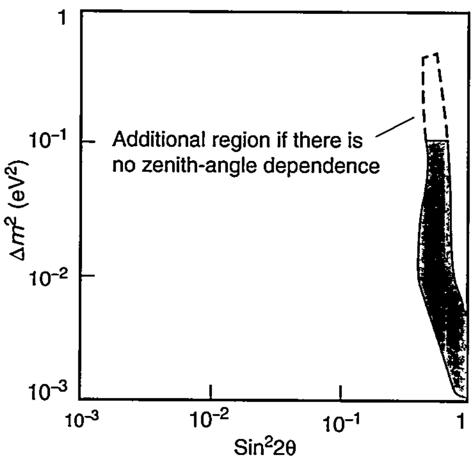

Figure 3. Allowed Δm^2 and $\sin^2 2\theta$ Region for Atmospheric Neutrinos

The data for the atmospheric-neutrino experiments is best explained with large mixing angles, and to be consistent with other experiments, the parameter space is limited to the region shown in gray. The disputed zenith-angle dependence of the data limits the values of Δm^2 to less than 0.1 eV^2. If the zenith-angle dependence can be discounted, then mass differences as high as 0.5 eV^2 are allowed. New data from the next generation of atmospheric-neutrino experiments should settle the question of zenith-angle dependence.

zenith-angle dependence shows up only for neutrinos with energies greater than 1.3 GeV.

This single piece of evidence has had a significant impact on the allowed region of Δm^2 and $\sin^2 2\theta$ (see Figure 3). The fact that little disappearance effect is observed for a zenith angle of ~0 degrees means that the oscillation length is much greater than 30 kilometers, so that

$$\frac{\pi E_\nu}{1.27\,\Delta m^2} \gg 30 \ .$$

With $E_\nu \approx 6$ GeV, one finds that $\Delta m^2 \ll 0.5$ eV^2. Given this small value for Δm^2, neutrinos emerging from some high-energy accelerators would have oscillation lengths on the order of hundreds of kilometers. A number of proposals have suggested placing huge neutrino detectors at comparable distances from an accelerator in an effort to investigate $\nu_\mu \rightarrow \nu_e$ oscillations.

However, the statistical significance of the reported zenith-angle dependence is not large. Moreover, a preprint from the Irvine-Michigan-Brookhaven (IMB) collaboration reports no such dependence, and early data from the experiment that has succeeded Kamiokande—super-Kamiokande—is consistent with only a slight zenith-angle dependence. If the zenith-angle dependence disappears, then the atmospheric data is consistent with $\Delta m^2 > 0.15$ eV^2 and an oscillation length on the order of 20 kilometers. This value of Δm^2 is compatible with the LSND observation discussed below.

Evidence from Accelerator-Produced Neutrinos. To date, LSND at the Los Alamos Neutron Science Center (LANSCE) is the only accelerator experiment to have evidence for neutrino oscillations. The experiment uses a detector that contains 167 metric tons of dilute liquid scintillator placed 30 meters from the beam stop for the LANSCE proton beam. Neutrinos are produced from the decay of positive pions that come to rest in the beam stop:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \ .$$

No electron antineutrinos are produced in this reaction chain. Thus, LSND seeks evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations by looking for electron antineutrino interactions in the detector. The charged-current weak interaction of electron antineutrinos with protons results in the creation of a positron and a free neutron:

$$\bar{\nu}_e + p \rightarrow e^+ + n \ .$$

The positron instantly streaks through the detector and produces both Cerenkov and scintillation light. The neutron, after a mean lifetime of 186 microseconds, is captured by a proton to form deuterium, D, and a 2.2-MeV gamma ray is produced:

$$n + p \rightarrow \mathrm{D} + \gamma \ .$$

The gamma ray also creates light in the detector. The signature for the electron antineutrino event is the correlation of the positron's Cerenkov and scintillation light with scintillation light produced by the 2.2-MeV gamma ray. Because of the low energy of the LANSCE beam (800 MeV), the neutrino backgrounds in LSND are quite small and well understood. The largest background is from electron antineutrinos that are produced when negative muons decay at rest in the beam stop. This decay channel, however, is suppressed by a factor of 7×10^{-4}