Updated results are presented of low-energy ($E_\nu \sim 5$ GeV) neutrino interactions observed by the MACRO detector. Two analyses (of different topologies) are presented: individually, and especially in their ratio, they are inconsistent with no oscillations and consistent with maximal mixing at $\Delta m^2$ of a few times $10^{-3}$.

1. Introduction

Recent measurements of atmospheric neutrino flux by the Super-Kamiokande, Soudan, and MACRO experiments all suggest oscillations with $\Delta m^2$ a few times $10^{-3}$ and $\sin^2 2\theta \sim 1$. The MACRO analysis has recently been extended to event topologies that probe lower neutrino energies, and the results are updated here.

MACRO is a large detector located deep underground at the Gran Sasso laboratory in Italy. The active detector elements are layers of liquid scintillator and layers of streamer tubes (with wire and strip views) with a pitch of 3 cm. Most neutrino interactions take place in the massive bottom half of the detector which is filled with crushed rock absorber. The interior of the upper portion of the detector is hollow. (See Figure 1.)

Fig. 1. Event topologies of neutrino-induced events in MACRO.
2. The Analyses

Because of its large granularity, MACRO is sensitive only to charged current $\nu_\mu$ interactions producing a muon that travels at least tens of cm. This talk examines two topologies of lower-energy neutrino-induced muons. The two analyses have very similar parent neutrino energy distributions, with $E_\nu \sim 5$ GeV. Upward contained-vertex events, in which the muon strikes two layers of scintillator and exits the detector, are labeled Pure-Up in Figure 2. Downward contained-vertex events and upward stopping events from below both hit only the bottom scintillator layer and have a few associated colinear streamer tube hits. In MACRO the direction (up or down) of these events cannot be determined and they are merged into an analysis labeled Mixed-Up-Down.

Predicted event rates are made using a Monte Carlo calculation combining a neutrino flux model, a neutrino cross section model, and detailed simulation of the detector geometry and response. We chose the Bartol flux calculation including geomagnetic effects, and the Lipari cross section model which includes quasi-elastic and resonant scattering in addition to deep inelastic scattering. The deep inelastic portion was calculated using the GRV-LO-94 parton distribution functions.

3. Results

Here results are updated through March, 2000 for a total of 5.1 live years, an increment of 25% over our last published result. Angular distributions, compared to no-oscillations and oscillated predictions, are given in Figure 2. Uncertainties on the neutrino flux (20%) and cross section (15%) lead to a large theoretical uncertainty in the predicted rates.

![Diagram](image)

Fig. 2. Zenith distributions of events selected in the two low-energy analyses. The shaded region gives the prediction (with uncertainties) of a no-oscillations Monte Carlo. The dashed line gives the prediction for $\Delta m^2 = 2.5 \times 10^{-3}$ and $\sin^2 2\theta = 1$. The third figure gives the ratio of the two analyses.

Integrating over all zenith angle bins and forming the ratio of observed to expected events, we find $R_{\text{Pure-Up}} = 0.55 \pm 0.04_{\text{stat}} \pm 0.06_{\text{sys}} \pm 0.14_{\text{theor}}$ and
$R_{\text{Mixed--Up--Down}} = 0.70 \pm 0.04_{\text{stat}} \pm 0.07_{\text{sys}} \pm 0.18_{\text{theor}}$. $R_{\text{Pure--Up}}$ could be a statistical fluctuation from the no-oscillations model with probability 4.3%. For $R_{\text{Mixed--Up--Down}}$ the probability is 12%. It is the theoretical uncertainty on the flux and cross section normalizations that makes these numbers so large.

We can reduce the uncertainties by considering the two analyses simultaneously rather than independently. For example, if we consider one of the measurements to fix the normalization at a level far below the calculated normalization, we find that the other measurement is incompatible with that normalization. To put it in different language, when we form the ratio of the two analyses, most theoretical error and some systematic error cancels. This comes at the expense of a greater statistical uncertainty, because we are dividing two uncertain numbers by each other. The results (also shown in Figure 2) are $R_{\text{Data}} = 0.59 \pm 0.07_{\text{stat}}; R_{\text{Expected}} = 0.75 \pm 0.04_{\text{sys}} \pm 0.04_{\text{theor}}$. The probability of attaining this result due to statistical fluctuations is only 2.7%. Combining the ratio and the individual measurements we may deduce the exclusion region in oscillations parameter space shown in Figure 3.

Fig. 3. Region of parameter space excluded by this analysis at 90% confidence level, which is compatible with the more precise result from MACRO’s high energy analysis (labeled UPMU).

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