Solar Neutrinos: Present and Future

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On the Study of Neutrino Properties

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• Neutrinos: An Overview
• The Solar Neutrino Problem
• Tackling the Solar Neutrino Problem
  – Neutrino Oscillations
• Experiments
  – Now
  – Future
• Conclusions
Neutrinos!

- Fermions…
- Left-Handed Helicity…
- Massive…

- Interact only via the weak interaction.
  - Small weak interaction cross-section allows neutrinos to pass through matter easily thus making neutrinos difficult to detect.
Figure I: The Proton-Proton Chain (D. Szam)
The Solar Neutrino Problem

As neutrino detectors became more accurate, researchers noted a serious discrepancy between the number of solar neutrinos detected versus the number predicted by the standard model.

This became known as the solar neutrino problem.

Possible solution: Change the Standard Model!
Neutrino Oscillations

Measurements by SNO of CC and NC reactions

\[ \nu_e + d \rightarrow p + p + e^- \quad \text{(CC)} \]
\[ \nu_x + d \rightarrow p + n + \nu_x \quad \text{(NC)} \]

provide results that are inconsistent with the hypothesis that neutrino flavor is invariant by more than seven standard deviations.
Neutrino flavor field is a linear combination of neutrino mass fields (with definite mass):

\[
\begin{align*}
\left| \mathbf{\nu}_f \right\rangle &= \sum_{m=1}^{3} U_{fm}^* \left| \mathbf{\nu}_m \right\rangle \\
&= U_{e1} \mathbf{\nu}_{e1} + U_{\mu1} \mathbf{\nu}_{\mu1} + U_{\tau1} \mathbf{\nu}_{\tau1} + U_{e2} \mathbf{\nu}_{e2} + U_{\mu2} \mathbf{\nu}_{\mu2} + U_{\tau2} \mathbf{\nu}_{\tau2} + U_{e3} \mathbf{\nu}_{e3} + U_{\mu3} \mathbf{\nu}_{\mu3} + U_{\tau3} \mathbf{\nu}_{\tau3}
\end{align*}
\]

Where \( f = e, \mu, \tau \) and \( U_{fm} \) are the entries of a unitary mixing matrix:

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
c_{12} & s_{12} & 0 & 1 & 0 & 0 & 1 & 0 & 0 & c_{13} & 0 & s_{13} \\
-s_{12} & c_{12} & 0 & 0 & c_{23} & s_{23} & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & -s_{23} & c_{23} & 0 & 0 & \epsilon^{i\delta} & -s_{13} & 0 & c_{13}
\end{pmatrix}
\]
For oscillations in vacuum, survival probability for solar electron neutrinos traveling a distance $L$ is:

$$P = 1 - \sin^2\left(2\theta_{12}\right) \sin^2 1.27 \frac{\Delta m_{12}^2 L}{E}$$

Repeated measurements determine parameters.

Figure III: (a) Solar Neutrino Analysis, (b) SN + KamLAND results (from SNO)
Figure II: Calculated Spectrum of Solar Neutrinos (Bahcall et al.)
Experiment

- Main objectives:
  - Improve accuracy of oscillation parameters $\theta_{12}, \Delta m_{12}^2$ and $\theta_{13}$.
  - Confirmation of matter effects (MSW)
  - Searching for effects from new physics:
    - Sterile Neutrinos.
    - Non-standard flavor-changing interactions.
    - Mass-varying neutrinos.
Two Classes

- Measurements of elastic scattering from electrons with some sensitivity to all neutrino flavors.

- Measurements using the Charged Current reaction sensitive only to electron neutrinos.
Elastic Scattering Experiments

• Borexino (NOW)
  – Plans to start filling detector in early ’06.
  – Expect to be able to observe flux from $^7\text{Be}$ clearly.

• KamLAND (2007)
  – Working now to reduce radioactive background signatures.
  – Goal is observation of $^7\text{Be}$ with 1000 ton liquid scintillator.
• SNO →SNO+ (2008)
  – Replacing heavy water in SNO detector with 1000 metric tons of liquid scintillator.
  – Measuring pep neutrino flux to test MSW energy dependence.

• CLEAN (?)
  – Developing liquid neon detector to detect pp neutrinos.

• HERON (?)
  – Designing liquid helium detector.
Charged Current

- **LENS**
  - Developing 190 ton In-load liquid scintillator for measurement of $pp$, $7\text{Be}$, and CNO neutrinos via electron capture:

$$p^+ + e^- \rightarrow n + \nu_e$$

- **MOON**
  - Developing a Molybdenum detector to hopefully observe neutrinoless double beta decay, as well as study study $7\text{Be}$ neutrinos.
Conclusions

• Neutrinos have interesting properties and hence are worth studying.

• Solar neutrino experiments have provided very valuable results, showing clear evidence for neutrino oscillations.

• Future experiments will more clearly define predicted neutrino fluxes based on oscillation parameters.