Bounds on $\nu_\mu$ Oscillations from Atmospheric Neutrinos

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(November 4, 2021)

Abstract

A reanalysis of identified muon neutrino interactions from IMB 3 yields bounds on $\sin^2(2\theta)$ and $\Delta m^2$. The limit $\sin^2(2\theta) < 0.72$ is in conflict with the recent announcement of a neutrino mass.

Subject headings: Cosmic Rays — Elementary Particles — Neutrino Oscillations
Atmospheric neutrinos have always held the possibility of providing a large range of propagation coupled with a near source to provide a convenient calibration. With a reasonable choice of angular cuts a sample of neutrinos traveling about 10,000 km can easily be compared with a sample traveling on the order of 20 km collected in the same experiment at the same time. Early work using these concepts was hampered by low statistics and poor particle identification. In a mixed sample of 25 upward neutrino interactions was compared with a sample of 25 downward neutrino interactions. The neutrino propagation distance is a function of the neutrino direction, so scattering can, in principle, make the distance estimate ambiguous. In reality the propagation distance varies very slowly with angle near the vertical so as long as regions near the vertical are compared scattering will have a negligible effect on the sensitivity. In most analyses regions containing 20% of the solid angle over the upward and downward direction have been used.

Depending on the location of the detector the upward and downward fluxes may be influenced differently by geomagnetic effects. IMB was located at 52° north geomagnetic latitude. This meant that the local flux, coming from above, had a lower geomagnetic cut off than the Earth at large. As such one would expect a greater rate of downward going events since the lower cutoff permitted more of the extraterrestrial cosmic ray flux to descend and hit the atmosphere. But such effects are small and have not been observed in a statistically significant way even in a sample of 401 neutrino interactions. In the 401 IMB 1 sample 55 events were measured in the upward going 20% of the solid angle and 65 were found in a comparable portion of downward solid angle. comparison of the 15 upward events and 21 downward events which were classified as muon neutrino induced because of the presence of a muon decay in the event yielded limits on $\Delta m^2$ in the range of $5 \times 10^{-5}$ eV$^2$.

IMB 3 provided a comparable sample of events but with better light collection and with morphologically based muon identification methods as well as those based on muon decay signatures. An analysis comparing the shape of the energy distribution for the upward and downward 20% of the solid angle confirmed the IMB 1 results but with a larger sample and with particle identification. The IMB 3 work was done with 34 downward going and 32 upward going $\nu_\mu$. These two samples have energy distributions which are statistically indistinguishable.

The excluded region derived in is bounded in the range $4.5 \times 10^{-5} < \Delta m^2 < 1.1 \times 10^{-4}$ eV$^2$. Outside of this range distortion of the upward going neutrino spectrum by neutrino oscillations would not make its shape statistically distinguishable from the measured downward spectrum.

The contained neutrino interactions can be used to study neutrino oscillations over a broader range of $\Delta m^2$. The lowest limits on $\Delta m^2$ are found in comparisons of the shape of the observed contained event energy spectra for samples of events near the vertical. Such a test is insensitive to detailed flux calculations, since the downward sample constitutes a measured near source. The method has a limited range because for larger $\Delta m^2$ the upward going sample would be fully mixed via multiple oscillations and hence would have a spectrum shape that was similar to the unoscillated downward sample. The upward sample would be reduced by an overall factor, which is $1 - \frac{1}{2} \sin^2(2\theta)$. So comparison of rate of upward to downward going $\nu_\mu$ interactions can extend the sensitive range. This comparison eventually fails at even higher $\Delta m^2$ because at large $\Delta m^2$ both the upward and downward going samples will have oscillated. In such cases oscillations may be noted by deviations of the observations.
from expectations. Estimates of $\Delta m^2$ would be unreliable since no distance scale would be present in the observations.

The first two methods, comparison of up and down spectral shape and comparison of up and down interaction rate are insensitive to most systematic errors in the neutrino flux calculations. For example they are insensitive to the normalization uncertainty, the $\nu_\mu$ to $\nu_e$ ratio uncertainty and the temporal modulation caused by the solar wind’s impact on the Earth’s magnetosphere. They may be influenced by geomagnetic effects that produce modest variations of the neutrino flux at various points on Earth. The downward neutrino component is produced locally and so is sensitive to local magnetic field properties.

The result of [4] can be extended by comparing the rate of upward going to downward going $\nu_\mu$ interactions. For the range of $\Delta m^2$ of greatest interest for the Super Kamioka [5] results one would expect a two to one rate difference [6].

For the data of reference [4] the up to down event ratio is

$$\frac{32}{34} = 0.94 \pm 0.23 > 0.64$$

where the bound is the 90% confidence lower limit on the ratio of up to down flux. As mentioned above, due to geomagnetic effects this ratio is expected to be less than one due to a small enhancement of the downward flux. We neglect the effect of the geomagnetic enhancement of the downward flux in calculating our neutrino oscillation limits. This makes the limits a bit conservative since any reduction in the upward relative rate due to geomagnetic effects will instead be ascribed to possible oscillation effects.

In the region $2.5 \times 10^{-4} < \Delta m^2 < 7.0 \times 10^{-3} \text{ eV}^2$ where the upward neutrinos have traveled over several oscillations and the downward neutrinos have not had a chance to oscillate this bound on the ratio can be converted into a limit on $\sin^2(2\theta)$.

$$1 - \frac{1}{2} \sin^2(2\theta) > 0.64$$

$$\sin^2(2\theta) < 0.72$$

This is in direct conflict with the results [5] $\sin^2(2\theta) > 0.82$ within the mass range $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3} \text{ eV}^2$. A possible source of this discrepancy is a misinterpretation of their angular distribution in terms of low mass neutrino oscillations [6] by the Super Kamioka collaboration.

A plot of the region excluded by this analysis and the analysis of reference [4] is shown in figure [8]. The section marked “Super Kamioka Allowed” on the figure is not their true allowed region but an outline of the maximum range permitted for some values of $\Delta m^2$ and some values of $\sin^2(2\theta)$. The Super Kamioka fit implies that $\sin^2(2\theta) = 1$. Figure [8] was calculated by integrating over the observed energy and distance distribution.

This rate analysis fails to exclude $\Delta m^2 > 2.5 \times 10^{-2} \text{ eV}^2$ because the upper hemisphere starts to show evidence of oscillations (in this low energy sample) so the downward rate would also be reduced. A shape test could be used to extend the results in this area. (The fact that the upward rate is not significantly greater than the downward rate permits one to exclude the range $\Delta m^2 < 0.1 \text{ eV}^2$. To calculate detailed limits one must integrate over the source to detector distance since the muon decay length is comparable to the path length.)
The region $6.3 \times 10^{-5} < \Delta m^2 < 1.0 \times 10^{-4}$ is more sensitive to rate effects than our simple analytical analysis above indicated. In this mass region the oscillation hypothesis takes the bulk of the upward data through the maximum. The ripples in the figure are indications of the repeat of this effect for the second and third oscillation etc.

These results confirm the excluded region calculated from a study of an independent sample of upward going muons by IMB [7].

A larger sample of IMB 3 contained event data [8] is available and could be used to extend these results. With double the data sample the upper bound on $\sin^2(2\theta)$ would drop to 0.54. The Super Kamioka single ring showering events [5] should yield a limit on $\nu_e \rightarrow \nu_e$ of the order of $\sin^2(2\theta_{\text{ex}}) < 0.23$ over a comparable range of $\Delta m^2$. Precise contours depend on details of the measured $\nu_e$ energy distribution.

ACKNOWLEDGMENTS

I am grateful to the The Institute for Nuclear Research of the USSR Academy of Sciences for the opportunity to participate in their Particles and Cosmology School in 1991. I am grateful to Richard Feynman for suggesting we extend the results of reference [1] to higher $\Delta m^2$. 
FIG. 1. 90% confidence level excluded region
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