Solar neutrinos

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

\[ 4 \, ^1\text{H} \rightarrow \, ^4\text{He} + 2e^+ + 2\bar{\nu}_e \]

+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 \((E = 0 - 0.42\ \text{MeV})\), 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):

<table>
<thead>
<tr>
<th>Particle</th>
<th>Associated neutrino</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>Muon</td>
<td>$\bar{\nu}_\mu$</td>
</tr>
<tr>
<td>Tau lepton</td>
<td>$\bar{\nu}_\tau$</td>
</tr>
</tbody>
</table>

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 $\sigma \sim 10^{-44} \text{ cm}^2$. Mean free path is:

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

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

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

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:

$$\text{Neutrino flux} = \frac{2L_{\text{sun}}}{28 \text{ MeV}} \frac{1}{4\pi d^2} \text{ units of particles per second per cm}^2$$
Neutrino flux = \( \frac{2 \cdot 3.9 \cdot 10^{33} \text{ erg s}^{-1}}{28 \cdot 1.6 \cdot 10^{-6} \text{ erg}} \cdot \frac{1}{4 \sqrt{1.5 \cdot 10^{13} \text{ cm}^2}} \)

= \( 6 \cdot 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \)

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: Interaction rate = Flux \( \cdot \) target area

Target area = number of particles \( \times \) cross-section: \( \sim \frac{M\Box}{m_H} \)

…where \( M \) is the mass of the detector.

Taking \( M = 1000 \text{ kg} \), \( \Box = 10^{-44} \text{ cm}^2 \), rate is \( \sim 10^{-4} \text{ s}^{-1} \) 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:

\[ p + e^- + p \rightarrow ^2H + \nu_e \]  
\[ ^3He + p \rightarrow ^4He + e^+ + \nu_e \]  
\[ e^- + ^7Be \rightarrow ^7Li + \nu_e \]  
\[ ^8B \rightarrow ^8Be + e^+ + \nu_e \]

`pep’ - 1.4 MeV neutrino  
0 - 18.8 MeV  
0.383, 0.861 MeV  
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 \( v_{\text{particle}} > v_{\text{light}} \), 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$_2$Cl$_4$, situated at 1500m depth in a mine in South Dakota.

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

\[
\epsilon^- + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + \text{e}^-
\]

+ 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:

\[ e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + e^- + \text{additional electrons} \]

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!
Express results in `SNU’ (Solar Neutrino Units).

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

Average result: $2.6 \pm 0.3$ SNU
Theoretical predictions is: $7.6 \pm 1.0$ 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: $\bar{\nu}_e + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge}$

Result: $67 \pm 10$ SNU

Theory: $129$ SNU

SAGE was sensitive to some p-p neutrinos

Very difficult experiment…
Super Kamiokande

Measure: $\overline{\nu}_e + e^- \rightarrow \nu_e + e^-$

look for Cherenkov radiation from high energy electron in water

Threshold of around 5 MeV

Measure: 0.5 SNU

Theory: 1.0 SNU