+ an electron which is not observed.

Argon is periodically removed from the tank by bubbling helium through the liquid. Then:

- Argon is separated from the helium
- Placed in a proportional counter
- Wait to see the radioactive argon decay:

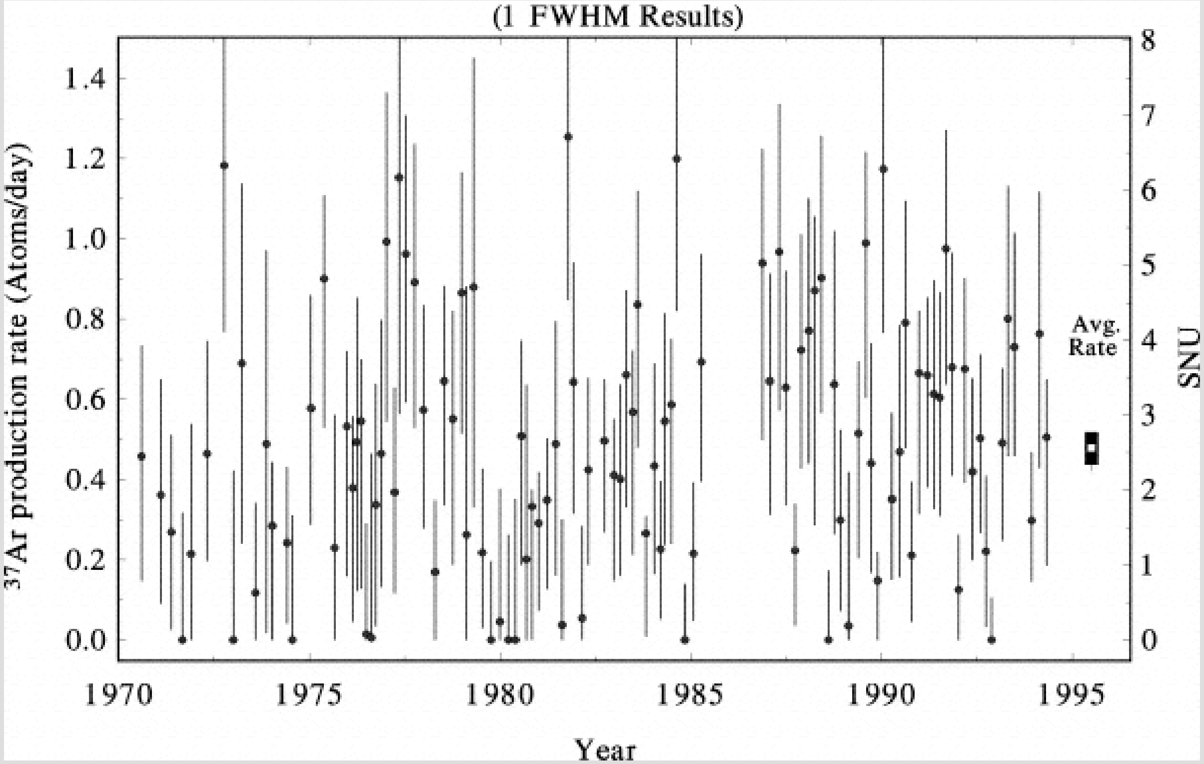
$$e^{-} + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e + \text{additional electrons}$$

↑

signal

By adding non-radioactive argon as well, efficiency of extracting the radioactive isotope is measured - around 95% - almost all the chlorine atoms that undergo a reaction with neutrinos are able to be removed and measured!

Solar neutrino problem



Results from the experiment - note units of atoms per day…

Express results in `SNU' (Solar Neutrino Units).

1 SNU = 1 interaction per 10^{36} target atoms per s

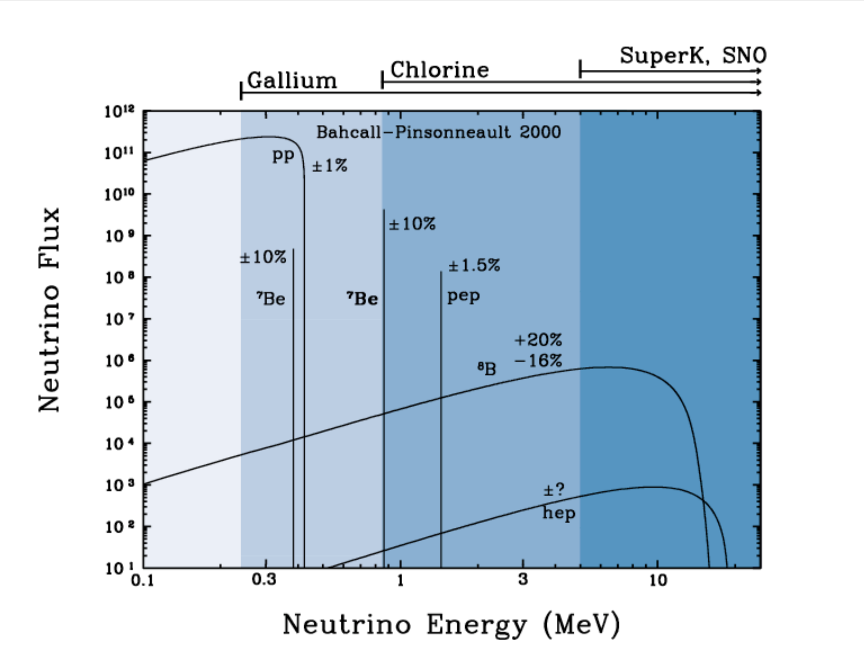
Average result: 2.6 ± 0.3 SNU

Theoretical predictions is: 7.6 ± 1.0 SNU

…for this experiment, i.e. discrepant by roughly a factor of three.

➡ **Solar neutrino problem**

Reaction on chlorine requires a neutrino with energy greater than about 0.8 MeV - so not measuring the full spectrum of neutrinos from the Sun here…



Actually miss **all** of the p-p neutrinos - only measure the rarer types…

Existence of this deficit was subsequently confirmed by two further experiments:

SAGE - Soviet-American Gallium Experiment

Measured: $\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$

Result: 67 ± 10 SNU

Theory: 129 SNU

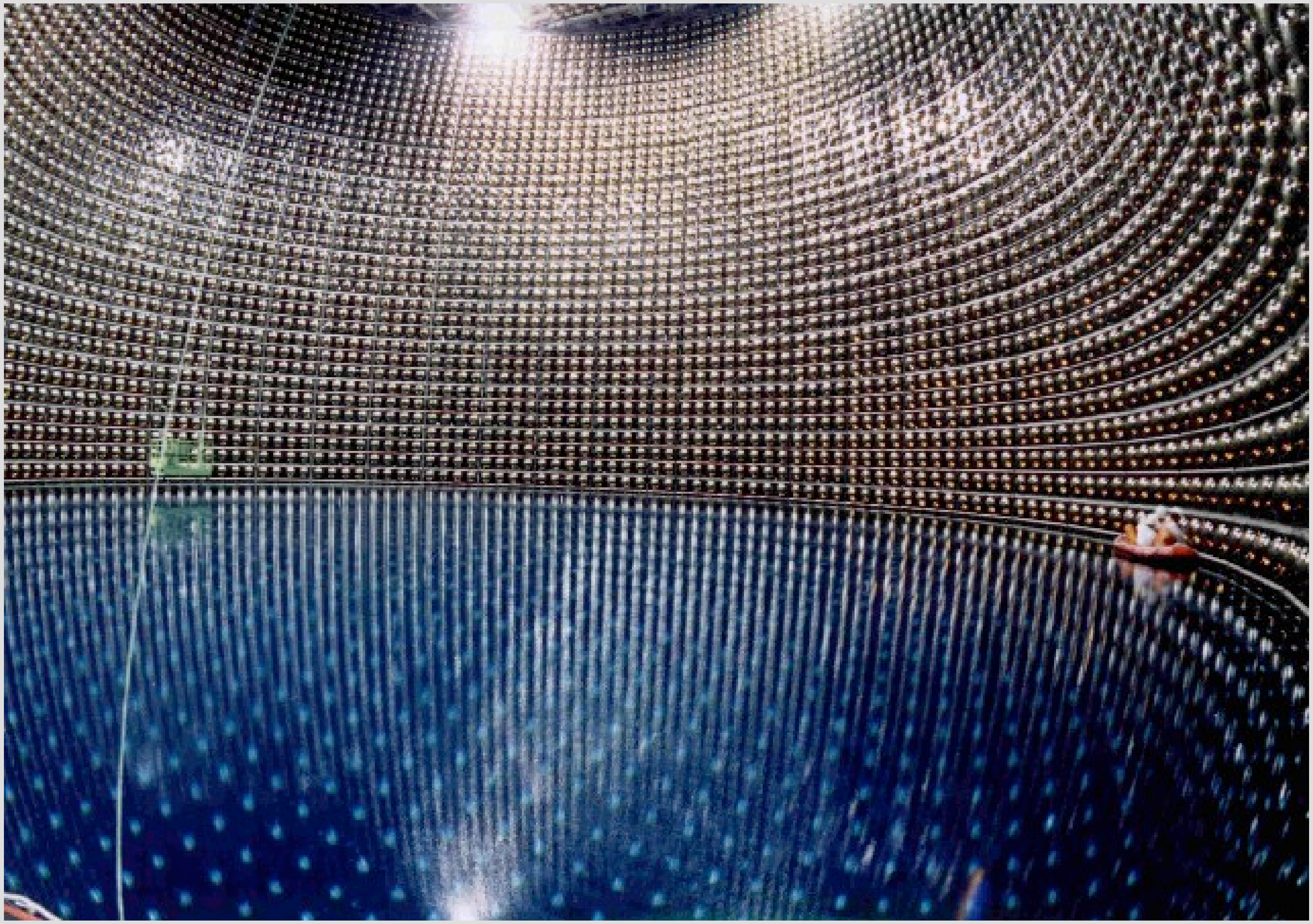
SAGE was sensitive to some p-p neutrinos

Very difficult experiment…

Super Kamiokande

Measure: $\nu_e + e^- \rightarrow \nu_e + e^-$

look for Cherenkov radiation from high energy electron in water



Threshold of around 5 MeV

Measure:
0.5 SNU

Theory:
1.0 SNU