Neutrino Oscillation Experiments

- **Reactor Experiments**

  - **CHOOZ** (hep-ex/9711002)
    Chooz set a limit of $\Delta m^2 < 0.9 \times 10^{-3}$ eV^2 at $\sin^2 2\theta = 1$ and $\sin^2 2\theta < 0.18$ at large Δm^2 by observing reactor neutrinos at Chooz in the Ardennes. The detector was located about 1 km from the 8.3 GW reactor. The actual result is given as $R_{measured}/R_{expected} = 0.98 \pm 0.04 \pm 0.04$ This is based on 1320 measured neutrino events accumulated in 2718 hours of running with a 5-ton target of 0.09% Gd-loaded scintillator.

  - **Palo Verde** (verbatim from an abstract from Bull. Am. Phys. Soc., April 1997)
    A new long baseline neutrino oscillation experiment is being built at the Palo Verde Nuclear Generating Station near Phoenix, Arizona. The detector is based on Gd-loaded liquid scintillators with water shielding and veto countors. Its sensitivity after three years running will be $\Delta m^2 = 1.5 \times 10^{-3}$eV^2, one order of magnititude smaller than the current limits. This will conclude whether the atmospheric neutrino anomaly is caused by neutrino oscillations or not. We will descirbe the principles and report the current status of the experiment.

  - **KamLAND** (Stanford-HEP-98-03)
    KamLAND will use the Kamiokande cavern to house a 1 kt liquid scintillator target. A total of 750 events per year are expected, dominated by five reactors at distances from 140 to 210 km. The factor of 200 increase in L relative to CHOOZ and thus 200^2 in flux is offset by a factor of 130 GW/8 GW = 16 in power and a factor of 200 in detector mass. This still leaves a deficit of say, 13. CHOOZ obtained events at about 4000/y, while KamLAND predicts 750/y. This accounts for a factor of 5 (out of the 13), giving rough agreement. Because of the factor of 200 in L, the limit on Δm^2 should be decreased from 0.9×10^{-3}eV^2 to about 4.5×10^{-6}eV^2, in rough agreement with the KamLAND prediction of 7×10^{-6}eV^2.

- **Accelerator Experiments: e appearance**
  - **LSND** (PRL, 81, 1774 (1998); op. cit. 77, 3082 (1996); PRC 54, 2685 (1996))
    LSND has reported evidence for $\overline{\nu}_\mu \to \overline{\nu}_e$ using μ^+ decay at rest and for $\nu_\mu \to \nu_e$ from π^+ decay in flight. In the latter, 40 events of electron appearance are found with a background of 21.9 ± 2.1. The ν_μ flux is in the 60 - 200 MeV range. The muons are generated at a target 30 m upstream from the detector and also by two thin carbon targets further upstream. The oscillation probability is claimed to be $2.6 \pm 1.0 \pm 0.5) \times 10^{-3}$. Using $L = 30$m, $E = 150$ MeV, we would deduce $\Delta m^2 = 0.2\mathrm{eV}^2$, in good agreement with the LSND figure.
  - **KARMEN** (hep-ex 9809007)
    KARMEN uses decay at rest of π^+ and μ^+, giving equal numbers of $\nu_\mu, \overline{\nu}_\mu$, and ν_e. The goal is to look for oscillations into $\overline{\nu}_e$. For full mixing, the expected number of events would have been 811. Instead, none was observed, though the background was calculated to be 2.88 ± 0.13. They set a limit of $N = 1.07$ events at 90%CL. Taking $L = 17.7$ m and $\langle E \rangle = 40$ MeV, we find $\Delta m^2 < (40/(17.7 \times 1.27))(1/\sqrt{811}) = 6 \times 10^{-2}$, in some disagreement with LSND.
  - **MiniBooNE**(portia.fnal.gov/ jconrad/miniboone.html)
    MiniBooNE would use neutrinos produced in the interactions of 8 GeV protons from the Fermilab booster and a 445 t (fiducial) target of mineral oil located 500 m away. This experiment would produce enormous numbers of events, on the order of 10^6. If the LSND results are correct, there would be of order 1000 electron appearance events in MiniBooNE.
- **Accelerator Experiments: $\overline{\nu}_\mu$ disappearance**
  - **MINOS** (www.hep.anl.gov/NDK/Hypertext/numi.html)
    MINOS will use the 120 GeV beam from the Fermilab Main Injector and an 8 kt detector in the Soudan Mine, 730 km away. Of the 8.1 kt, 5.6 kt are inside the fiducial volume. If only two of the three supermodules are built, the fiducial volume is 3.3 kt.

The original design called for a wide-band beam "H66," but the current baseline design uses a lower energy configuration, either PH2(medium), with a mean energy of about 7 GeV or PH2(low) with a mean energy of about 3 GeV. While the H66 beam would have given about 3000 event/kt/y, the lower energy beams will give more like 1000 events/kt/y (medium) or 200 events/kt/y (low). A limit of 10% for disappearance would give limits of $\Delta m^2 = 1 - 2 \times 10^{-3}\mathrm{eV}^2$.

MINOS would measure several independent quantities: the energy spectrum for "CC" (charged current events of $\overline{\nu}_\mu$), the ratio of "NC" (not just neutral current events, but events without muons) to "CC," the energy spectrum for "NC" events, and also the number of electron appearance events. For $\overline{\nu}_\mu \to \overline{\nu}_\tau$ oscillations, the most powerful statistic is the ratio NC/CC. For $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations, the most powerful measurement is actual appearance of charged current $\overline{\nu}_e$ events, recognized by the shower patters in the calorimeter. The limitation is said to be the fluctuations in such events originating from initial contamination of the beam by $\overline{\nu}_e$. At $\sin^2 2\theta = 1$, a limit of $\Delta m^2 = 3 \times 10^{-3}\mathrm{eV}^2$ is said to be attainable in 16 kt-y of running.

- **Muon storage ring**

- **Accelerator Experiments: τ appearance**

  - **CHORUS** (hep-ex/9807024) CHORUS uses 770 kg of nuclear emulsion with auxilliary electronic tracking to search for τ appearance. The mean neutrino energy is 27 GeV and the distance from the target to the emulsion is about 850 m. An analysis of 68 k charged current events and 7 k events without a visible muon led to no τ candidates. From this, CHORUS derived a limit $P(\nu_\mu \to \nu_\tau) < 6.0 \times 10^{-4}$. Using these numbers, the high Δm^2 limit is $\sin^2 2\theta < .13 \times 10^{-3}$ and the $\sin^2 2\theta = 1$ limit is $\Delta m^2 < 0.6\mathrm{eV}^2$.

  - **NOMAD** (*Phys. Lett.* **B431**, 219 (1998))
    NOMAD has published limits on $\nu_\mu \to \nu_\tau$ based on kinematical identification of τ decays. The NOMAD detector has a small mass (2.7 t) but is located only 625 m from the target. The result

is a large sample of charged current events (162 k events). The signature for a τ is the missing momentum carried away by the ν_τ in $\tau \to \nu_\tau X$, where X can be e, μ, or hadrons. The active target is the drift chamber itself.

Very roughly the numbers work out as follows. The typical efficiency for each mode is about 3%. The total branching ratio for the modes searched is 70%. The cross section for τ production is suppressed by about 0.5 from threshold effects (the mean ν_μ energy is 23.6 GeV for which I find $\Theta \approx 1/3$). We can estimate the total number of τ produced ignoring the factors for mixing and oscillation as $1.6 \times 10^5 \times 0.03 \times 0.7 \times 0.5 = 1700$. The more detailed calculation in the NOMAD paper gets 1582. They end up taking a 90% CL limit of 3.3 events (they found one τ^- with a background of $2.7^{+3.0}_{-0.8}$ and 27 τ^+ with a background of 28 ± 6. In the "high Δm^2" domain this gives $\sin^2 2\theta < 4.2 \times 10^{-3}$ while for $\sin^2 2\theta = 1$, it gives $\Delta m^2 < 1.4$ eV^2.

- **Solar neutrino experiments** The 1998 RPP review of solar neutrino experiments, written by Nakamura lists the following results:

Experiment	Technique	Result	Expectation
Homestake	$^{37}\mathrm{Cl} \to ^{37}\mathrm{Ar}$	2.33 ± 0.25 SNU	≈ 8 SNU
GALLEX	$^{71}\mathrm{Ga} \to ^{71}\mathrm{Ge}$	$69.7 \pm 6.7^{+3.9}_{-4.5}$ SNU	≈ 130 SNU
SAGEX	$^{71}\mathrm{Ga} \to ^{71}\mathrm{Ge}$	$73^{+18}_{-16}{}^{+5}_{-7}$ SNU	≈ 130 SNU
Kamiokande	water cerenkov	$2.80 \pm 0.19 \pm 0.33$ (some units)	≈ 6(same units)

To explain this with ordinary (vacuum) neutrino oscillations would require $\Delta m^2 \times 1.5 \times 10^8$km/few $MeV \approx 1$, or $\Delta m^2 \approx 10^{-11}$eV^2. Moreover this would have to work over a range of neutrino energies to account for the suppression in the variety of experiments with different thresholds. A solution of this sort needs to be very delicately tuned.

The ordinary solutions to the solar neutrino problem rely on the Mikheyev-Smirnov-Wolfenstein mechanism. The passage of neutrinos through matter can be analyzed as if it were described by an index of refraction. The index of refraction is determined by the forward elastic scattering amplitude. This amplitude is due to neutral current scattering alone for ν_μ and ν_τ. However ν_e also has a contribution from charged current scattering off electrons. This leads to additional mixing over and above the mixing that would be present in vacuum. Using MSW, solutions are found in the region $\Delta m^2 = 5 \times 10^{-6}\mathrm{eV}^2, \sin^2 2\theta = 8 \times 10^{-3}$ and $\Delta m^2 = 1.6 \times 10^{-5}\mathrm{eV}^2, \sin^2 2\theta = 0.6$.

- **Cosmic ray experiments**
  - **Super Kamiokande**(hep-ex/9807003)
    Super K uses a 50 kt water cerenkov detector with 11k PMTs. They report on 4 k events in a 33-kt y exposure restricted to the 22.5 kt fiducial volume. The primary comparison is between ν_μ and ν_e from cosmic rays. These are generated as a result of collisions of primary cosmic rays about 15 km above the Earth. The expected ratio is very nearly 2 ν_μ for every ν_e as a result of $\pi^+ \to \mu^+\nu_\mu$, $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$. To minimize uncertainties they form the ratio of ratios, $R = \frac{(\mu/e)_{obs}}{(\mu/e)_{MC}}$ and find R near 0.65. Moreover, the μ signal shows a strong directional dependence. The neutrinos that passed through more of the Earth (assuming always that they are created high in the atmosphere) are more depleted. If this is ascribed to oscillations, they the oscillation length is of the order of the diameter of the Earth or less. Since ν_es seem depleted, the preferred explanation is oscillation of ν_μ to ν_τ or to a sterile neutrino. The 90% CL region is $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ and $\sin^2 2\theta > 0.82$.
  - **Kamiokande**
    Kamiokande also finds evidence for neutrino oscillations, but larger values of Δm^2.