Problems with Atmospheric Neutrino Oscillations

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Abstract

The neutrino oscillation hypothesis does a poor job of representing the atmospheric neutrino anomaly. The anomaly is observed over 4 decades in path length and at least a factor of 30 in energy. This restricts the potential oscillation solutions to those with large amplitudes and mixing mass differences that are ruled out by other observations. The Δm^2 region in the range $10^{-4} - 10^{-2}$ leads to inconsistencies within the atmospheric neutrino data itself. The observed value of R seems to be incompatible with the Δm^2 implied by recent results

Prior experiments that were sensitive to the suggested range of Δm^2 fail to provide support for the Super Kamioka conclusions.

The atmospheric neutrino anomaly (Haines 1986, Hirata 1988, Becker-Szendy 1992) is the discrepancy between the observed and expected rate of electron and muon neutrino interactions in underground detectors. In general it is believed that these neutrinos originate in the Earth's atmosphere as a consequence of the decay of short lived particles created by cosmic ray interactions.

The atmospheric neutrino anomaly is characterized by a low fraction of muon neutrino interactions relative to the observed rate of electron neutrino interactions (Fukuda 1998). Only 61% of the expected rate is found. The deficiency is energy independent in the range 200 MeV to 4000 MeV. The deficiency appears to be isotropic up to at least 1200 MeV. In particular neutrinos entering the detector from above evidence the same muon neutrino deficiency as in other directions.

The Kamioka experiments present their results on the atmospheric neutrino anomaly in terms of R. R is interpreted as the fraction of muon neutrino events observed compared to what is expected. R is defined as

$$R = \frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}}$$

Underground detectors sample the neutrino flux from all directions. Since the neutrinos are produced by particle decays in the atmosphere, different directions correspond to different neutrino flight distances. Neutrinos coming from below the detector are primarily from a distance of the order of 8,000 km. Those from above have a flight path on the order of 20 km. Since a decay can occur anywhere in the atmosphere the decay distance is uncertain by about 10 km. The transition from the short flight distance to the long flight distance is rather rapid (figure 1).

Most of the solid angle is composed of sources at the two distances. 40% of the solid angle corresponds to a flight length under 45 km. 40% of the solid angle corresponds to a flight length in excess of 2600 km. The neutrino spectrum peaks at 200 MeV but the contained sample extends out to about 1300 MeV.

Figure 1 shows the approximate neutrino flight path as a function of the zenith angle. The path length as a function of zenith angle can be represented (approximately) by $L(\cos(\theta_z)) = \sqrt{R_1^2(\cos^2(\theta_z) - 1) + R_2^2} - R_1 \cos(\theta_z)$ With R_2 representing the distance from the center of the earth to the upper atmosphere where the neutrinos are born and R_1 representing the distance from the center of the earth to the detector ($R_2 > R_1$).
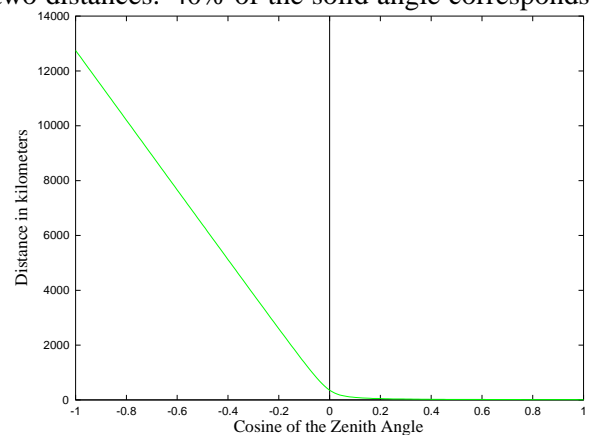

Figure 1: Approximate neutrino flight path as a function of the cosine of the zenith angle. Distances are in kilometers.

The most popular explanation for the source of the anomaly is the oscillation of muon neutrinos. Recently the Super-Kamioka collaboration has provided strong evidence for neutrino oscillations as a source of the atmospheric neutrino anomaly(Fukuda ... osc 1998). But these results seem to be inconsistent with other recent Super-Kamioka observations of atmospheric neutrinos(Fukuda ... mult 1998) and much of the prior work on the anomaly (Haines 1986, Hirata 1988, Becker-Szendy 1992).

Oscillations must be capable of mixing the neutrino flux over the energy and distance scales observed. The oscillation length is given by:

$$L_\nu = \frac{2\pi}{1.27\Delta m^2}E_\nu$$

or

$$\Delta m^2 = \frac{2\pi}{1.27}E_\nu/L_\nu$$

So the neutrino energy and oscillation distance set the scale for the neutrino mass. At $E_\nu = 600$ MeV and $L_\nu = 120$ km (4 times 30 km since the amplitude is proportional to $\sin^2(1.27\Delta m^2 \frac{L}{E})$) gives a mass scale of 2.5×10^{-2} eV^2. At lower mass scales the downward flux will not have had a chance to fully oscillate. Isotropy would no longer be apparent.

For mass scales below these it also becomes very difficult to obtain the observed deficiency in the global sample since the upper hemisphere would not have oscillated in the short distance available and the maximum attenuation from the long path length lower hemisphere would be 50% (if no other oscillation length were comparable). So the maximum attenuation of the global muon neutrino signal under these conditions would be on the order of 75%.

To explain the isotropic reduction of the contained event sample in the momentum range less than about 1 GeV/c^2 requires a Δm^2 in the range of $10^{-1} - 10^{-2}$ eV^2. But the reduction appears to be constant out to about 4 GeV(Fukuda ... mult 1998) which implies a mass near the upper part of this range. IMB has presented evidence that the isotropy extends out to at least a mean energy of 4 GeV (Clark 1997). Super-Kamiokande indicates a value of R is about 0.6 at 4 GeV(Fukuda ... mult 1998). These observations push the minimum mass scale possible up to 1.7×10^{-1} eV^2. While we have based these arguments on "isotropy" the mass scale is actually set by the shortest distance in the problem. That is the presence of an $R < 1$ in the downward going bin is indicative of short path length oscillations that require the high mass scale.

These arguments about isotropy and maximal flux reduction are well known and have motivated the energy-distance scale of a number of long baseline accelerator and reactor neutrino experiments designed to study the oscillation hypothesis. Such regions have been probed, and limited by studying energetic upward going muons in underground detectors (Becker-Szendy ... up 1992). Upward

Figure 2: Maximum attenuation of the neutrino flux as a function of energy and cosine of the zenith angle. A mass scale $\Delta m^2 = 6 \times 10^{-3}$ eV^2 was used for this plot.

going muons come from the interactions of energetic muon neutrinos in the rock underneath the detector. They, in general, come from a much higher region of the neutrino energy spectrum.

Figure 2 shows a contour plot of the function $\sin^2(1.27\Delta m^2 \frac{L(\cos(\theta_z))}{E})$ for a range of neutrino energies from 200 MeV to 6200 MeV. The plot is made for the mass

scale $\Delta m^2 = 6 \times 10^{-3}$ eV^2 suggested by recent Super-Kamioka results. The lowest contour present in the figure represents a 20% reduction in flux. Almost no reduction is seen for neutrinos originating in the upward
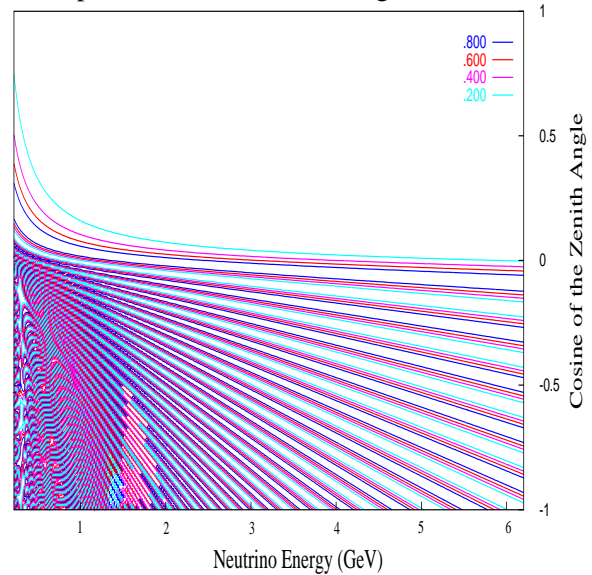
hemisphere. Plots for Δm^2 down to 5×10^{-4} eV^2 look similar.

Integrals over portions of Figure 2 give the maximum decrease in muon neutrino flux attributable to oscillations for that interval. (Maximum since these plots have been made for the maximum mixing angle.) This, of course, must be weighted by the neutrino interaction rate, which is a function of energy if the integral is made over much of a range of energies. The global attenuation factor at an energy E is given by:

$$\frac{1}{2} \times \int_{-1}^{1} \sin^2(1.27\Delta m^2 \frac{\sqrt{R_1^2(\cos^2(\theta_z) - 1) + R_2^2} - R_1\cos(\theta_z)}{E})d\cos(\theta_z)$$

Figure 3 is a plot of numerical evaluations of these integrals, as a function of energy.

Figure 3 is the R values that would be found if the anomaly could be explained by a simple neutrino oscillation hypothesis that would remove muon neutrinos by turning them into inactive objects, such as tau neutrinos. We note that it seems to be hard to get a value of $R \approx < 0.75$ this way.

To be isotropic the integrals over subranges in solid angle should also give the same value. For example:

$$\int_{.6}^{1} \sin^2(1.27\Delta m^2 \frac{L}{E})d\cos(\theta_z) = \int_{-1}^{-.6} \sin^2(1.27\Delta m^2 \frac{L}{E})d\cos(\theta_z)$$

It should be clear from figure 2 that these integrals will differ. For all mass scales permitted by the recent results these integrals differ by about $\frac{1}{2}\sin^2(2\theta_{Mix})$ since the upper region is not mixed and the lower region has been, in general, mixed over several cycles. In cases where the oscillation length is comparable to the Earth's diameter even larger asymmetries would be seen. The two integrals are equal in both the low and high Δm^2 limit. At very small Δm^2 both integrals are zero. At very high values of Δm^2 both sides average over many cycles and are hence $\frac{1}{2}$. If they are not equal and yet the short distance region indicates a deficiency of ν_μ's this would imply two distance scales and hence two mass scales in the problem. The puzzling feature that the attenuation attributable to oscillations for these values of Δm^2 is smaller than that observed could be due to a number of factors. If the Δm^2 is large and mixing is maximal as much as 50% of the muon sample could be removed. If muon neutrinos oscillate into electron neutrinos, either via a direct path or via other neutrinos this would raise the observed electron rate above expectations and therefore lower the value of R. But

Figure 3: Maximum global attenuation of the neutrino flux as a function of energy. A mass scale $\Delta m^2 = 6 \times 10^{-3}$ eV^2 was used for this plot.

the Super-Kamioka data(Fukuda ... osc 1998) shows no evidence for electron modulation. The Chooz reactor experiment (Apollonio 1997) has fairly strong limits on electron antineutrino oscillations at comparable Δm^2. One might evade the Chooz limit with CP violation since Chooz limits $\bar{\nu}_e \rightarrow$ not $\bar{\nu}_e$ and one might fix the atmospheric R with $\nu_\mu \rightarrow \nu_e$. But CP violation effects are unlikely to work in a 3 neutrino scheme since the $\nu_\mu \rightarrow \nu_e$ transition must have a short wavelength and the other amplitudes needed to interfere with it to get CP violation have at least one long wavelength part. It might be possible in a 4 neutrino scheme with 14 parameters. But the $\bar{\nu}_\mu/\nu_\mu$ ratio observed seems to be normal.
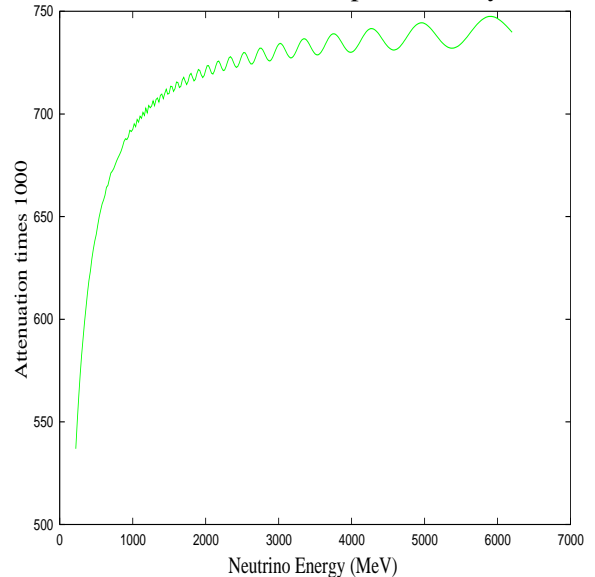
A puzzling feature of most atmospheric neutrino experiments has been that the rate of neutrino interactions agrees fairly well with expectations even though the number of muon neutrino induced events is low. The observed event rate (Fukuda 1998) is 96±2% of the expected value (94±3% of the expected rate for the multi

GeV sample(Fukuda ... mult 1998)). Since the muon neutrino rate appears to be reduced by about 39% and the muon neutrino rate is expected to be about twice that of the electron neutrino rate one might expect an observed flux of only about 75% of that predicted. The true neutrino flux would have to be 25% higher than predicted.

This might imply that the electron neutrino rate is too high and compensates for the loss. It is also possible that there are sources other than the atmosphere for "neutrinos" observed in these detectors. (LoSecco 1997)

The Super-Kamioka result (Fukuda ... osc 1998) came as a bit of a surprise to the community since the mass scale in question had been probed and ruled out by prior experiments. For example the Super-Kamioka 90% confidence level contour of neutrino oscillation parameters is barely consistent with that from Kamioka. IMB (Clark 1997) failed to confirm the modulation observed in the Kamioka Multi GeV data (Fukuda 1994). IMB published an exclusion plot (Becker-Szendy ... up 1992) rulling out all large mixing angle fits to muon neutrino oscillations for Δm^2 greater than about 2×10^{-5} eV^2. Aside from concluding that some of these observations were wrong is there a physical picture which is compatible with most of them? The mass of the neutrino is a constant of nature that can not be different at different times or places. Since the Earths magnetic field is not a simple dipole aligned along the Earth's axis one does not expect the cosmic ray flux to be uniform (Honda 1995). The most difficult observation to interpret is the isotropy of the electron sample in (Fukuda ... osc 1998) in the presence of a large muon anisotropy. While geomagnetic effects and the solar cycle can be expected to modulate the atmospheric spectrum and to give it temporal variation. These changes would be manifest in all neutrinos of atmospheric origin.

It may be difficult to rule out *any* neutrino oscillation hypothesis from the atmospheric results alone. The prior, unmodulated, results are insensitive to large Δm^2 scales. It was these relatively large Δm^2 that provided the motivation for long baseline reactor and accelerator neutrino experiments. The magnitude of the atmospheric effect means that at least some of the mixings to the muon neutrino would be large and observable in these experiments.

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