

distortion. The compatibility between the data for the low energy events and expectations for no oscillations has a $< 3\%$ probability, while the data is in good agreement with the hypothesis of $\nu_\mu \rightarrow \nu_\tau$ oscillation with large mixing angle and $10^{-3} < \Delta m^2 < 2 \times 10^{-2} \text{ eV}^2$. A consistent scenario arises from both high and low energy MACRO ν events as can be seen in Figure 9.

REFERENCES

1. S. Ahlen et al. (MACRO Collaboration) Phys. Lett. B 357 (1995) 481, D. Michael (MACRO collaboration) Nucl. Phys. Proc. Suppl. 35.(1994) 235, F Ronga (MACRO Collaboration) Helsinki 1996 Neutrino Conference World Scientific.
2. M. Ambrosio *et al.* (MACRO Collaboration) 434, 451 (1998) hep-ex/9807005. (1999) 371.
3. Agrawal et al. Phys Rev D53 1314 (1996)
4. Gluck M., Reya E. and Stratmann M.1995, Z.Phys. C67, 433.
5. Lipari P. Lusignoli M. and Sartogo F. 1995 ,Phys. Rev. Lett. 74 4384.
6. Lohmann H. Kopp R.,Voss R. 1985, CERN-EP/85-03.
7. P. Lipari and M. Lusignoli, Phys. Rev. D57, 3842 (1998).
8. Ambrosio, M., et al. (MACRO Collaboration) particle Physics 9 (1998) 105.

randomly merged and directly scanned with the MACRO Event Display. About 90% of the events are estimated to be ν_μ charged current interactions. The main background for this search is the low energy particles produced by downgoing muons [8]. After background subtraction, 229 events are classified as *Internal Downgoing* and *Upward Stopping* events. The Monte Carlo simulation for the low energy events uses the Bartol neutrino flux [3] and the neutrino low energy cross sections reported in [4] and yields a predicted number of events of $329 \pm 33_{\text{sys}} \pm 82_{\text{theo}}$. The angular distributions of data and predictions are compared in Figure 8. The low energy samples show a uniform deficit of the measured number of events over the whole angular distribution with respect to the predictions, while there is good agreement with the predictions based on neutrino oscillations. The ratio of Data / Monte Carlo = $0.55 \pm 0.04_{\text{stat}} \pm 0.06_{\text{sys}} \pm 0.14_{\text{th}}$.

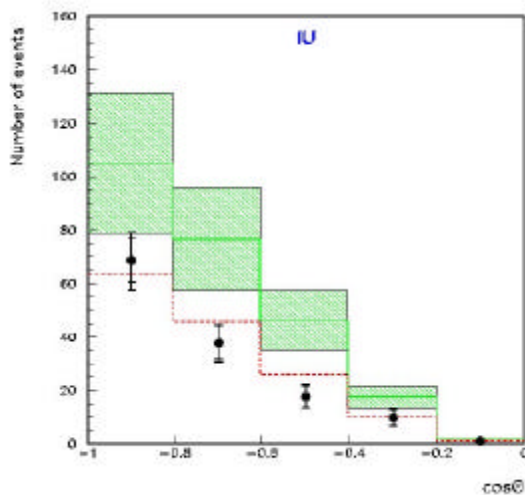


Figure 8. Zenith angle distributions for *Internal Upwardgoing Stopping* and *Internal Downward* events. The background corrected data points (black points with error bars) are compared with the Monte Carlo expectation assuming no oscillation (shaded region, including theoretical uncertainties) and $\nu_\mu \rightarrow \nu_\tau$ oscillation (dashed line) using maximum mixing and $\Delta m^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$.

The theoretical errors coming from the neutrino flux and cross section uncertainties

almost cancel if the ratio between the measured number of events *Internal Upgoing/ (Internal Downward + Upwardgoing Stopping)* [IU/(ID+IGS)] is compared with the expectations. The partial error cancellation arises from the nearly equal energy spectra of parent neutrinos for the IU and the ID+UGS events. The experimental systematic uncertainty on the ratio is 6%. The measured ratio is $IU / (ID+UGS) = 0.59 \pm 0.07$, while the one expected without oscillations is $R = 0.75 \pm 0.04_{\text{sys}} \pm 0.04_{\text{th}}$, while the expectation with neutrino oscillations is $R = 0.58 \pm 0.03_{\text{sys}} \pm 0.03_{\text{th}}$.

4. SUMMARY AND CONCLUSIONS

Atmospheric neutrino events in MACRO come in several types. The most statistically significant data is from the high energy ($\sim 100 \text{ GeV}$) *Upward Throughgoing* events originating from neutrino interactions in the rock below the detector. We have presented a detailed analysis of 769 events of that type. The data favors $\nu_\mu \rightarrow \nu_\tau$ oscillation with large mixing angle and $\Delta m^2 \sim 2.5 \cdot 10^{-3} \text{ eV}^2$. The case of sterile neutrinos is disfavoured at the $\sim 2\sigma$ level.

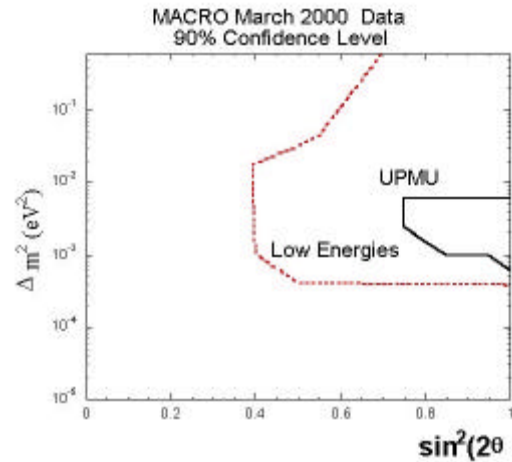


Figure 9. The regions of Δm^2 vs $\sin^2 2\theta$ determined with 90% confidence by the MACRO low energy and high energy atmospheric neutrino events.

We have also analyzed a smaller sample of low energy events. We observe a deficit with respect to expectations for *Internal Upward*, and *Internal Downward + Upwardgoing Stopping* events and the angular distribution shows no zenith angle

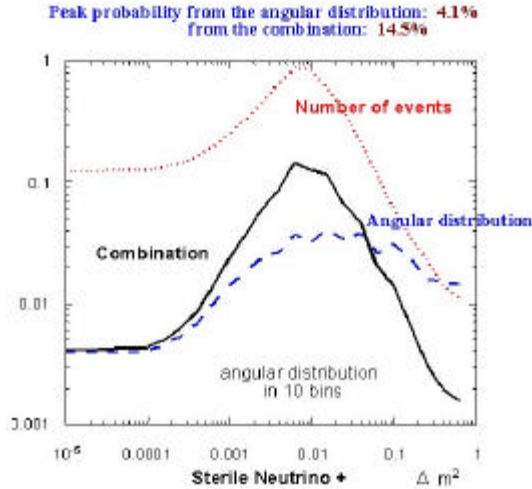


Figure 5. The probabilities are shown for neutrino oscillations $\nu_\mu \rightarrow \nu_s$ from zenith angular distributions, number of events and the combination.

We have also investigated oscillations into a sterile neutrino. The maximum probability for the sterile neutrino from the angular distribution alone is 4.1%, while the probability is 14.5% including both flux measurement and angular distribution. This is not as good a fit as for $\nu_\mu \rightarrow \nu_\tau$ oscillations shown earlier, but gives the best fit for $\Delta m^2 \sim 10^{-2} \text{ eV}^2$.

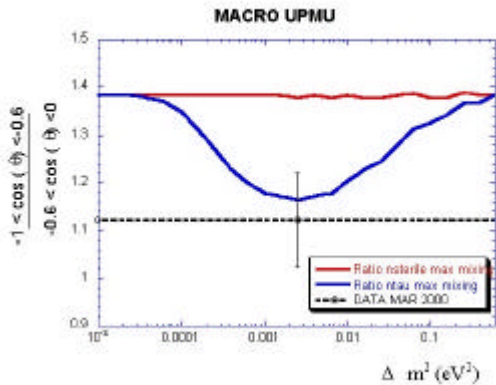


Figure 6. The ratio obtained binning the data in two bins and the comparison with the ν_τ and ν_s oscillations with maximum mixing

Another way to try to discriminate between the oscillation of $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ is to study the angular distribution in two bins, computing the ratio between the two bins as shown in Figure 6. The statistical significance is higher then in the

case of data binned in 10 bins, but some features of the angular distribution could be lost using this ratio. The advantage is that the ratio is insensitive to most of the errors on the theoretical prediction of the flux and cross section[7]. From this plot we conclude that the sterile neutrino hypothesis is disfavored at 2σ level.

3. THE MACRO LOW ENERGY EVENTS

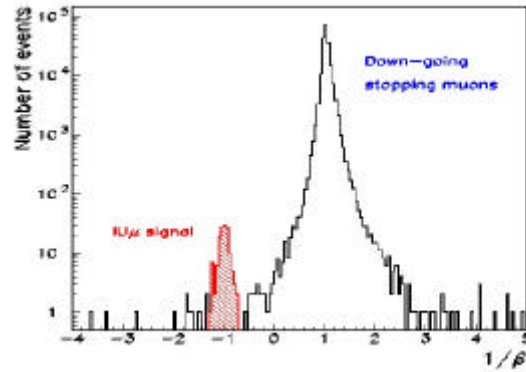


Figure 7. Time of flight selection of *Internal Upward* events and discrimination from downward events.

The analysis of the *Internal Upward* events is similar to the analysis of the *Upward Throughgoing* events. The main difference is due to the requirement that the interaction vertex should be inside the apparatus. About 87% of events are estimated to be ν_μ charged current interactions with $\langle E_\nu \rangle \sim 5 \text{ GeV}$. The uncertainty due to the acceptance and analysis cuts is 10%. After the background subtraction, there are $135 \pm 12_{\text{stat}}$ *Internal Upward* events. This should be compared with the Monte Carlo prediction of $247 \pm 25_{\text{sys}} \pm 62_{\text{theo}}$. The *Internal Downward* and the *Upward Stopping* events are identified via topological constraints. The main requirement is the presence of a reconstructed track crossing the bottom scintillator layer. The tracking algorithm for this search requires at least 3 streamer hits (corresponding roughly to 100 gr cm^{-2}). All the track hits must be at least 1 meter from the detector's edges. The criteria used to verify that the event vertex (or stopping point) is inside the detector are similar to those used for the *Internal Upward* events. To reject ambiguous and/or wrongly tracked events which survived automated analysis cuts, real and simulated events were

Tung parton distribution used in the past. The systematic error on the upgoing muon flux due to uncertainties in the cross section including low energy effects [5] is $\pm 9\%$. The propagation of muons to the detector has been estimated using the energy loss calculation of reference [6] for standard rock (estimated systematic error $\pm 5\%$). The total systematic uncertainty on the expected flux of muons adding the errors from neutrino flux, cross-section and muon propagation in quadrature is $\pm 17\%$. This systematic error in the flux of events predicted and does not change the shape of the zenith angular distribution. The expected total number of events integrated over all zenith angles is 989, compared to 723 observed. The observed deficit is statistically significant and is the first indication in atmospheric neutrino data of oscillations. The ratio of the observed to the expected number of events is $R = 0.731 \pm 0.028$ (stat) ± 0.044 (systematic) ± 0.12 (theoretical).

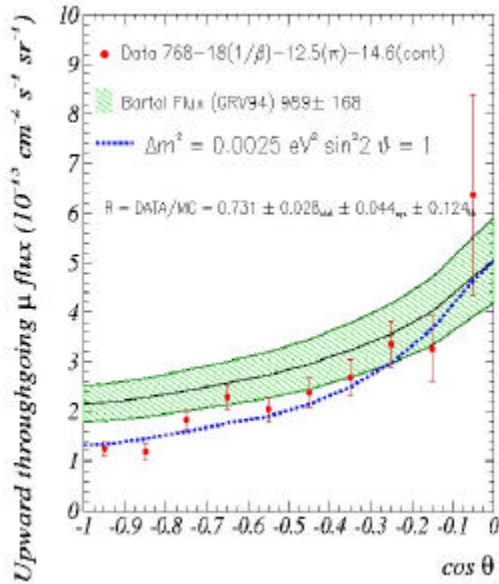


Figure 3. The zenith angular distribution for upgoing muons with energy greater than 1 GeV for both data and Monte Carlo for no oscillations are shown for the total MACRO data set. The shaded region shows the expectation with the 17% systematic uncertainty in the flux prediction indicated. The dashed line shows the expectation including neutrino oscillations for a solution with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025 \text{ eV}^2$.

The shape of the angular distribution has been tested with the hypothesis of no oscillations normalizing data and predictions. The fit for 8 degrees of freedom gives a Probability of only 0.4% for a shape at least this different from the expectation. This deviation from the expectations is the second independent evidence for neutrino oscillations. We have fit the angular distributions assuming $\nu_\mu \rightarrow \nu_\tau$ oscillations. The peak probability from the angular distribution alone is 26% a much better fit than without oscillations. Our earlier data gave a much lower probability, but with increased statistics the fit to oscillations has become increasingly probable. The best χ^2 is for $\Delta m^2 \sim 0.0025 \text{ eV}^2$ and maximum mixing (the best χ^2 is actually outside the physical region). It is notable that the value of Δm^2 , suggested from the shape of the angular distribution is similar to the value necessary to explain the observed reduction in the total number of events.

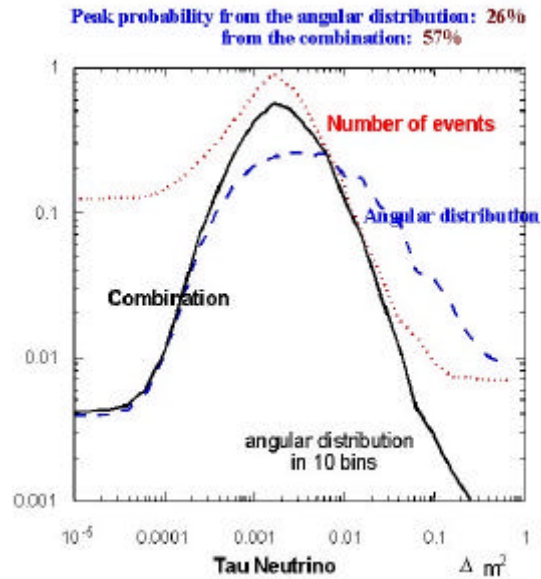


Figure 4. The probabilities for neutrino oscillations $\nu_\mu \rightarrow \nu_\tau$ having maximum mixing are shown as a function of Δm^2 . The dotted line corresponds to the probability from comparing the observed and predicted number of events. The dashed line shows the probability from the fit to the zenith angular distribution with data and prediction normalized. Finally, the solid line gives the combined probability of the two independent measurements.

typical neutrino energy for this kind of events is of the order of 100 GeV.

The *Internal Upward* events come from ν_μ interactions inside the apparatus producing a muon that exits the top of the detector. Since two scintillator layers are intercepted, the time-of-flight method can be applied to distinguish the upward going neutrino induced events from the much larger flux ($\sim 10^5$ times) of downward penetrating cosmic ray muons. The typical neutrino energy for this kind of events is ~ 4 GeV. If the atmospheric neutrino anomalies are the result of ν_μ oscillations with maximum mixing and Δm^2 between 10^3 eV^2 and 10^2 eV^2 , one expects a reduction in the flux for this kind of events of about a factor of two without any measurable distortion in the shape of the angular distribution.

The *Upward Stopping* and the *Internal Downward* events are due to external interactions with upward going tracks stopping in the detector (*Upward Stopping*) and to neutrino induced downgoing tracks with vertex in the lower part of MACRO (*Internal Downward*). These events are identified by means of topological criteria. The lack of time information prevents distinguishing these two event types so we analyze the sum of these two types of neutrino topologies. An almost equal number of *Upward Stopping* and *Internal Downward* events are expected if neutrinos do not oscillate. The average neutrino energy for this type of event is around 4 GeV. For the case of oscillations, we do not expect a reduction in the flux of the *Internal Downward* events (having path lengths only of the order of 20 km), while a reduction in the number *Upward Stopping* events is expected similar to the one for Internal Upward events.

2. UPWARD THROUGH-GOING MUONS

The direction that muons travel through MACRO is determined by the time-of-flight between two different layers of scintillator counters. The measured muon velocity is calculated with the convention that muons going down through the detector are expected to have $1/\beta$ near +1 while muons going up through the detector are expected to have $1/\beta$ near -1. Several cuts have been imposed to remove backgrounds caused by radioactivity or showering events, which may result in bad time reconstruction.

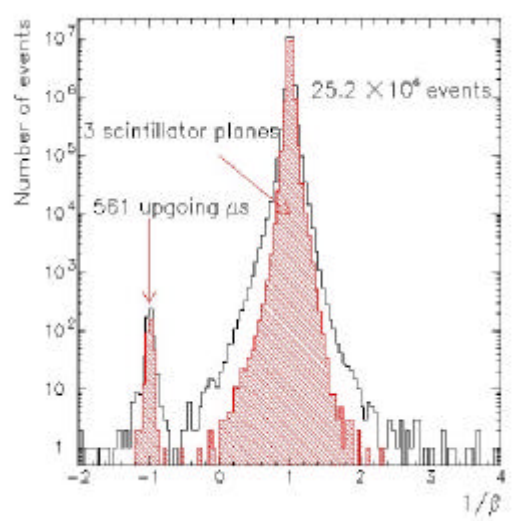


Figure 2. The measured time of flight distribution for MACRO events is shown. The large peak at $1/\beta = +1$ is from downward muons penetrating the mountain and traversing MACRO. The peak at $1/\beta = -1$ is the sample of upward throughgoing muons. The shaded region corresponds to the subset of events crossing three scintillator planes. (This figure is not for the complete data sample reported here)

For our entire data set, there are 768 events in the range $-1.25 < 1/\beta < -0.75$ which we have define as *Upgoing Throughgoing* muon candidates. This sample contains both the signal events and some contamination and background. Based on the events outside the upgoing muon peak in the $1/\beta$ plot (figure 2), it is estimated there are 18 background events in the total data set from mismeasured time of flight. In addition to these events, we have estimated that there are 12.5 background events that result from upgoing charged particles produced by downgoing muons interacting in the rock near MACRO. Finally, it is estimated that there are 14.6 events that result from interactions of neutrinos in the very bottom layer of MACRO scintillator (therefore not external events). Subtracting the backgrounds yields 723 events.

We have used the parameterization of the neutrino flux computed by the Bartol group [3] in our upgoing muon simulation (estimated systematic error $\pm 14\%$). The cross-sections for the neutrino interactions have been calculated using the GRV94 [4] parton distributions set, which varies by +1% respect to the Morfin and

Atmospheric Neutrinos in MACRO

Barry C. Barish

California Institute of Technology
Pasadena, CA 91125

ABSTRACT

Results from MACRO on atmospheric neutrinos are presented. For high energy events, $\langle E_\nu \rangle \sim 100$ GeV, a fit to the total measured flux and angular distributions yield a poor fit without the inclusion of neutrino oscillations. The data favors $\nu_\mu \rightarrow \nu_\tau$ oscillations with large mixing angle and $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV² and disfavors a sterile neutrino hypothesis at the $\sim 2 \sigma$ level. Low energy events, both stopping and internal, have also been analyzed. In MACRO, statistics are poorer for this type of event. The results for *Internal Upward*, and *Internal Downward + Upwardgoing Stopping* events also have a deficit with respect to expectation (no oscillations), but there is no observed zenith angle distortion. Detailed fits to the low energy data are also in agreement with the hypothesis of $\nu_\mu \rightarrow \nu_\tau$ oscillations with large mixing angle and $10^{-3} < \Delta m^2 < 2 \times 10^{-2}$ eV². The fit with no oscillations has a probability of less than 3%. Overall, a consistent scenario arises from both high and low energy MACRO atmospheric neutrino events.

1. INTRODUCTION

The MACRO experiment in the Gran Sasso Laboratory began operations for neutrino physics in 1989 with a small fraction of the final detector. The results [1] from MACRO presented in 1995 with a small fraction of the final detector already indicated a deficit of events, particularly in the vertical direction. However, the statistics were not enough at that time to discriminate between an oscillation and a no oscillation hypothesis and the zenith angular distribution had anomalous structure.

The MACRO detector is described elsewhere [1][2]. Active elements are streamer tube chambers used for tracking and liquid scintillator counters used for the time measurement. Figure 1 shows a schematic end view of the 80m long detector with the different topologies indicated for atmospheric neutrino events: *Upward Throughgoing* events, *Upward Stopping* events; *Internal Downgoing* events and *Internal Upward* events. The requirement of a reconstructed track selects events having a muon, because muons are the only charged penetrating particle to traverse MACRO and make a straight track.

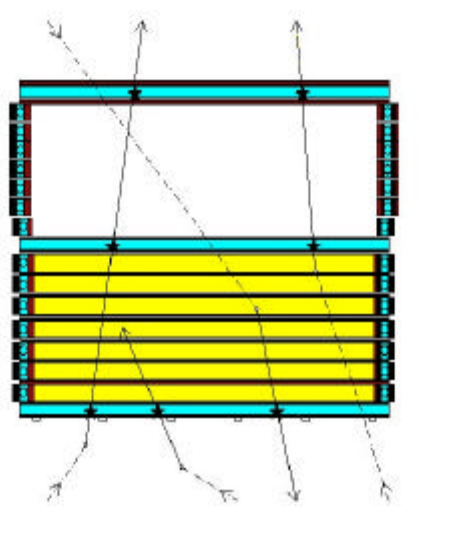


Figure 1. An end view of the MACRO detector showing the various types of neutrino events: *Upward Throughgoing*, *Upward Stopping*; *Downward Internal* and *Upward Internal*.

The *Upward Throughgoing* tracks come from ν_μ interactions in the rock below MACRO. The muon crosses the whole detector ($E_{min} > 1$ GeV). The time information provided by scintillator counters gives the direction (time-of-flight method). The