Neutrino Oscillations

1. Introduction
2. Status and Prospects
   A. Solar Neutrinos
   B. Atmospheric Neutrinos
   C. LSND Experiment
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3. Conclusions

Plenary talk given at
DPF’99
UCLA, January 9, 1999
Introduction

Leptons and quarks are closely related (GIM, 1970).

Either neutrino masses are zero (due to some symmetry) or they will have different weak and mass eigenstates, as quarks do. The evidence is now extremely strong for the latter.

Neutrinos differ from charged leptons and quarks in two ways:

• They have tiny masses (experimental).
• They can have Majorana mass terms (theoretical).

The conventional wisdom is that these are related (e.g. the see-saw mechanism). Thus the study of neutrino oscillations may give us a window on the physics of very high energies.
In analogy to the quarks, we can express the relationship between the weak eigenstates \((\nu_e, \nu_\mu, \nu_\tau)\) and the mass eigenstates \((\nu_1, \nu_2, \nu_3)\) as

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}.
\]

Then the probability of oscillation is

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i=1}^{3} \sum_{j=i+1}^{3} U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}^* \sin^2 \left( \frac{1.27 \Delta m_{ij}^2 L}{E} \right),
\]

where \(E\) is in GeV, \(L\) is in km, and \(\Delta m_{ij}^2 = |m_i^2 - m_j^2|\) is in \((eV/c^2)^2\).

Note that there are 3 \(\Delta m_{ij}^2\), but only 2 are independent.

Thus, if there are 3 experimental mass scales, for which we now have some evidence, there must be either

- a sterile neutrino, or
- at least one mass scale has not been correctly determined.
Oscillations (continued)

In general, oscillations will decouple so that they can be approximated by a two-neutrino oscillation:

\[
\begin{pmatrix}
\nu_\alpha \\
\nu_\beta
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix},
\]

and

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 (2\theta) \sin^2 \left( \frac{1.27 \Delta m_{12}^2 L}{E} \right).
\]

Note that at low $\Delta m_{12}^2$, $P \propto \frac{L^2}{E^2}$, whereas at high $\Delta m_{12}^2$, $P(\nu_\alpha \rightarrow \nu_\beta) \approx \frac{1}{2} \sin^2 (2\theta)$.

For $\Delta m_{12}^2 = 5 \times 10^{-3} \left( \text{eV} / c^2 \right)^2$. 

![Graph showing neutrino oscillations](image)
Solar Neutrinos

The sun produces electron neutrinos with energies up to 18 MeV, and they can oscillate over a path of 150,000,000 km, and be detected by either radiochemical techniques or by neutrino-electron scattering in water.

The major mechanism for producing neutrinos in the sun is the p-p cycle. (See figures).

The measured rates are inconsistent with any solar model. (See figure).

The rates suggest neutrino oscillations either due to vacuum oscillations (“just-so”) at around $\Delta m^2 \approx 10^{-10} \ (eV / c^2)^2$, (see figure), or matter oscillations (Mikheyev-Smirnov-Wolfenstein) around $\Delta m^2 \approx 10^{-5} \ (eV / c^2)^2$ (see figure).
Solar $p-p$ Cycle

$$p + p \rightarrow d + e^+ + \nu_e$$

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

$$d + p \rightarrow ^3\text{He} + \gamma$$

$$^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p$$

$$^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e$$

$$^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$$

$$^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e$$

$$^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$$

$$^7\text{Be} + p \rightarrow ^8\text{B} + \gamma$$

$$^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_e$$

$$^8\text{Be} \rightarrow ^4\text{He} + ^4\text{He}$$
Solar Energy Spectrum

From http://www.sns.ias.edu/~jnb/
Solar Rate Results

Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 98

From http://www.sns.ias.edu/~jnb/
SuperK Fits to Ga+Cl+SK Rates

99% Confidence Level
SuperK Fits to Ga+Cl+SK Rates
SuperKamiokande

50,000 T water Cerenkov detector with 13,000 20-inch photomultipliers.

New solar data at this conference:

- Data extended from 504 days to 708 days
- Energy spectrum extended from 6.5 MeV to 5.5 MeV
“Super Low Energy” Analysis (419 days)
A deviation from flat would be a smoking gun for oscillations.

We see a deviation at the high $E$ end, but this is not theoretically reliable, because the hep contribution in this region could be off by more than an order of magnitude. (Bahcall and Krastev, PL B436,243). Leaving the hep contribution open is equivalent to ignoring the last four points (Smy).

(Red line is my hand-drawn fit.)
Solar Spectrum Fits

\[ \sin^2 \theta = 0.0063 \]
\[ \Delta m^2 = 7.9 \times 10^{-9} / 5 \times 10^{-6} \text{ eV}^2 \]

\[ \sin^2 \theta = 0.87, \Delta m^2 = 4.3 \times 10^{-5} \text{ eV}^2 \]
Day-Night Effect

A day-night difference would be a smoking gun for a large-angle MSW effect.

Day-night asymmetry = -0.026 ± 0.016 ± 0.013
A seasonal variation beyond $1/r^2$ would be a smoking gun for vacuum oscillations.
Solar Region Prospects

• In spite of increased statistics and lower energy data from SuperK, our qualitative understanding of the solar neutrino region has not changed at this conference.

• More data from SuperK and an extension of the analysis to 5 MeV should provide additional discrimination among oscillation regions, clarify the hep cross section, and possibly provide a smoking gun.

• SNO is a 1 kT D$_2$O detector with 10,000 8-inch photomultipliers, giving 30% photocathode coverage.

The deuterium target opens up two important new channels:

**Charged current:** $\nu_e + d \rightarrow p + p + e^-$, 12.7 events/day
   The electron carries most of the neutrino energy giving good energy resolution (see figure).

**Neutral current:** $\nu_x + d \rightarrow p + n + \nu_x$, 5.5 events/day
   A test of $\nu_e \rightarrow \nu_{\mu,\tau}$ vs. $\nu_e \rightarrow \nu_s$. 

SNO CC Electron Spectrum

SNO CC Electron Spectrum
6000 Events (2 year)

- MSW Nonadiabatic
- MSW Large-Angle
- Vacuum (B)
- Vacuum (D)
- Vacuum (F)

Events / MeV

$E_e$ (MeV)
SNO Schedule

Feb 99    Finish filling
Aug 99    Finish commissioning, start runs:
          1 yr run without MgCl$_2$
          1 yr run with MgCl$_2$
          1 yr run with $^3$He neutron detectors
Cosmic rays hit the atmosphere, creating pions:

\[ p + N \rightarrow X + \pi^\pm \]

\[ \rightarrow \mu + \nu_\mu \]

\[ \rightarrow e + \nu_e + \nu_\mu \]

Absolute flux is uncertain to 20%, so most measurements use ratios, which are better determined.
Up/Down Asymmetry

New SuperKamiokande data (736 days FC / 685 days PC)
Angular Distributions

For $\nu_\mu \rightarrow \nu_\tau$ oscillations.

Fit probability 58%.
10-Bin Angular Distributions

For $\nu_\mu \rightarrow \nu_\tau$ oscillations.
Angular Distributions

For $\nu_\mu \rightarrow \nu_s$ oscillations
Angular Distributions

For $\nu_\mu \to \nu_e$ oscillations.

Fit probability < 0.1%.
SuperK Atmospheric Allowed Region

\( \nu_\mu - \nu_\tau \)

\( \Delta m^2 (\text{eV}^2) \)

\( \sin^2 2\theta \)

- 68\% C.L.
- 90\% C.L.
- 99\% C.L.
Allowed Regions

\[
\nu_\mu - \nu_\tau
\]

\[\Delta m^2 (\text{eV}^2)\]

90% C.L.

- Kamiokande
- Super-Kamiokande (Dec. 98)
- Super-Kamiokande (Jun. 98)

\[\sin^2 2\theta\]
Allowed Region

$\nu_\mu - \nu_S$

$\Delta m^2$ (eV$^2$)

$\sin^2 2\theta$

68% C.L.
90% C.L.
99% C.L.
Upward Through and Stopping Muons

Parent Neutrino Energy Distribution (muon track length > 7m)

Super-Kamiokande (Preliminary)

Bartol-GRY94

Honda-GRY94

Upward Through-Going Muons

Upward Stopping Muons

$\frac{d\text{flux}}{d\log E} \times 10^{-3} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$

$E_{\nu}$ (GeV)
Stopping Muon Angular Distribution

Zenith Angle Dist. of Upward Stopping Muon Flux

Super-Kamiokande (Preliminary) statistical error only

Upward Stopping Muons (>7m) BG subtracted
123.8 events/516 livedays (Apr 1996 - Jan 1998)
Ave. Flux $0.36 \pm 0.02 \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$

Expected Flux (Honda-GRV94)
- no oscillation $\alpha = -10\%$
- $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.2 \times 10^{-3}$, $\alpha = +10\%$, $\eta = -7\%$
Stopping/Through Ratio

Zenith Angle Dist. of Ratio (Upward Stop/Thru)

Super-Kamiokande (Preliminary) statistical error only

- Upward Stopping Muons (>7m) BG subtracted
  123.8 events/516 liveldays (Apr 1996 - Jan 1998)
- Upward Through Going Muons (>7m) BG subtracted
  609.7 events/537 liveldays (Apr 1996 - Jan 1998)

Expected Ratio (Honda: GRV94)
- no oscillation
- \( \sin^2 2\theta = 1.0, \Delta m^2 = 3.2 \times 10^{-3}, \eta = -7\% \)

Theo. Avg. Ratio 0.37 ± 0.05
Obs. Avg. Ratio 0.22 ± 0.03
Upward Muons Allowed Regions

\[ \text{SK prelim. } \nu_\mu \leftrightarrow \nu_\tau \text{ osc. Conf. Intervals} \]

\[ \star \text{ Best Fit for combined upmu shape+ratios} \]
\[ \sin^2 2\theta = 1, \Delta m^2 = 3.2 \times 10^{-3} \text{ eV}^2 \]
\[ \alpha = +10\%, \eta = -7\% \]

\[ \Delta m^2 (\text{eV}^2) \]

\[ \sin^2 2\theta \]

- 68% CL
- 90% CL
- 99% CL
SuperKamiokande Best Fit to All Data

- Best Fit for all atm-ν
  \( \sin^2 2\theta = 1, \Delta m^2 = 3.2 \times 10^{-3} \text{ eV}^2 \)

- Uses FC+PC+upthru-μ+upstop-μ
  \( \alpha = +9\%, \eta = -4\%, \text{FC+PC/upthru}=0.2\% \)

- \( \chi^2_{\text{min}} = 70.2/82 \text{ dof} \)
- No-osc. \( \chi^2 = 214.3/84 \text{ dof} \)
Soudan 2 Atmospheric $L/E$

Soudan 2 is a 1 kT, fine-grained, gas-iron detector. It uses its ability to see proton recoils to define a high angular-resolution sample. Based on 4.2 kT-yr,

\[
\Delta m^2 = 1 \times 10^{-3} 
\]

\[
\Delta m^2 = 5 \times 10^{-3} 
\]

\[
\Delta m^2 = 1.1 \times 10^{-2} 
\]

\[
\Delta m^2 = 1 \times 10^{-2} 
\]
Soudan 2 Atmospheric Allowed Regions
MACRO Atmospheric Allowed Region
Atmospheric Region Prospects

K2K is an experiment sending a neutrino beam from KEK to SuperKamiokande over a 250 km baseline. It will start this year.
MINOS is an experiment sending a neutrino beam from Fermilab’s Main Injector to the Soudan mine over a 730 km baseline. It is scheduled to start in 2002.

The far detector is 468 plane, 5.4 kT magnetized iron-scintillator sandwich.

The MINOS beams:
MINOS Charged Current Spectra

Gary Feldman  Neutrino Oscillations
MINOS Sensitivity

CC Disappearance Test

$\Delta m^2 (eV^2)$

$\sin^2 (2\theta)$

- 90% C.L. (1.28 sigma)
- 99.8% C.L. (4. sigma)

PH2(low) beam
10 kt years
2% flux unct.

KAMIOKANDE Sub/Multi-GeV data
SUPER-KAMIOKANDE Sub/Multi-GeV
The LSND experiment at Los Alamos detects neutrinos from a stopped pion beam:

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

\[ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]

The experiment then looks for \( \nu_\mu \rightarrow \nu_e \) oscillations, where the \( \nu_e \) is detected by observing \( \nu_e p \rightarrow e^+ n \), followed by a \( \gamma \) from \( np \rightarrow d\gamma \).

Current status:

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<th>Mode</th>
<th>Total</th>
<th>Backgrnd</th>
<th>Excess</th>
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<tr>
<td>DAR</td>
<td>70</td>
<td>30.5 ± 2.0</td>
<td>39.5 ± 8.8</td>
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<tr>
<td>DIF</td>
<td>40</td>
<td>20.1 ± 2.1</td>
<td>18.1 ± 6.6</td>
</tr>
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LSND DAR Spectrum
LSND Allowed Regions

- BNL776
- Karmen
- Buğey
- CCFR
- NOMAD

90% (L/L_{max} > 0.1)
99% (L/L_{max} > 0.01)

LSND 93-97 Preliminary
The Karmen experiment is similar to LSND, but it does not appear it will have enough sensitivity to make a definitive statement.

The MiniBooNE experiment at the 8 GeV Fermilab Booster using a tank of pure mineral oil as a detector. It plans to cover the whole LSND region:
High-Mass Region

The motivation for searching for neutrino oscillations in the range \( \Delta m^2 > \text{few (eV} / c^2 \text{)}^2 \) was that such neutrinos would form the hot dark matter that fits to galactic structure and cosmic background anisotropy seem to require.

The major experiments are CHORUS and NOMAD at CERN, both of which have now completed data taking.

CHORUS searches for \( \tau \)’s that leave a kinked track in a photographic emulsion. NOMAD searches for kinematic \( \tau \) signatures due to missing transverse momentum carried off by neutrinos in the \( \tau \) decay.

NOMAD has analyzed most of its data and has 21 candidates for 24 expected background. CHORUS has only analyzed 15% of its low-background data (muonic mode) and has observed no candidates.

Both experiments report high-\( \Delta m^2 \) upper limits at 90% C.L. of \( \sin^2(2\theta) < 1.2 \times 10^{-3} \) (see figure).
High-Mass Excluded Regions

\[ \Delta m^2 \ (\text{eV}^2) \]

\[ \sin^2 2\theta \]

- NOMAD
- CCFR
- CHARM II
- CHORUS
- E531
- CDHS

\[ \nu_\mu \rightarrow \nu_\tau \]

90\% C.L.
High-Mass Region Prospects

The U.S. next generation experiment, COSMOS, has folded, and the future of the European next generation experiment, TOSCA, is not clear.

I do not think that there will be a next generation high-mass experiment in the near future, unless CHORUS finds some hints in the remainder of its data.
Conclusions

Atmospheric ★★★
Consistent picture seen in several ways by several experiments. Detailed fit to the angular distribution is a smoking gun. Parameters are beginning to be pinned down.

Solar ★★
Large effect seen by all experiments. Mass-angle region not pinned down. Still questions about the solar model. No smoking guns.

LSND ★

High-Mass
No signal $\Rightarrow$ no star.