Proceedings of ICRC 2001: 1077 © Copernicus Gesellschaft 2001

ICRC 2001

Low-energy atmospheric ν_μ flux measurement with MACRO

M. Spurio for the MACRO Collaboration

Università di Bologna and INFN- Sezione di Bologna, Italy

Abstract. The MACRO experiment has studied the flux of atmospheric muon neutrinos in the GeV-range through the detection of ν_μ interactions inside the apparatus, and also through the detection of upward-going, stopping muons. We present the analysis of the full data sample (from Spring 1994 up to the end of 2000). The measured flux shows a deficit with respect to the Monte Carlo predictions. We interpret the deficit in terms of neutrino oscillations, and we present the allowed region in the oscillation parameter space. The preferred values of oscillation parameters are in agreement with those obtained in the analysis of the higher energy data set of upward throughgoing muons.

1 MACRO as a atmospheric ν_μ detector

The MACRO detector (Ahlen, 1995) is a large rectangular box (76.6 m× 12 m× 9.3 m) whose active detection elements are planes of streamer tubes for tracking and liquid scintillation counters for fast timing. The lower half of the detector is filled with streamer tube planes alternating with trays of crushed rock absorber, while the upper part is open. The crushed rock provides most of the 5.3 kton target mass for partially-contained neutrino interactions.

The neutrino oscillations are studied using three neutrino event topologies, shown in Fig. 1: *Up throughgoing* events (median neutrino energy ~ 50 GeV) (Ahlen, 1995; Ambrosio, 1998; Montaruli, 2001) induced by neutrinos in the rock below the detector; *Internal Up* events and *Internal Down + Up Going Stopping* events (both with median neutrino energy ~ 4 GeV) (Ambrosio, 2000; Spurio, 2001).

Here we present the results for the low energy events ($E_\nu \sim 4$ GeV). A global reanalysis to combine all experimental data sets and to reduce the systematic errors is in progress. The *Internal Up* events are induced by neutrinos interacting in the lower part of the apparatus. The upgoing muon is detected by the two upper layers of liquid scintillation counters and the direction measured through time-of-flight. The *Internal Down* events are semi-contained interactions, giving a muon crossing only the lower layer of scintillators. Because of the lack of time-of-flight measurement, these events are indistinguishable from upward going stopping muons (UGS). For the latter the ν_μ, interacting below MACRO, yields an upgoing muon which stops inside the detector.

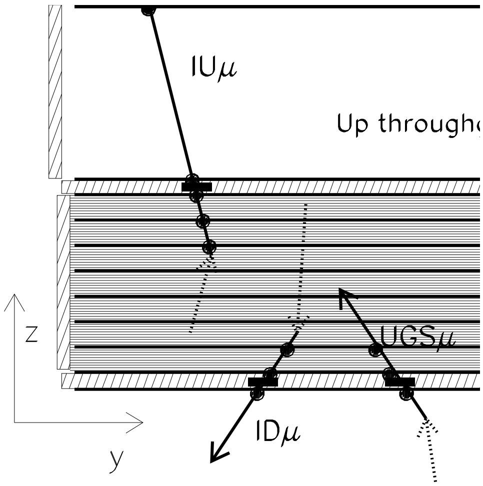

Fig. 1. Topologies of events induced by neutrino interactions in or around MACRO. IU= Internal Upgoing μ; ID= Internal Downgoing μ; UGS= Upgoing Stopping μ; Up throughgoing = upward throughgoing μ. The black circles indicate the streamer tube hits, and the black boxes the scintillator hits. The time-of-flight of the muon is measured for the IU and Up throughgoing tracks.

Figure 2 shows the parent neutrino energy distribution from a Monte Carlo calculation for the three event topologies detectable in MACRO. The energy spectrum and the median energy of *Internal Up* and *Internal Down + Up Going Stopping* are almost the same.

The results showed here concern the running period with the full configuration detector from April 1994 to December 2000, when the acquisition was stopped. During this period

---

Correspondence to: M. Spurio (spurio@bo.infn.it)

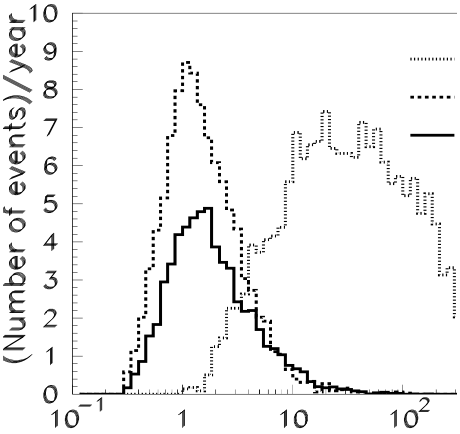

Fig. 2. Monte Carlo simulated distribution of the parent neutrino energy giving rise to the three different topologies of events detectable by MACRO. The distributions are normalized to one year of data taking; the analysis cuts are included.

more than 40 million downgoing muons have been collected. Because of the difference between the two topologies of low energy events, two separate analyses were performed.

2 Internal Upgoing events (IU)

The identification of IU events is based both on topological criteria and time-of-flight measurements. The data used for the Internal Upgoing sample correspond to an effective live time of 5.8 years. The basic requirement is the presence of at least two scintillator clusters in the upper part of the apparatus (see Fig. 1) matching a streamer tube track reconstructed in space. A similar request is made in the analysis for the up throughgoing events produced by ν_μ interactions in the rock below the detector (Ambrosio, 1998).

For IU candidates, the track starting point must be inside the apparatus. To reject fake semi-contained events entering from a detector crack, the extrapolation of the track in the lower part of the detector must cross and not fire at least three streamer tube planes and one scintillation counter.

Based on the study of simulated events the above conditions account for detector inefficiencies and reduce the contribution from upward throughgoing muons which mimic semi-contained muons to less than $\sim 1\%$. The measured muon velocity βc is evaluated with the sign convention that upgoing (downgoing) muons have $1/\beta \sim -1$ ($\sim +1$). A total of 161 events survive in the range $-1.3 < 1/\beta < -0.7$, which is taken as the range of IU signal.

We expect some background events in the signal region; they are mostly due to wrong time measurements or secondary particle hits, yielding an almost flat $1/\beta$ distribution. We estimate 7 background events in the signal region. The estimate is based on the measurement outside the $1/\beta$ signal region. After background subtraction, we have 154 upgoing partially contained events.

3 Upgoing Stopping (UGS) and Internal Downgoing (ID) muons.

The identification of $ID + UGS$ events is based on topological criteria. The candidates have a track starting (ending) in the lower apparatus, and crossing the bottom detector face. The track must also be located or oriented in such a way that it could not have entered (exited) undetected through insensitive zones in the apparatus. For this analysis, the effective live time is 5.6 years.

The event selection requires $i)$ the presence of one reconstructed track crossing the bottom layer of the scintillation counters (see Fig. 1) and $ii)$ all hits along the track confined one meter inside each MACRO supermodule. The event vertex (or μ stop point) in the detector is selected in the same way as for the IU search. So the probability that an atmospheric muon produces a background event is reduced to a negligible event.

To reject ambiguous and/or wrongly tracked events that passed the event selection, a scan with the MACRO Event Display was performed. All the real and simulated events which passed the event selection were randomly merged. The accepted events passed a double scan procedure. (Differences are included in the systematic uncertainty.) The main background is due to upward going charged pions induced by interactions of atmospheric downgoing muons in the rock around the detector. The pion could simulate an upgoing muon induced by a neutrino, if the downgoing muon is undetected. The background 10 events has been evaluated using a full simulation, based on our measurements (Ambrosio, 1998)

After the full analysis chain, 272 events were classified as $ID + UGS$ events; we have 262 events after the background subtraction.

4 Comparisons between data and Monte Carlo

The expected rates were evaluated with a full Monte Carlo (MC) simulation. The events are mainly due to ν_μ charged current (CC) interactions, with a contribution from neutral current (NC) and ν_e interactions ($\sim 13\%$ for IU and $\sim 10\%$ for $UGS + ID$). An almost equal number of UGS and ID neutrino induced events are expected in our data sample. The ν_e and ν_μ were allowed to interact in a volume of rock containing the experimental Hall B and the detector. The rock mass in the generation volume is $169.6\ kton$, while the MACRO mass is $5.3\ kton$. The atmospheric ν flux of the Bartol group (Agrawal, 1996) and the cross sections of Lipari,1995 were used. The detector response has been simulated using GEANT and simulated events are processed in the same analysis chain as the real data. In the simulation, the parameters of the streamer tube and liquid scintillation systems have been chosen in order to reproduce the real average efficiencies.

MACRO partially contained and stopping events are ($\sim$ 90%) induced by parent atmospheric neutrinos whose energy

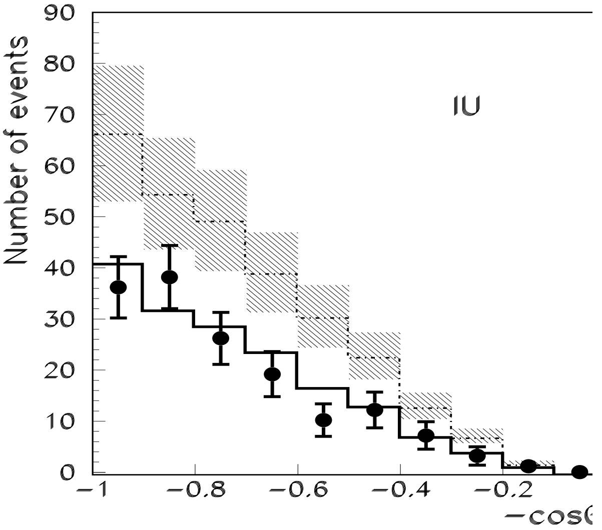

Fig. 3. Measured distributions in the cosine of the zenith angle Θ for the IU events (black points with error bars). The shadowed region corresponds to the Monte Carlo predictions assuming no oscillations. The full line is the expectation for $\nu_\mu \to \nu_\tau$ oscillations with $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and maximal mixing.

is less than 10 GeV (see Fig. 2). Those ν_μ are produced by pion (more than 70%) and kaon decay after primary proton interactions in the upper atmosphere (Gaisser, 2001). The primary energy (giving rise to our events) is well below 100 GeV. In this energy interval, the primary spectrum was recently measured by BESS (Sanuky, 2000) and AMS (Alcaraz, 2000), with a reciprocal agreement within 5% and a systematic uncertainty smaller than 5%.

We estimated an overall total theoretical uncertainty on detected muons (from the errors on ν flux and cross sections) of the order of 25%. This value is probably overestimated; at present there is no unique and reliable estimate of the total theoretical uncertainty for the rate calculation at these energies. This problem probably will be solved with the announced releases of the neutrino flux calculations based on the new primary measurements. Our systematic uncertainty is 10%, arising from the simulation of detector response, data taking conditions, analysis algorithm efficiency, and the mass and acceptance of the detector.

With our full MC simulation, the prediction for IU events is $285 \pm 28_{syst} \pm 71_{theor}$, while the observed number of events is $154{\pm}12_{stat}$. The ratio $R_{IU} = (DATA/MC)_{IU} = 0.54 \pm 0.04_{stat} \pm 0.05_{syst} \pm 0.13_{theor}$ = $0.54 \pm 0.15_{total}$.

The prediction for $UGS + ID$ events is $375 \pm 37_{syst} \pm 94_{theor}$, while the observed number of events is $262{\pm}16_{stat}$. The ratio $R_{UGS+ID} = (DATA/MC)_{UGS+ID} = 0.70 \pm 0.04_{stat} \pm 0.07_{syst} \pm 0.17_{theor}$ = $0.70 \pm 0.19_{total}$. Figure 3 shows the measured angular distribution of the IU and Fig. 4 for the $UGS + ID$ data samples, with the Monte Carlo predictions.

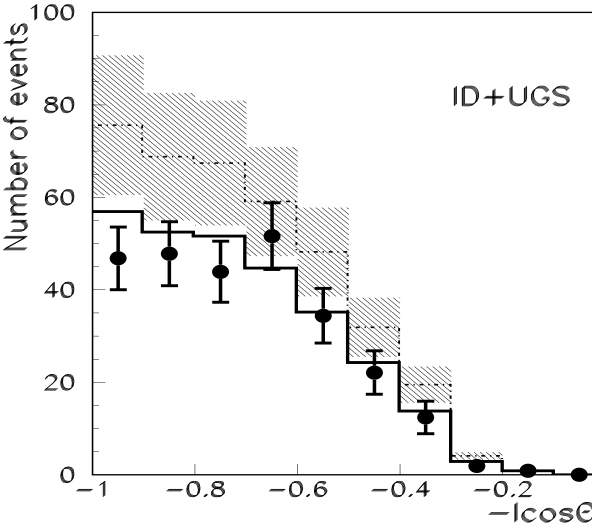

Fig. 4. The same as Fig. 3, but for the $ID + UGS$ events.

5 Discussion of the results

The measured number of IU events (154) is far from the value (285) expected in the case of no ν_μ oscillations. Combining (in quadrature) the statistical, systematic and theoretical errors, the one-tailed gaussian probability of this reduced measurement is 4.9%.

If the observed deficits were due to a theoretical overestimate of the neutrino fluxes and/or cross sections, one would expect to measure the same reduction, i.e. $R_{IU} = R_{ID+UGS}$. Using the ratio between the number of IU and $UGS + ID$ events, the theoretical uncertainty almost disappears. This is due to the fact that the events are induced by parent neutrinos with almost the same energy spectrum (Fig. 2), with a relatively small difference due to geomagnetic effects. We evaluated a residual 5% due to the small differences between the energy spectra of the two samples. Due to some cancellations, the systematic uncertainty on the ratio is reduced to $\sim 6\%$.

The measured ratio $IU/(UGS + ID)$ is $R = 0.59 \pm 0.06_{stat}$, while the expected one (for no oscillation) is $R = 0.76 \pm 0.06_{syst+theor}$. The probability to obtain a ratio at least so far from the expected one is 2.2%, taking into account the non gaussian shape of the uncertainty on the ratio. This probability is almost independent of the neutrino fluxes and neutrino cross sections used.

Our data disfavor the no-oscillations hypothesis regardless of overall normalization. The combination of significance levels for the two independent tests : 1-the reduction of IU with respect to the nominal ν_μ flux without oscillations; 2-the different value of the measured $IU/(ID + UGS)$ ratio from the expected one (almost flux and cross section independent), gives a combined probability of 0.8%.

The two data sets are consistent with neutrino oscillations

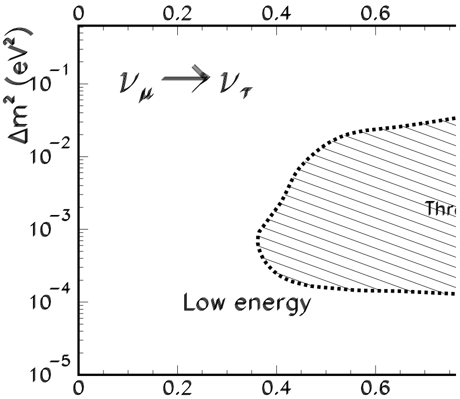

Fig. 5. Allowed contours at 90% C.L. for $\nu_\mu \rightarrow \nu_\tau$ oscillations obtained by combining the low energy neutrino events (IU and $ID + UGS$) using the prescription of (Feldman,1998).

(ν_μ disappearance) with maximal mixing and $\Delta m^2 \sim (1 \div 10) \times 10^{-3}\ eV^2$. In this case (for a pure ν_μ CC interaction sample) upgoing neutrinos which induce IU and UGS events, travelling thousands of kilometers through the Earth, are reduced by 50%. No reduction is expected for downgoing partially contained muons. As a rough prediction, we expect a rate reduced by 50% for IU and by 25% for $ID + UGS$ events. Using the best-fit parameters from high-energy analysis, the expected angular distributions (indicated by the full histograms in Fig. 3 and Fig. 4) are in good agreement with the measured data; the total number of IU events is 168 (154 measured), while it is 284 for the $ID + UGS$ events (262 measured).

We estimate the most likely values of Δm^2 and $sin^2 2\theta_{mix}$ using a χ^2 method for the distributions of Fig. 3 and 4. Figure 5 shows the 90% confidence level region, based on the application of the MC prescriptions (Feldman, 1998) on a $sin^2 2\theta_{mix}$, Δm^2 grid. The expected flux for a given point of $sin^2 2\theta_{mix}$, Δm^2 in the grid is obtained by weighting each simulated event with its survival probability $P(\nu_\mu \nu_\mu)$ in that bin. The maximum of the χ^2 probability (87%) occurs at $sin^2 2\theta_{mix} = 1.0$ and $\Delta m^2 = 1. \times 10^{-3}\ eV^2$.

6 Conclusions

We presented measurements of two samples of events induced by relatively low-energy atmospheric neutrinos ($\overline{E}_\nu \sim 4\ GeV$) interacting in MACRO or in the surrounding rock. The ratio of the number of observed to expected events (no oscillations) is 0.54 ± 0.15 for the IU sample and 0.70 ± 0.19 for the $ID + UGS$ sample. Within statistics, the observed deficits are uniform over the zenith angle. We disfavor (99.2% confidence level (CL)) the hypothesis that the reduction is due to a theoretical overestimate of the event prediction rate. The hypothesis of muon neutrino oscillations explains our data with higher probability. The region with $2 \times 10^{-2} > \Delta m^2 > 2 \times 10^{-4}\ eV^2$ and $sin^2 2\theta_{mix} > 0.4$ is allowed at 90% CL. The maximum of the probability corresponds to $sin^2 2\theta_{mix} = 1.0$ and $\Delta m^2 = 1. \times 10^{-3}\ eV^2$.

This result confirms the scenario proposed by the measurement of higher-energy neutrino-induced muons by MACRO (Ambrosio, 1998; Montaruli, 2001) as well as by other experiments (Fukuda, 1999; Mann, 2000), all of which favor the ν_μ oscillation hypothesis with maximal mixing and Δm^2 of a few times $10^{-3}\ eV^2$.

The MACRO Collaboration: M. Ambrosio, R. Antolini, G. Auriemma, D. Bakari, A. Baldini, G. C. Barbarino, B. C. Barish, G. Battistoni, Y. Becherini, R. Bellotti, C. Bemporad, P. Bernardini, H. Bilokon, V. Bisi, C. Bloise, C. Bower, M. Brigida, S. Bussino, F. Cafagna, M. Calicchio, D. Campana, M. Carboni, R. Caruso, S. Cecchini, F. Cei, V. Chiarella, B. C. Choudhary, S. Coutu, G. De Cataldo, H. Dekhissi, C. De Marzo, I. De Mitri, J. Derkaoui, M. De Vincenzi, A. Di Credico, O. Erriquez, C. Favuzzi, C. Forti, P. Fusco, G. Giacomelli, G. Giannini, N. Giglietto, M. Giorgini, M. Grassi, L. Gray, A. Grillo, F. Guarino, C. Gustavino, A. Habig, K. Hanson, R. Heinz, E. Iarocci, E. Katsavounidis, I. Katsavounidis, E. Kearns, H. Kim, S. Kyriazopoulou, E. Lamanna, C. Lane, D. S. Levin, P. Lipari, N. P. Longley, M. J. Longo, F. Loparco, F. Maaroufi, G. Mancarella, G. Mandrioli, S. Manzoor, A. Margiotta, A. Marini, D. Martello, A. Marzari-Chiesa, M. N. Mazziotta, D. G. Michael, S. Mikheyev, L. Miller, P. Monacelli, T. Montaruli, M. Monteno, S. Mufson, J. Musser, D. Nicolò, R. Nolty, C. Orth, G. Osteria, O. Palamara, V. Patera, L. Patrizii, R. Pazzi, C. W. Peck, L. Perrone, S. Petrera, P. Pistilli, V. Popa, A. Rainò, J. Reynoldson, F. Ronga, A. Rrhioua, C. Satriano, L. Satta, E. Scapparone, K. Scholberg, A. Sciubba, P. Serra, M. Sioli, G. Sirri, M. Sitta, P. Spinelli, M. Spinetti, M. Spurio, R. Steinberg, J. L. Stone, L. R. Sulak, A. Surdo, G. Tarlè, V. Togo, M. Vakili, C. W. Walter, and R. Webb.

Bari, Bologna, Boston, Caltech, Drexel, Frascati, Gran Sasso, Indiana, L'Aquila, Lecce, Michigan, Napoli, Pisa, Roma, Texas A&M, Torino, Oujda, Roma Tre

References

Agrawal V. *et al.*, Phys. Rev. **D53** (1996) 1314
Ahlen S. *et al.* (MACRO Coll.), Nucl. In. Meth. **A324**(1993)337.
Ahlen S. *et al.* (MACRO Coll.), Phys. Lett. **B357**(1995)481.
Alcaraz J. *et al.*, Phys. Lett.B 490(2000)27
Ambrosio M. *et al.*, (MACRO Coll.), Phys. Lett. **B434**(1998) 451;
Ambrosio M. *et al.*, (MACRO Coll.), Astrop. Phys. **9** (1998) 105
Ambrosio M. *et al.*, (MACRO Coll.), Phys. Lett. **B478** (2000) 5
Feldman G.J., Cousins R.D. Phys. Rev. **D57** (1998) 3873
Fukuda Y. *et al.*, (SK Coll.), Phys. Rev. Lett. **82** (1999) 2644
Gaisser T.K., Astro-ph/0104327.
Lipari P.*et al.*, Phys. Rev. Lett. **74** (1995) 4384
Mann W. A. (Soudan 2 Coll), Nucl.Phys.Proc.Suppl.91 (2000) 134
Montaruli T., at this conference.
Sanuky T. *et al.*, Astro-ph/0002481
Spurio M., *MACRO and the atmospheric neutrino problem* hep-ex/0101019