ELSEVIER

Nuclear Physics B (Proc. Suppl.) 100 (2001) 113–118

NUCLEAR PHYSICS B
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Atmospheric neutrinos in the Soudan-2 and MACRO experiments

F. Ronga [a]

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

The results of Soudan-2 and MACRO experiments are summarized. Both experiments observe atmospheric neutrino anomalies in agreement with $\nu_\mu \to \nu_\tau$ oscillations with maximum mixing. The $\nu_\mu \to \nu_s$ oscillations are disfavoured by the MACRO experiment at 98% C.L.

1. INTRODUCTION

Neutrino oscillations[1] were suggested by B. Pontecorvo in 1957 after the discovery of the $K^0 \leftrightarrow \overline{K^0}$ transitions.

A big step forward in the search for neutrino oscillations in atmospheric neutrinos is due to the Superkamiokande experiment. In 1998 at the Takayama Neutrino conference[2] there was the announcement of the observation of neutrino oscillation (ν_μ disappearance) from the Superkamiokande experiment. It is notable that, at the same conference, the two other running experiments Soudan-2 and MACRO have presented results in strong support of the same ν_μ oscillation pattern observed by SuperKamiokande. Soudan-2 and MACRO detectors are completely different from SuperKamiokande. The Soudan-2 and MACRO data are limited in statistics and event topologies respect to SuperKamiokande, but the use of completely different detectors can give important information concerning the systematic on the atmospheric neutrino measurements.

2. THE SOUDAN-2 EXPERIMENT

The Soudan-2 experiment[3] is currently taking data using its fine-grained iron tracking calorimeter of total mass 963 tons. This detector tracks non-relativistic as well as relativistic charged particles produced in atmospheric neutrino reactions. It is operating underground at a depth of 2100 meters-water-equivalent.

The calorimeter is surrounded on all sides by a shield array of two or three layers of proportional tubes. Using this shield it is possible to measure the background due the downward going cosmic ray muons producing neutral particles in the rock around and simulating neutrino interactions in the calorimeter (rock events). The calorimeter's modular design enabled data-taking to start in April 1989 when the detector was one quarter of its full size; assembly of the detector was completed during 1993. Data-taking has continued with 85% live time.

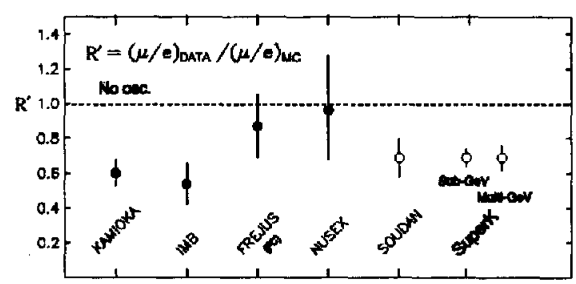

Figure 1. Measurements of the atmospheric neutrino flavor ratio.

Topologies for contained events in Soudan 2 include single track and single shower events (mostly ν_μ and ν_e quasi-elastic reactions) and multiprong events. Flavor-tagging proceeds straightforwardly: an event having a leading, non-scattering track with ionization dE/dx compatible with muon mass is a ν_μ candidate charged current (CC) event; an event having a prompt,

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PII S0920-5632(01)01422-0

relatively energetic shower prong is a candidate ν_e CC event. Recoil protons of momenta greater than 350 MeV/c are imaged by the calorimeter, allowing a much-improved measurement of the incident neutrino direction, especially for sub-GeV quasi-elastic reactions.

The results of the Soudan-2 experiment are discussed in detail in the proceedings of the neutrino 2000 conference[4]. Here I want to stress the importance of this experiment for the Sub-GeV events (events having energies of the order of 1 GeV or less) where a possible contradiction between the iron sampling calorimeters and the water Cherenkov detector was suggested in the past.

3. SOUDAN-2 RESULTS

The measurement of the atmospheric neutrino ν_μ / ν_e flavor ratio-of-ratios R is done using single track and single shower events which are fully contained within the calorimeter (all hits more than 20 cm from the nearest surface). The track and shower event samples for the 5.1 kton year exposure are summarized in Table 1. The full detector Monte Carlo simulation of atmospheric neutrino interactions is based on the 1996 Bartol flux for the Soudan site [6]. The flavor ratio-of-ratios obtained is $R = 0.68 \pm 0.11(stat) \pm 0.06(sys)$ with no change respect to the previous Soudan-2 value.

Table 1
Soudan-2 track and shower event samples from the 5.1 fiducial kiloton-year exposure.

	Tracks	Showers
Data, raw	133	193
Monte Carlo events	193.1	179.0
Data, bkgrd subtr.	105.1±12.7	142.3±13.9

Figure 1 shows the current experimental situation together with the new results of Soudan-2 with 5.1 Ktons/year of data.

Soudan-2 measures a flux of ν_e neutrinos smaller than the one expected while SuperKamiokande finds agreement between predictions and data. This disagreement could be due to a statistical fluctuation or to some physical effect due to the different geomagnetic cuts or to differences in the energy distribution of the neutrino samples.

The Soudan-2 group has been able to study the L/E distribution for a sample of events selected to have an high energy resolution (HiRes events). They use a quasi-elastic track or shower event provided that the recoil proton is measured and that P_{lept} exceeds 150 MeV/c; otherwise, if the recoil nucleon is not visible, they require the single lepton to have E_{vis} greater than 600 MeV. They also select multiprong events, provided they are energetic (E_{vis} greater than 700 MeV) and have vector sum of P_{vis} exceeding 450 MeV/c (to ensure clear directionality). Additionally, the final state lepton momenta are required to exceed 250 MeV/c. After background subtraction they have 106.3 ν_μ CC events and 132.8 ν_e CC events.

The L/E distributions are shown in Figure 2. Using these events, whose mean energy is higher than that of single track and shower events, the ratio-of-ratios is $R = 0.67 \pm 0.12$, which is also significantly less than 1.0.

Due to the nuclear effects and to the limited statistics it is not possible to see the sinusoidal pattern of the oscillation formula with the first minimum at $Log(\frac{L}{E}) = 2.5$ predicted in the case of oscillations with $\delta m^2 \sim 3 \times 10^{-3} eV^2$. One of the main goal of the next generation atmospheric neutrino experiments is the measurement of this pattern that could provide a precise measurement of the oscillation parameters and a way to discriminate alternative hypothesis with neutrino decays[7].

To find the region allowed for the oscillation parameters by the data at 90% confidence level (CL), Soudan-2 uses the method of Feldman and Cousins [5] and a χ^2 in 8 bins:

$$\chi^2 = \sum_{k=1}^{8} \frac{(N_k(data - bkg) - f_\nu \cdot N_k(MC))^2}{\sigma_k^2}. \quad (1)$$

The χ^2 is summed over data bins containing the selected (HiRes) ν_μ and ν_e samples, where $k = 1-7$ are ν_μ log (L/E_ν) bins, with $k = 8$ containing all the ν_e events. The normalization f_ν factor is a parameter to be fitted. Not yet included are

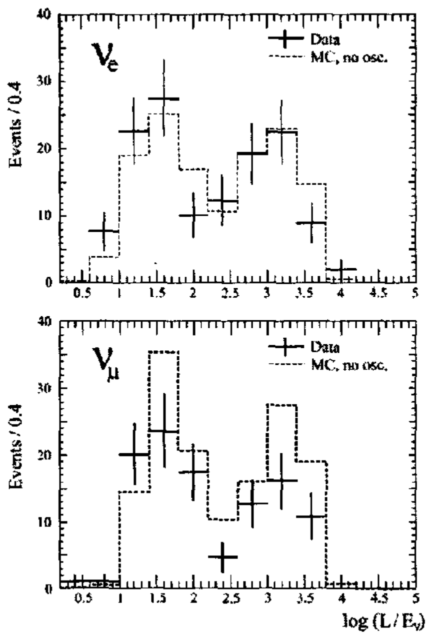

Figure 2. $\frac{L}{E}$ distribution for the Soudan-2 experiment[4]. Top: ν_e with data normalized to the prediction. Bottom : ν_μ with normalization taken from ν_e.

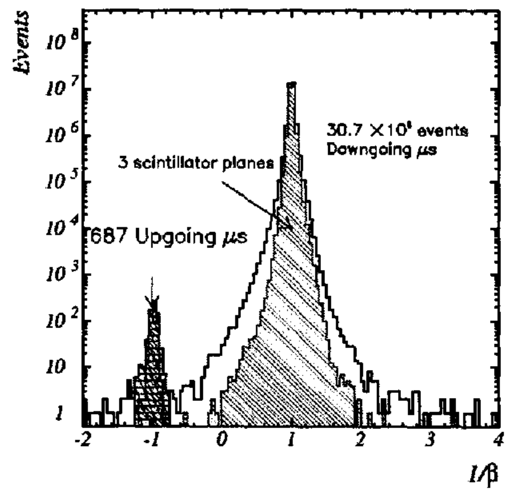

Figure 3. The $1/\beta$ distribution for the data with full MACRO. The peak at $1/\beta = 1$ is due to donward going muons. The peak at $1/\beta = -1$ is due to ν events producing upward going muons. The shadowed area is due to events intercepting 3 scintillator counters.

error terms which address systematic errors in the analysis, however preliminary examination shows statistical errors to be the dominant errors.

Due to the use of the Feldman-Cousins procedure, the allowed regions shown in figure 7, are smaller than the one presented previously by the Soudan-2 collaboration.

4. THE MACRO EXPERIMENT

Now I report the update to March 2000 of the atmospheric neutrino results already published by the MACRO collaboration [8,9].

The active detectors in MACRO are streamer tube chambers, which are used for tracking, and liquid scintillator counters used for timing. The requirement of a reconstructed track selects muon events.

Three different topologies of neutrino events are analysed up to now: *Up Through* events (high energy events), *Internal Up* events and *Internal Down* events together with *Up Stop* events (low energy 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 conters gives the flight direction (time-of-flight method). The median neutrino energy for this kind of events is of the order of 50 GeV. The data have been collected with different detector configurations starting in 1989 with a small part of the apparatus.

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 median neutrino energy for this kind of events is around 3.5 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 it is expected a reduction in the flux of this kind of events of about a factor

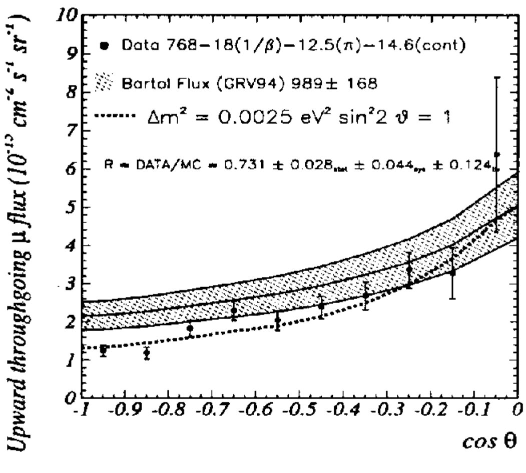

Figure 4. Zenith distribution of the flux of upgoing muons with energy greater than 1 GeV for the combined MACRO data and Monte Carlo for. The shaded region shows the expectation for no oscillations with the 17% normalization uncertainty. The solid line shows the prediction for an oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2.

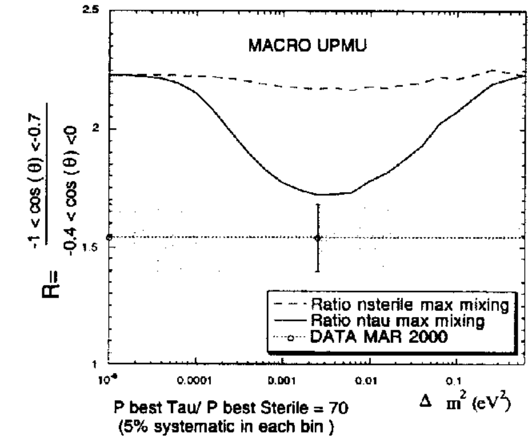

Figure 5. The ratio between the data in two bins and the comparison with the ν_s and ν_τ oscillations with maximum mixing

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 the vertex in the lower part of MACRO (*Internal Down*). These events are identified by means of topological criteria. The lack of time information prevents to distinguish the two sub-samples. The median neutrino energy is around 4.2 GeV. An almost equal number of *Up Stop* and *Internal Down* is expected if neutrinos do not oscillate. In case of oscillations, it is not expected a reduction in the flux of the *Internal Down* events (having path lengths of the order of 20 km), while it is expected a reduction in the number of the *Up Stop* events similar to the one expected for the *Internal Up*.

Only the data collected with the full MACRO (live-time around 5.1 years) have been used in the low energy event analysis.

5. MACRO UPWARD THROUGH-GOING MUONS

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. Upward going muons are selected with the requirement $-1.25 \leq 1/\beta \leq -0.75$. The $1/\beta$ distribution is shown in Figure 3.

Several cuts are imposed to remove backgrounds caused by radioactivity or showering events which may result in bad time reconstruction. The most important cut requires that the position of a muon hit in each scintillator, as determined from the timing within the scintillator counter, agrees within ±70 cm with the position indicated by the streamer tube track.

Removing the backgrounds, the observed number of upward through-going muons integrated over all zenith angles is 723.

The total systematic uncertainty on the expected flux of muons, adding the errors from the Bartol neutrino flux, neutrino cross-section and muon propagation in quadrature is ±17%. This theoretical error in the prediction is mainly a scale error that doesn't change the shape of the angular distribution. The number of expected events integrated over all zenith angles is 989, giving a ratio of the observed number of events to the expectation of 0.73 ±0.028(stat) ±0.044(systematic) ±0.12(theoretical).

Figure 4 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 $\nu_\mu \rightarrow \nu_\tau$ oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2.

The shape of the angular distribution has been tested with the hypothesis of no oscillations normalizing data and predictions. The χ^2 is 24.3, for 9 degrees of freedom. Also $\nu_\mu \rightarrow \nu_\tau$ oscillations are considered. The best χ^2 in the physical region of the oscillation parameters is 11.2 for Δm^2 around 0.0025 eV^2 and maximum mixing (the minimum is outside the physical region).

The 90% confidence level regions of the MACRO upgoing events are shown in Figure 7. The MACRO limits are computed using the Feldman-Cousins procedure[5]. In Figure 7 the results obtained using the angular distribution alone and the angular distribution together with the information due to the overall normalization are shown. The 90% confidence level regions are a bit smaller than the regions obtained by SuperKamiokande for the upgoing muon events. This is due to several reasons: Superkamiokande has an average energy threshold of the order of 7 GeV while for MACRO it is 1.5 GeV; large fluctuations in the contour plots are expected for statistical fluctuations and finally the statistical method to draw contour plot is different (Supekamiokande doesn't use the Feldman-Cousins procedure). We have verified that most of the difference is due to the use of Feldman-Cousins procedure.

Using the matter effect it is possible to discriminate between $\nu_\mu - \nu_s$ oscillation and $\nu_\mu - \nu_\tau$ computing the ratio between the number of events in the two angular regions shown in Figure 5. The angular regions are chosen according to a Montecarlo study which provides the bins which should be used to have the best discrimination between the two kind of oscillations. Using this ratio the statistical significance is higher than in the case of a χ^2 test with data binned in 10 bins, but some features of the angular distribution could be lost. The ratio is insensitive to most of the errors on the theoretical prediction of the ν flux and cross section[10]. From the plot in Figure 5 using the statistical error and a systematic error of 5% for each angular region (mainly due to the acceptance) the ratio between the best probability for tau neutrino and the best for sterile neutrino is 70. This means that the $\nu_\mu \rightarrow \nu_s$ oscillation is disfavoured by the MACRO experiment at 98% C.L. respect to $\nu_\mu \rightarrow \nu_\tau$.

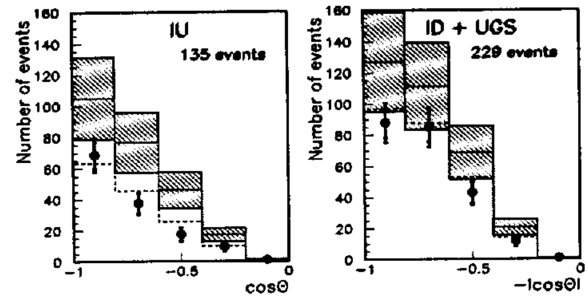

Figure 6. Zenith angle (θ) distribution for IU and $UGS + ID$ events. The background-corrected data points (black points with error bars) are compared with the Monte Carlo expectation (25% uncertainty) assuming no oscillation (full line) and two-flavor oscillation (dashed line) using maximum mixing and $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$.

6. MACRO LOW ENERGY EVENTS

The analysis of the *Internal Up* events is similar to the analysis of the *Up Through* events. The main difference is due to the requirement that the interaction vertex should be inside the apparatus. After the background subtraction (6 events) 135 events are classified as *Internal Up* events

The *Internal Down* and the *Up Stop* events are identified by topological constraints. The main requirement is the presence of a reconstructed track crossing the bottom scintillator layer. All the track hits must be at least 1 m from the detector's edges. After background sub-

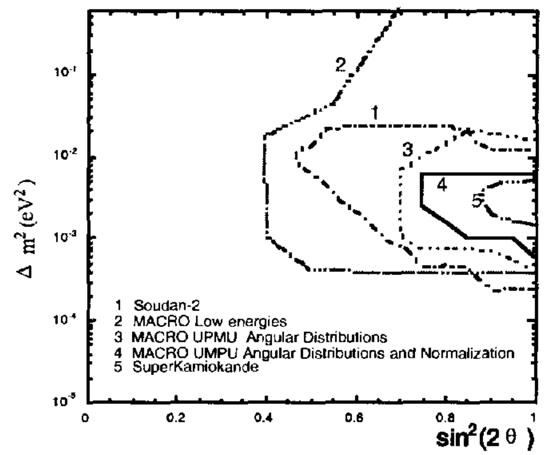

Figure 7. Summary of the 90% confidence level regions. The MACRO and Soudan-2 limits are computed using the Feldman-Cousins procedure. This procedure gives regions smaller than the one obtained with the method used by SuperKamiokande

traction (9 events), 229 events are classified as *Internal Down* and *Up Stop* events.

The angular distributions of data and predictions are compared in Figure 6. The low energy samples show an 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 theoretical errors coming from the neutrino flux and cross section uncertainties almost cancel if the ratio between the measured number of events $\frac{IU}{(ID+UGS)}$ is compared with the expected one. The partial error cancellation arises from the nearly equal energy distributions of parent neutrinos for the IU and the ID+UGS events. The experimental systematic uncertainty on the ratio is 6%. The measured ratio is $\frac{IU}{ID+UGS} = 0.59 \pm 0.07_{stat}$, while the one expected without oscillations is $0.75 \pm 0.04_{sys} \pm 0.04_{theo}$. The probability (one-sided) to obtain a ratio so far from the expected one is 3%, nearly independent of the neutrino flux and neutrino cross sections. The 90% confidence level level region for the low energy events is shown in Figure 7.

7. CONCLUSIONS

The Soudan-2 detector is able to study atmospheric neutrino oscillations in the Sub-GeV region. MACRO is able to cover the Multi-GeV and the $\sim 100\ GeV$ region. MACRO and Soudan2 results can be compared to SuperKamiokande that covers all the three region. The statistical power of the Superkamiokande experiment is larger than the others, but it is remarkable to note that it is possible to see the same effect detected in Superkamiokande with detectors using completely different experimental techniques and in similar energy regions.

I would like to thank T. Mann for the information on the Soudan-2 results, T. Kaijta for the useful discussions on the comparison of the MACRO and SuperKamiokande data and T. Montaruli for the careful reading of this paper.

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