Lecture 16: Solution to Solar $\nu$ Problem

1. Homestake $^{37}Cl$ exp. $2.56 \pm 1.6 \pm 1.6 $ SNO
   Theory $8.6 \pm 1.2 $ SNO
   First results in late 1960s

2. Kamiokande $\nu-e$ exp. 1989
   $< 0.45$ of theory
   Refined by Super K

3. Gallium experiments 1991: SAGE
   and GALLEX: Low threshold sees pp $\nu$.$\nu$
   See approx. $2/3$ exp. flux.
   1995 analysis
   If no change in $\nu$ properties than three experiments
   together imply
   1. $^{8}B$ flux was $< 0.45$ theory
   2. $^{7}Be$ flux was $< 0$
   3. $pp$ flux slightly reduced but near theory.

Since $^{8}B$ from $^{7}Be$, it is hard
to have flux $^{7}Be = 0$ and at
same time flux $^{8}B \neq 0$. This
strongly suggested solution
is new neutrino physics and not
a collection to the solar model. For
example no one solar central temp.
can fit all experiments.
Recently, the situation qualitatively changed with first results from SNO.

One kiloton of heavy water worth ≈ 300+ million $ was used as a target.

Note: Canada has nuclear power reactors which use heavy water as a moderator to slow down fast neutrons from fission. The slow neutrons can more efficiently cause additional fissions.

Light water H2O **cannot** as a moderator capture some neutrons via

\[ n + p \rightarrow d + \gamma \]

Therefore, light water can not be used as a moderator with natural uranium since it absorbs too many neutrons.

However, the US had large 235U enrichment capacity as a result of the atomic bomb project. Therefore in the US, reactors use slightly enriched uranium which will work with a light water reactor moderator.

Canada did not want to rely on US enrichment plants so it developed heavy water moderated reactors and plants to make lots of heavy water.
The reactor business is very soft so the Canadian government was willing to lend the kiloton of heavy water.

Note cross section for
\[ n + d \rightarrow 3H + X \]

is much smaller than \( n + p \rightarrow d + X \)

For our purposes 1 provides loosely bound neutrons. For \( B, \nu \rightarrow E_x < 15 \text{ MeV} \) and most are \( > 2.2 \text{ MeV} \).

However, normal nuclei have neutrons bound by \( \sim 8 \text{ MeV} \) so cross sections for neutron knockout are very small.

SNO can see three reactions from solar \( \nu \)

1. \( \nu_e + d \rightarrow p + p + e^- \) [Charged Current] CC
2. \( \nu_x + d \rightarrow n + p + \nu_x \) [Neutral Current] NC
3. \( \nu_x + e \rightarrow \nu_x + e \) [Elastic Scattering] ES

Reaction 1 only sensitive to \( \nu_e \)

Reaction 2 equally sensitive to \( \nu_e \) and \( \nu_x \) or \( \nu_x \)
Reaction 3) sensitive to $\nu_e$ plus $1/6$

Because

\[ \sigma_{\nu_e - e} \sim \frac{1}{6} \sigma_{\nu_e - e} \]

So.

\[ \phi_{cc} = \phi_{\nu_e} \]
\[ \phi_{nc} = \phi_{\nu_e} + \phi_{\nu_x} \]
\[ \phi_{es} = \phi_{\nu_e} + 6 \phi_{\nu_x} \]

SNO detects the $e^-$ from CC or ES via its Cerenkov light, just like Kamiokande. It isolates small ES event rate because of direction of recoil.

Note SNO was much smaller volume than SK so its ES measurements have less statistics.

First SNO result
\[ \phi_{cc} \leq \frac{1}{3} \phi(\beta)_{theory} \]

This is noticeably smaller than SK result
\[ \phi_{es} \leq 0.43 \phi(\beta)_{theory} \]
If \( \frac{2}{3} \) of original \( \nu_e \) had oscillated into either \( \nu_m \) or \( \nu_\tau \) than

\[
\phi_{\nu_e} = \frac{1}{3} \phi(B) \\
\phi_{\nu_x} = \phi(B) - \phi_{\nu_e} = \frac{2}{3} \phi(B)
\]

So,

\[
\phi_{ES} = \phi_{\nu_e} + \frac{1}{6} \phi_{\nu_x} = \left[ \frac{1}{3} + \frac{1}{6} \cdot \frac{2}{3} \right] \phi(B) = \frac{4}{9} \phi(B) = 0.44 \phi(B)
\]

Thus the small difference between SNO's \( \phi = \frac{1}{3} \phi(B) \) and SK \( \phi_{ES} = 0.43 \phi(B) \) is taken as evidence that SK is seeing some contribution from \( \nu_e \) or \( \nu_\tau \) coming from Sun.

Note because of the \( \nu_6 \) sensitivity it is hard to make a very precise measurement of the \( \phi_{\nu_x} \) this way.

Finally, last year SNO published its neutral current flux measurement from

\[
\nu_x + d \rightarrow p + n + \nu_x
\]

Followed by \( n + d \rightarrow ^3{}H + Y \)

SNO only detects 6 MeV \( \nu \) so it is sensitive to all \( \nu_x \) above 2.2 MeV threshold but has no information on energy of \( \nu_x \).
Smoking Gun

SNO finds $\phi \sim 3 \phi_{CC}$

$\phi_{CC} \Rightarrow \phi_{CC}$

This is direct proof that non-electron flavor neutrinos are coming from the Sun. $B$ decays have energies too small to make $\nu_e$ or $\nu_\mu$, directly.

Thus, somewhere between production and detection we have flavor conversion.

$\nu_e \rightarrow \nu_\mu$ or $\nu_\tau$

Note, we don't know which $\mu$, or $\tau$ at this time.

The solution to the solar $\nu$ problem involves new neutrino physics!

30 Years ago Davis found solar $\nu$ problem. Since then 5 other experiments have confirmed it and finally disprove that...
it involves new neutrino physics.

By studying the Sun with solar neutrino oscillations, we have learned not about the solar core environment or about the nuclear reactions themselves, but about neutrinos themselves.

We will discuss neutrino oscillations next.

What does the Sun bring to us? Studies

1. Source of low energy $\nu_e$ vs. $\bar{\nu}_e$ In general, accelerators make $\nu_e$ and $\bar{\nu}_e$ at higher energies. We will see that low $E_\nu$ are more likely to oscillate.

2. Very long baseline [1 AU] to probe oscillations that only take place over very long distances.

**Important Note**

SNO's predictions agree well with $\Delta m^2$ and $\sin^2(\theta)$, including its dependence on $T_{\text{sol}}$ and all. This is the first time a solar $\nu$ result agrees with theory!
Once we measure the oscillation parameters [\nu masses and mixing angles] we can use the solar \nu results to start probing the Sun.

**What comes next?**

Further solar \nu experiments to better pin down the oscillation parameters. These include real time measurements of the Be \nu flux [Borexino and Kamland] and low E pp flux.

Can one directly test neutrino oscillation parameters with terrestrial experiment? Surprisingly yes. Kamland looks at oscillations \nu_e \rightarrow \nu_x or \nu_x \rightarrow \nu_e from reactor antineutrinos over 100s of km.

**Neutrino Oscillations**