First Results from KamLAND

Evidence for Reactor Anti-neutrino Disappearance

G. Gratta, Stanford University for the KamLAND Collaboration
$\nu_e$ are abundant by-products of nuclear fusion in the sun

\[ p + p \rightarrow ^{2}H + e^+ + \nu_e + 0.42\text{MeV} \]

\[ p + e^- + p \rightarrow ^{2}H + \nu_e + 1.44\text{MeV} \]

"pp" 99.75%

\[ ^{2}H + p \rightarrow ^{3}He + \gamma + 5.49 \text{MeV} \]

86%

\[ ^{3}He + ^{3}He \rightarrow \alpha + 2p + 12.86\text{MeV} \]

14%

\[ ^{3}He + \alpha \rightarrow ^{7}Be + \gamma + 1.59\text{MeV} \]

"hep" 2.4*10^{-5}

\[ ^{3}He + p \rightarrow \alpha + e^+ + \nu_e \]

"7Be" 99.89%

\[ ^{7}Be + e^- \rightarrow ^{7}Li + \gamma + \nu_e + 0.8617\text{MeV} \]

0.11%

\[ ^{7}Be + p \rightarrow ^{8}B + \gamma + 0.14\text{MeV} \]

"8B" 0.11%

\[ ^{8}B \rightarrow ^{8}Be + e^+ + \nu_e + 14.6\text{MeV} \]

\[ ^{8}Be \rightarrow \alpha + \alpha + 3\text{MeV} \]
Homestake Mine, Lead SD
1400 m underground

615 tons of perchloroethilene
\((C_2Cl_4)\)

2.2\times10^{30} \text{ atoms of } ^{37}\text{Cl}
^{36}\text{Ar or } ^{38}\text{Ar added to the fluid as carrier gas}

Data taken continuously since 1967 (!)
3 types of experiments detecting solar neutrinos

- **Chlorine**: $^{37}\text{Cl} + \nu_\text{e} = ^{37}\text{Ar} + \text{e}^-$
  1 exp running >30 yrs (US)
- **Gallium**: $^{71}\text{Ga} + \nu_\text{e} = ^{71}\text{Ge} + \text{e}^-$
  3 exp (Russia, Italy)
- **Cerenkov**: $\text{e}^- + \nu_\text{e} = \text{e}^- + \nu_\text{e}$
  3 exp (Japan, Canada)

$L = 10^8\text{km}$
Conclusion':

We do not see enough vs !

• do we understand the sun well enough ?

• are vs playing tricks ?

"It starts to be really interesting ! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately it will not be easy to demonstrate this, even if nature works this way...”  B.Pontecorvo, 1972
SNO: 1 kton of D$_2$O

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]
\[ \nu_e + e^- \rightarrow \nu_e + e^- \]
\text{sensitive to a } \nu_e, \nu_x \text{ mix}

\[ \nu_e + ^2H \rightarrow \nu_x + p + n \]
\text{equally sensitive to all neutrinos}

\[ \nu_e + ^2H \rightarrow p + p + e^- \]
\text{sensitive to } \nu_e \text{ only}
For 2 flavors this simplifies:

\[ U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \]

Only one mixing parameter \( \theta \)

\[ m_1^2 - m_2^2 \quad [\text{eV}^2] \]

\[ P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \quad \sin^2 \frac{1.3 \Delta m^2 L}{E} \quad [\text{MeV}] \]

Neutrino oscillations \( \Rightarrow \quad m_\nu \neq 0 \)
If the correct interpretation is that neutrinos oscillate only two solutions are compatible with all solar data.
All of this is very interesting…

…but wouldn’t it be great if we could reproduce it with artificial means?
Nuclear reactors are very intense sources of $\nu_e$ deriving from beta-decay of the neutron-rich fission fragments.

$N_1$ and $N_2$ still have too many neutrons and decay:

$$N_2 \rightarrow N_3 + e^- + \nu_e$$

Look for a deficit of $\bar{\nu}_e$ at a distance $L$. 

December 2002

KamLAND: Evidence for Neutrino Oscillations
Need to think regionally: large concentration of nuclear power plants exist in Europe, eastern US and Japan.
December 2002

KamLAND: Evidence for Neutrino Oscillations

~1 km high
Mt Ikenoyama
KamLAND: the ultimate reactor neutrino oscillation experiment

- 1 kton liq. Scint. Detector in the Kamioka cavern
- ~1300 17” fast PMTs
- ~700 20” large area PMTs
- 30% photocathode coverage
- H₂O Cerenkov veto counter
- Multi-hit deadtime-less electronics
- $\Delta m^2$ sensitivity $7 \times 10^{-6}$ eV²
LMA-MSW solution within reach on the earth!
The total electric power produced “as a by-product” of the vs is:

• ~60 GW or...
• ~4% of the world’s manmade power or...
• ~20% of the world’s nuclear power

Total expected signal from reactors in 1 kton:

≈ 2 ev/day

Expected S/N ratio ≈ 20

@ 10^{-14} U, Th, ^{40}K contamination in the scintillator
Since reactors produce $\bar{\nu}_e$ while the sun produces $\nu_e$ the equivalence of solar neutrino oscillations with what can be observed with the KamLAND reactor experiment rests on the validity of CPT.

An unexpected oscillation pattern in KamLAND could be an indication of CPT violation.
KamLAND: neutrino physics on a shinkansen

- Summer 2000: PMT installation
- Winter 2000-01: Veto counter installation
- Feb 2001: Balloon insertion
- Mar-Apr 2001: Balloon inflation and test
- Apr-May 2001: Plumbing for fill
- Jun-Sept 2001: Fill MO and LS
- Sept 2001: FEE/DAQ/Trigger int. (LBL)
- end Sept 2001: First data taking with FEE
- Jan 22, 2002: Begin Data Taking
- Dec 6, 2002: First Physics Paper (hep-ex/0212021)
Scintillator is a blend of 20% pseudocumene and 80% dodecane

Different density paraffines are used to tune the density of buffer to 0.995 of that of the scintillator

PPO concentration is 1.5 g/l of the final scint.

During blending the liquids are pre-purified.
Anti-Neutrino Candidate

**Prompt Signal**

- $E = 3.20$ MeV
- $\Delta t = 111$ $\mu$s
- $\Delta R = 34$ cm

**Delayed Signal**

- $E = 2.22$ MeV

December 2002

KamLAND: Evidence for Neutrino Oscillations
### Observed Event Rates with $E_{\text{prompt}} > 2.6$ MeV

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>54 events</td>
</tr>
<tr>
<td><strong>Expected</strong></td>
<td>86.8 ± 5.6 events</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>0.95 ± 0.99 events</td>
</tr>
<tr>
<td>accidental</td>
<td>0.0086 ± 0.0005</td>
</tr>
<tr>
<td>$^9\text{Li}/^8\text{He}$</td>
<td>0.94 ± 0.85</td>
</tr>
<tr>
<td>fast neutron</td>
<td>&lt; 0.5</td>
</tr>
</tbody>
</table>
Evidence for Reactor $\bar{\nu}_e$ Disappearance

for $E_\nu > 3.4 \text{ MeV}$

\[
\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085 \text{ (stat)} \\
\pm 0.041 \text{ (syst)}
\]

Inconsistent with $1/R^2$ flux dependence at 99.95 % C.L.
After 30 years of work reactor neutrinos finally are unmasked!
Fit to Oscillations for $E_{\text{prompt}} > 2.6$ MeV

Best fit:

$\Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2$

$\sin^2 2\theta = 1.0$
Conclusions:

KamLAND observes a >4 sigma deficit of reactor anti-neutrinos

Assuming that CPT is conserved the interpretation of this result in terms of oscillations is smack in the middle of the LMA-MSW solution: The solar neutrino puzzle is now completely understood: we can reproduce it on Earth!

We can move on and use neutrinos to do solar physics!

More precision data on oscillation and many other phenomena is on the way... stay tuned!