Nuclear Physics B (Proc. Suppl.) 75A (1999) 400–402

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Atmospheric neutrino induced muons in the MACRO detector

F. Ronga [a] for the MACRO collaboration *

[a]INFN Laboratori Nazionali di Frascati, P.O. Box 13 I-00044 Frascati Italy

A measurement of the flux of neutrino-induced muons using the MACRO detector is presented. Different event topologies, corresponding to different neutrino parent energies can be detected. The upward throughgoing muon sample is the larger event sample. We have investigated whether the observed number of events and the shape of the zenith distribution can be explained by an hypothesis of $\nu_\mu \to \nu_\tau$ oscillation. The best probability (17%) is obtained for $\sin^2 2\theta \simeq 1.0$ and Δm^2 of a few times 10^{-3} eV^2, while the probability for the no oscillation hypothesis is 0.1 %. The other samples are due to the internally produced events and to upward-going stopping muons; the average parent neutrino energy is of the order of 4 GeV. The low energy data sets show a deficit of observed events similar to the one predicted by the oscillation model with maximum mixing suggested from the upward throughgoing muon sample.

1. Introduction

The interest in precise measurements of the flux of neutrinos produced in cosmic ray cascades in the atmosphere has been growing over the last years due to the anomaly in the ratio of contained muon neutrino to electron neutrino interactions. The observations of Kamiokande, IMB and Soudan 2 are now confirmed by those of SuperKamiokande with larger statistics and the anomaly finds explanation in the scenario of ν_μ oscillations [1].

The effects of neutrino oscillations have to appear also in higher energy ranges. The flux of muon neutrinos in the energy region from a few GeV up to a few TeV can be inferred from measurements of upward throughgoing muons [2].Here the measurement about the high energy muon neutrino flux is presented, together with the first results on low-energy neutrino events in MACRO.

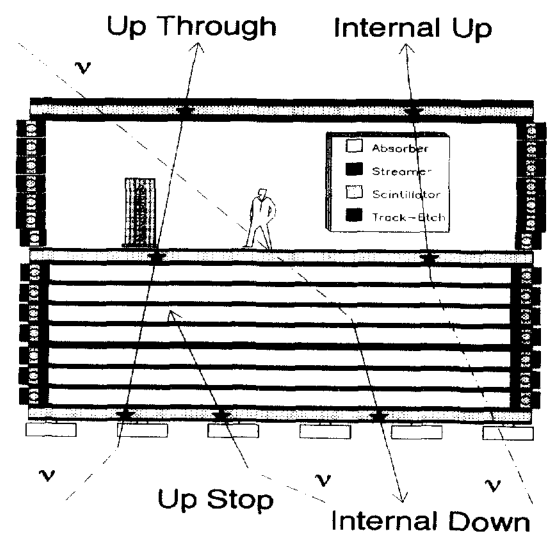

Figure 1. Sketch of different event topologies induced by neutrino interactions in or around MACRO (see text). In the figure, the stars represent the scintillator hits. The time of flight of the particle can be measured only for the *Internal Up* and *Up Through* events.

2. Neutrino events in MACRO

The MACRO detector is located in Hall B of the Gran Sasso Laboratory, with a minimum rock overburden of 3150 hg/cm^2. It is a large rectangular box, 76.6 m × 12 m × 9.3 m, divided in six similar supermodules. The active detection elements are planes of streamer tubes for track-

*For the complete author list see "Relevance of the hadronic interaction model in the interpretation of multiple muon data as detected with the MACRO experiment" by O.Palamara et al., these Proceedings.

0920-5632/99/$ – see front matter
PII S0920-5632(99)00305-9

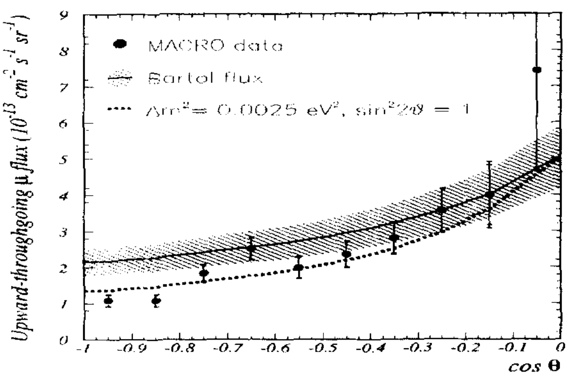

Figure 2. Zenith distribution of flux of upward throughgoing muons with energy greater than 1 GeV for data and Monte Carlo for the combined MACRO data. The solid curve shows the expectation for no oscillations and the shaded region shows the 17% uncertainty in the expectation. The dashed line shows the prediction for an oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2.

ing and of liquid scintillation counters for fast timing. The lower half of the detector is filled with trays of crushed rock absorbers alternating with streamer tube planes, while the upper part is open. Figure 1 shows a schematic plot of the three different topologies of neutrino events analyzed up to now: *Up Through* events, *Internal Up* events and *Internal Down* together with *Up Stop* events.

The *Up Through* tracks come from ν_μ interactions in the rock below MACRO. The muon crosses the whole detector ($E_\mu > 1$ GeV). The time information provided by scintillator counters permits one to know the flight direction (time-of-flight method). Almost 50% of the tracks intercept 3 scintillator counters. The average neutrino energy for this kind of events is around 100 GeV. Several cuts are imposed to remove backgrounds caused by radioactivity in near coincidence with muons and showering events which may result in bad time reconstruction. The observed number of upgoing throughgoing muons integrated over all zenith angles is 451 (backgrounds subtracted) to be compared with the prediction computed using the neutrino flux computed by the Bartol

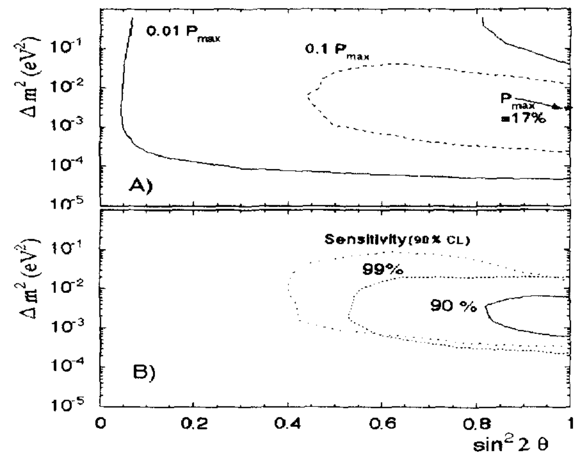

Figure 3. A) Probability contours for oscillation parameters for $\nu_\mu \to \nu_\tau$ oscillations based on the combined probabilities of zenith shape and number of events tests. The best probability in the physical regn is 17% and iso-probability contours are shown for 10% and 1% of this value (i.e. 1.7% and 0.17%). B) Confidence regions at the 90% and 99% levels calculated according to reference [4]. Since the best probability is outside the physical region the confidence intervals regions are smaller than the one expected from the sensitivity of the experiment.

group[5]. The theoretical error in the prediction is 17%. The expected number of events integrated over all zenith angles is 612, giving a ratio of the observed number of events to the expectation of 0.74 ± 0.036(stat) ± 0.046(systematic) ± 0.13(theoretical). Figure 2 shows the zenith angle distribution of the measured flux of upgoing muons with energy greater than 1 GeV for all MACRO data compared to the Monte Carlo expectation for no oscillations and with a $\nu_\mu \to \nu_\tau$ oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2 (dashed line).

Figure 3 A) shows probability contours for oscillation parameters using the combination of probability for the number of events and χ^2 of the angular distribution. The maximum of the probability is 17%. The probability for no oscillation is 0.1%. Figure 3 B) shows the confidence regions at the 90% and 99% confidence levels based on application of the Monte Carlo prescription of reference [4]. We plot also the sensitivity of the

Table 1
Event Summary. The predictions with oscillations are for maximum mixing and $\Delta m^2 = 0.0025eV^2$

	Events detected	Predictions (Bartol neutrino flux)	
		No Oscillations	With oscillations
Up Through	451	$612 \pm 104_{theoret} \pm 37_{syst}$	$431 \pm 73_{theoret} \pm 26_{syst}$
Internal Up	85	$144 \pm 36_{theoret} \pm 14_{syst}$	$83 \pm 21_{theoret} \pm 8_{syst}$
In Down + Stop	120	$159 \pm 40_{theoret} \pm 16_{syst}$	$123 \pm 31_{theoret} \pm 12_{syst}$

experiment. The sensitivity is the 90% contour which would result from the preceding prescription if the data and Monte Carlo happened to be in perfect agreement at the best-fit point.

The *Internal Up* events come from ν interactions inside the apparatus. Since two scintillator layers are intercepted, the time-of-flight method is applied to identify the upward going events. The average neutrino energy for this kind of events is around 4 GeV. If the atmospheric neutrino anomalies are the results of ν_μ oscillations with maximum mixing and Δm^2 between 10^{-3} and 10^{-2} eV^2 it is expected a reduction in the flux of this kind of events of about a factor of two, without any distortion in the shape of the angular distribution.

The *Up Stop* and the *Internal Down* events are due to external interactions with upward-going tracks stopping in the detector (*Up Stop*) and to neutrino induced downgoing tracks with vertex in lower part of MACRO (*Internal Down*). These events are identified by means of topological criteria. The lack of time information prevents distinguishing the two sub samples. An almost equal number of *Up Stop* and *Internal Down* is expected if neutrinos do not oscillate. The average neutrino energy for this kind of events is around 4 GeV. In case of oscillations we expect a reduction in the flux of the *Up Stop* events similar to the one expected for the *Internal Up* events, while we do not expect any reduction of the *Internal Down* events (having path lengths of the order of 20 km).

The uncertainty on the expected muon flux for the low energy events is about 25%. In the Table 1 the total number of events is compared with the predictions based on the Bartol neutrino flux [5] and on the neutrino low energy cross sections reported in [6].The low energy samples show a deficit of the measured number of events with respect to the predictions, while there is a good agreement with the predictions based on neutrino oscillations.

REFERENCES

1. Y. Fukuda et al. (SuperKamiokande collaboration) : 1998, hep-ex/9807003 and T.Kajita Neutrino 1998 proceedings.
K. S. Hirata et al. (Kamiokande collaboration) Phys. Lett. B280 (1992) 146 and Y. Fukuda et al. Phys. Lett. B335 (1994) 237.
R. Becker-Szendy et al (IMB collaboration): Phys. Rev.Lett. 66 (1991) 2561.
W.W.M. Allison et al (Soudan 2 Collaboration): Phys. Lett. B391,(1997) 491 and E. Peterson Neutrino 1998 proceedings
2. S. Ahlen et al. (MACRO collabor.), Phys. Lett. B 357 (1995) 481.
3. M. Ambrosio et al.(MACRO collabor.) hep-ex/9807005 to be published on Phys Lett. B.
4. G. Feldman and R. Cousins, Phys. Rev. D57 (1998) 3873.
5. V. Agrawal, T.K. Gaisser, P. Lipari and T. Stanev, Phys. Rev. D53 (1996) 1314.
6. P. Lipari, M. Lusignoli and F. Sartogo, Phys. Rev. Lett. 74 (1995) 4384.