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Neutrino physics and astrophysics with the MACRO detector(*)

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Summary. — After a brief presentation of the MACRO detector we discuss the data on atmospheric neutrinos and neutrino oscillations, on high energy ($E_\nu > 1$ GeV) neutrino astronomy, on indirect searches for WIMPs and low energy ($E_\nu \gtrsim 7$ MeV) stellar collapse neutrinos.

PACS 13.10 – Weak and electromagnetic interactions of leptons.
PACS 13.15 – Neutrino interactions.
PACS 14.60.Pq – Neutrino mass and mixing.
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1. – Introduction

MACRO is a multipurpose underground detector designed to search for rare events in the cosmic radiation. It was optimized to search for the supermassive magnetic monopoles (MMs) predicted by Grand Unified Theories (GUT) of the electroweak and strong interactions. MACRO performs measurements in areas of astrophysics, nuclear, particle and cosmic ray physics. In this paper we shall discuss atmospheric neutrinos and neutrino oscillations, high energy ($E_\nu \gtrsim 1$ GeV) neutrino astronomy, indirect searches for WIMPs and searches for low energy ($E_\nu \gtrsim 7$ MeV) stellar collapse neutrinos. The detector has global dimensions of $12 \times 9.3 \times 76.5$ m^3 and provides a total acceptance to an isotropic flux of particles of $\sim 10000\,\text{m}^2\,\text{sr}$. The total mass is $\simeq 5300$ t. A cross-section of the detector is shown in fig. 1 [1]. It has three sub-detectors: liquid scintillation counters, limited streamer tubes and nuclear track detectors. The mean rock depth of the overburden is $\simeq 3700$ m.w.e.; the minimum is 3150 m.w.e. This defines the minimum downgoing muon energy at the surface as $\sim 1.3\,\text{TeV}$ in order to reach the underground lab. The average residual energy and the muon flux at the lab depth are ~ 310 GeV and ~ 1 m^{-2} h^{-1}, respectively.

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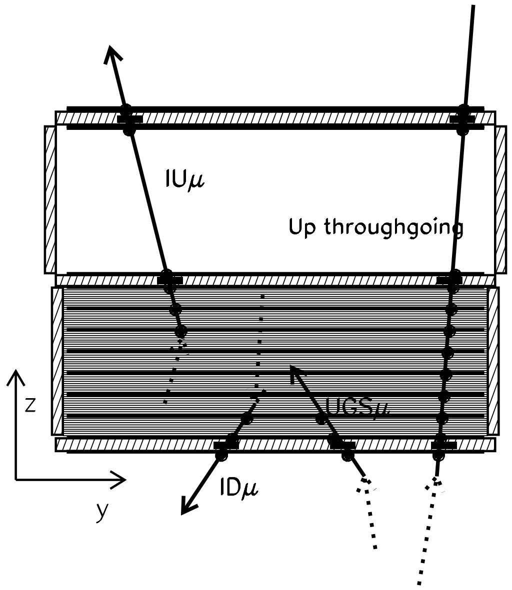

Fig. 1. – Event topologies induced by ν_μ interactions in and around MACRO. The black boxes are scintillator hits. The track direction and versus are measured by the streamer tubes and time of flight (ToF).

2. – Atmospheric ν. Neutrino oscillations

Neutrino oscillations. For massive neutrinos one has to consider the weak flavour eigenstates (ν_e, ν_μ, ν_τ, which are relevant for $\pi \to \mu\nu_\mu$, K$\to \mu\nu_\mu$ and $\mu \to e\nu_e\nu_\mu$ decays and for ν interactions) and mass eigenstates (ν_1, ν_2, ν_3, relevant for propagation). The flavour eigenstates are linear combinations of the mass eigenstates, $\nu_l = \sum_{m=1}^{3} U_{lm}\nu_m$. For two flavours

$$\begin{cases} \nu_\mu = \nu_2 \cos\theta + \nu_3 \sin\theta\,, \\ \nu_\tau = -\nu_2 \sin\theta + \nu_3 \cos\theta\,, \end{cases} \tag{1}$$

where θ is the mixing angle. The rate of ν_μ disappearance is given by

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E_\nu)\,, \tag{2}$$

$\Delta m^2 = {m^2}_{\nu_3} - {m^2}_{\nu_2}$, $L =$ distance (in m) from the decay point to the interaction point.

Only disappearance experiments have been performed until now; the final proof of ν-oscillations will come from appearance experiments, $P(\nu_\mu \to \nu_\tau) = 1 - P(\nu_\mu \to \nu_\mu)$, in which one observes neutrinos which have not been produced in the π, K decays.

Atmospheric neutrinos. Primary cosmic rays produce in the upper atmosphere pions and kaons, which decay, $\pi \to \mu\nu$, K $\to \mu\nu$; and $\mu^\pm \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_e + e^\pm$. Neutrinos are produced in a spherical surface, ~ 10 km from the Earth, and move towards the Earth.

Neutrino-induced upward-going muons. They are identified using the streamer tube system (for tracking) and the scintillator system (for time-of-flight (ToF) measurement). A rejection factor of at least 10^5 is needed in order to separate the up-going muons from

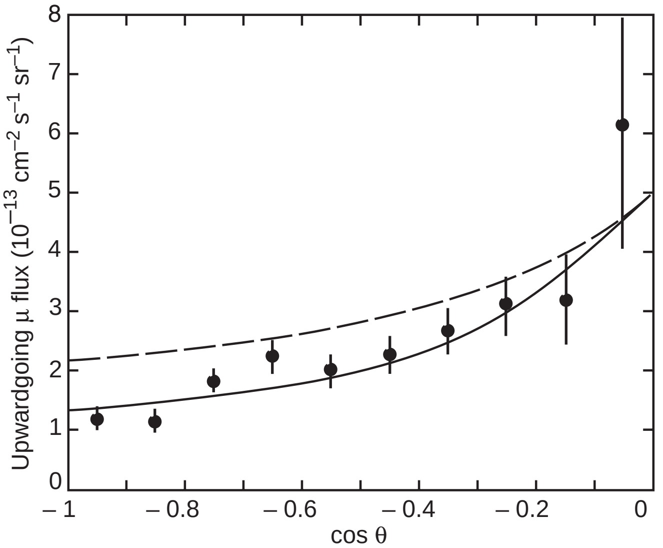

Fig. 2. – The black points are the measured fluxes of the up throughgoing muons with $E_\mu >$ 1 GeV plotted *vs.* zenith angle θ. The dashed line is the expectation for no oscillations; it has a 17 % scale uncertainty. The solid line is the fit to an oscillated muon flux, obtaining maximum mixing and $\Delta m^2 = 0.0025$ eV^2.

the large background coming from down-going muons [2]. Figure 1 shows three different topologies of neutrino events: up throughgoing muons, semicontained upgoing muons (IU) and up stopping muons+semicontained downgoing muons (UGS + ID) [2]. The parent ν_μ energy spectra for the three event topologies were computed with Monte Carlo methods. The number of events measured and expected for the three topologies is given in table I. Sources of background and systematic effects were studied in detail in [3] and found to be negligible.

High energy data. The *up throughgoing muons* come from ν_μ's interacting in the rock below the detector; the ν_μ's have a median energy $\overline{E}_\nu \sim$ 50 GeV. The muons with $E_\mu > 1$ GeV cross the whole detector; the ToF information provided by the scintillation counters allows the determination of their direction (versus).

Figure 2 shows the zenith angle distribution of the measured flux of up throughgoing muons with energy $\gtrsim 1$ GeV; the Monte Carlo expectation for no oscillations is shown as a dashed line, and for a $\nu_\mu \to \nu_\tau$ oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2, as a solid line. The data have been compared with Monte Carlo simulations, using the neutrino flux computed by the Bartol group and the cross-sections for neutrino interactions calculated using the GRV94 parton distribution; the propagation of muons to the detector was done using the energy loss calculation by Lohmann *et al.* [2]. The total theoretical uncertainty on the expected muon flux, adding in quadrature the errors from neutrino flux, cross-section and muon propagation, is 17 %; it is mainly a scale error that does not change the shape of the angular distribution. The ratio of the observed number of events to the expectation without oscillations is given in table I.

The independent probabilities for obtaining the number of events and the angular distribution observed have been calculated for various parameter values. The value of

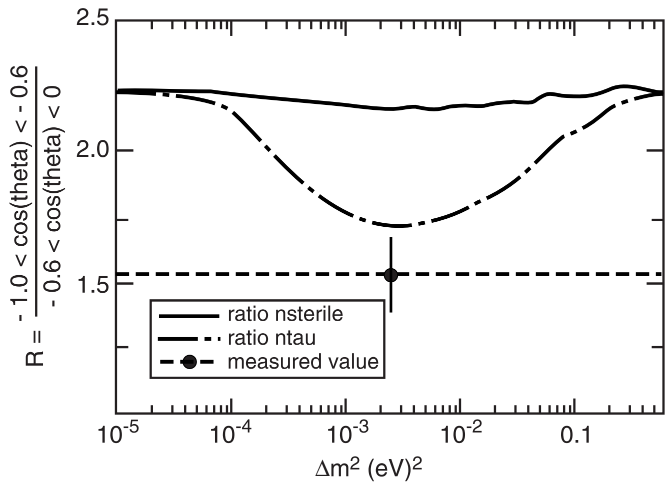

Fig. 3. – The flux ratio vertical/horizontal for upthroughgoing muons. The measured point is plotted at a Δm^2 around the minimum of χ^2 for $\nu_\mu \to \nu_\tau$ oscillations.

Δm^2 obtained from the shape of the angular distribution is equal to the value needed to obtain the observed reduction in the number of events; for $\nu_\mu \to \nu_\tau$ oscillations the maximum probability is 57 %, with best parameters $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta = 1$. The probability for no-oscillations is 0.4 %. The probability for $\nu_\mu \to \nu_{\rm sterile}$ oscillations is 0.15%; combining these probabilities with the measured ratio of horizontal/vertical muons (fig. 3) we conclude that $\nu_\mu \to \nu_{\rm sterile}$ oscillations are disfavoured compared to $\nu_\mu \to \nu_\tau$. Figure 4 shows the 90 % CL regions for $\nu_\mu \to \nu_\tau$, computed according to ref. [4].

Low energy data. The *upgoing semicontained muons* come from ν_μ interactions inside the lower apparatus. Since two scintillation counters are intercepted, the ToF is applied to identify the upward going muons (fig. 1). The average parent neutrino energy for these events is 4.2 GeV.

If the atmospheric neutrino anomalies are the results of $\nu_\mu \to \nu_\tau$ oscillations with maximum mixing and Δm^2 between 10^{-3} and 10^{-2} eV^2 one expects a reduction of about a factor of two in the flux of these events, without any distortion in the shape of the angular distribution. This is what is observed in fig. 5.

The *up stopping muons* are due to external ν_μ interactions yielding upgoing muon tracks stopping in the detector; the *semicontained downgoing muons* are due to ν_μ induced downgoing tracks with vertices in the lower MACRO (fig. 1). The events were selected by means of topological criteria; the lack of time information prevents to distinguish the two sub samples, for which an almost equal number of events is expected; the average neutrino energy for these events is $\simeq 3.5$ GeV. In case of oscillations with the quoted parameters, a reduction in the flux of the up stopping events as the semicontained upgoing muons is expected. No reduction is instead expected for the semicontained downgoing events (coming from neutrinos with path lengths of ~ 10 km).

The MC simulation for the low energy data uses the Bartol neutrino flux and the neutrino low energy cross-sections of ref. [5]. The number of events and the angular distributions are compared with the predictions in fig. 5 and table I. The measured low energy data show a uniform deficit with respect to the predictions; there is good agree-

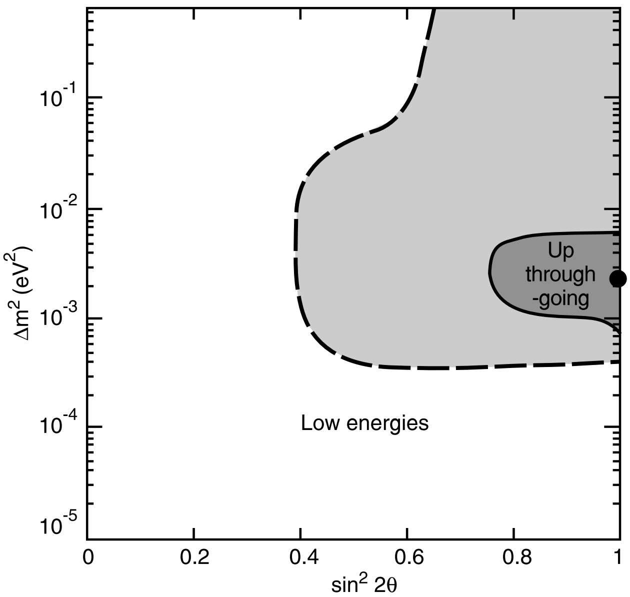

Fig. 4. – Confidence regions for $\nu_\mu \to \nu_\tau$ oscillations at the 90 % CL calculated according to [4], obtained from MACRO high energy and low energy data.

ment with the predictions based on neutrino oscillations using the parameters obtained from up throughgoing muons. The allowed region in the Δm^2, $\sin^2 2\theta$ plane is shown in fig. 4.

Using the double ratio $R = (\text{Data/MC})_{\text{IU}}/(\text{Data/MC})_{\text{ID+UGS}}$ between data and MC of the two low energy data sets, the theoretical uncertainties on neutrino flux and cross-sections almost disappear (a residual 5 % uncertainty remains due to the small differences between the energy spectra of the two samples). The average value of the double ratio over the measured zenith angle distribution is $R \simeq 0.59 \pm 0.07\,\text{stat}$. $R = 0.75$ is expected in case of no oscillations, $R = 0.58$ in case of $\nu_\mu \to \nu_\tau$ oscillations.

TABLE I. – *Event summary for the MACRO atmospheric neutrino flux analyses. The ratios R = Data/MC are relative to MC expectations assuming no oscillations (column 3).*

	Events selected	Predictions (Bartol flux) No. oscillations	R = Data/MC
Up throughgoing	768	989	$0.731 \pm 0.028_{\text{st}} \pm 0.044_{\text{sys}} \pm 0.124_{\text{th}}$
Internal Up	135	202	$0.55 \pm 0.04_{\text{st}} \pm 0.06_{\text{sys}} \pm 0.14_{\text{th}}$
Up Stop + In Down	229	273	$0.70 \pm 0.04_{\text{st}} \pm 0.07_{\text{sys}} \pm 0.18_{\text{th}}$

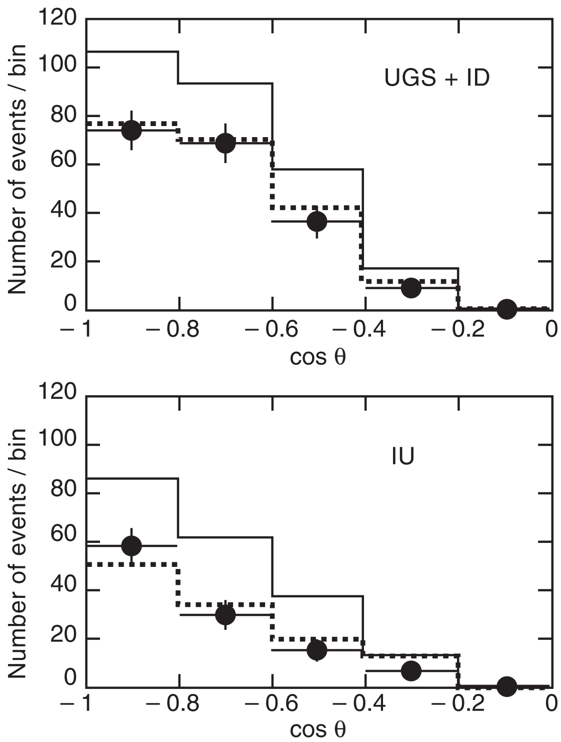

Fig. 5. – Measured and expected number of low energy muon neutrino events *vs.* zenith angle. Top graph: up stopping plus down semicontained; bottom graph: up semicontained. The solid lines are the predictions without oscillations; the dotted lines are the predictions assuming neutrino oscillations with the parameters obtained from the up throughgoing sample.

TABLE II. – *High energy neutrino astronomy: muon and neutrino flux limits (90 % CL) for selected sources calculated according to the prescription in* [4]. *Previous best limits (B is for Baksan, I is for IMB) were computed using the classical Poissonian method.*

Source	δ	Data $3°$	Backg $3°$	μ-Flux limit 10^{-14}cm^{-2}s^{-1}	Prev. best μ limit 10^{-14}cm^{-2}s^{-1}	ν-Flux limit 10^{-6}cm^{-2}s^{-1}
SN1987A	$-69.3°$	0	2.1	0.14	1.15 B	0.29
Vela P	$-45.2°$	1	1.7	0.45	0.78 I	0.84
SN1006	$-41.7°$	1	1.5	0.50	-	0.92
Gal. Cen.	$-28.9°$	0	1.0	0.30	0.95 B	0.57
Kep1604	$-21.5°$	2	1.0	1.02	-	1.92
ScoXR-1	$-15.6°$	1	1.0	0.77	1.5 B	1.45
Geminga	$18.3°$	0	0.5	1.04	3.1 I	1.95
Crab	$22.0°$	1	0.5	2.30	2.6 B	4.30
Her X-1	$35.4°$	0	0.2	3.05	4.3 I	6.45

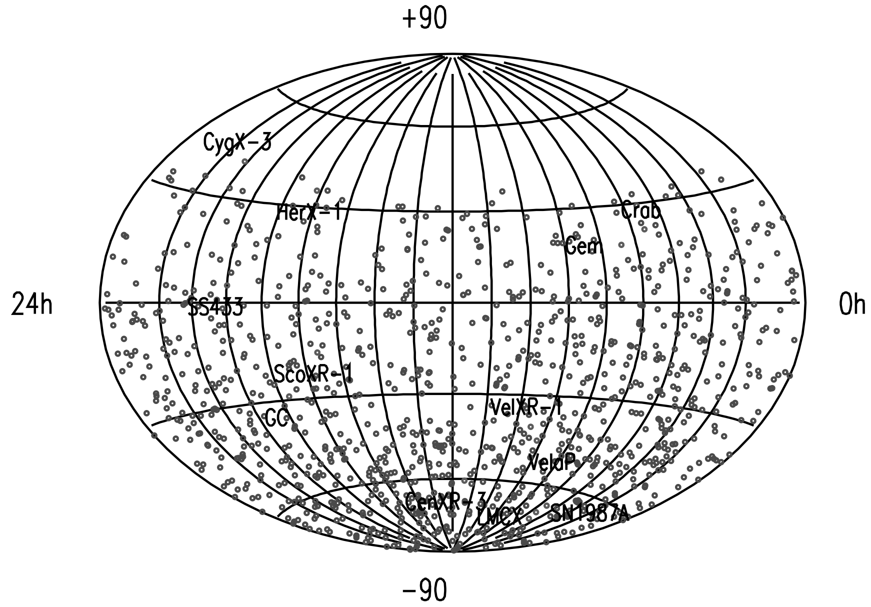

Fig. 6. – High energy neutrino astronomy. Upgoing muon event distribution in equatorial coordinates (1197 events).

3. – High energy muon neutrino astronomy

The excellent angular resolution of the detector allows a sensitive search for up-going muons produced by neutrinos coming from celestial sources; in this case the atmospheric neutrinos are the main background. The pointing capability of MACRO was demonstrated by the observed “shadows” of the Moon and of the Sun, which produce a “shield” to the cosmic rays. We used a sample of 45×10^6 downgoing muons, looking at the bidimensional density of the events around the center of the Moon and of the Sun [6]. The density of events shows a depletion with a statistical significance of 5.5 σ for the Moon and of 4.2 σ for the Sun. The slight displacements of the maximum deficits are consistent with the deflection of the primary protons due to the geomagnetic field for the Moon and to the combined effect of the magnetic field of the Sun and of the geomagnetic field. The angular resolution, corresponding to a cone angle containing 68 % of the events, is $0.9° \pm 0.3°$; it is obtained from double muon events. An excess of events over the atmospheric ν background was searched for around the positions of known sources in 3° (half width) angular bins. This value was chosen so as to take into account the angular smearing produced by the multiple scattering in the rock below the detector and by the energy-integrated angular distribution of the scattered muon, with respect to the neutrino direction. A total of 1197 events was used in this search, see fig. 6. No excess was observed; the 90 % CL limits on the neutrino fluxes from specific celestial sources are at the level of $\sim 10^{-6}$ cm^{-2} s^{-1}, see table II [7].

We also searched for time coincidences of our upgoing muons with γ-ray bursts as given in the BATSE 3B and 4B catalogues, for the period April 91–October 99 [7]. No statistically significant time correlation was found.

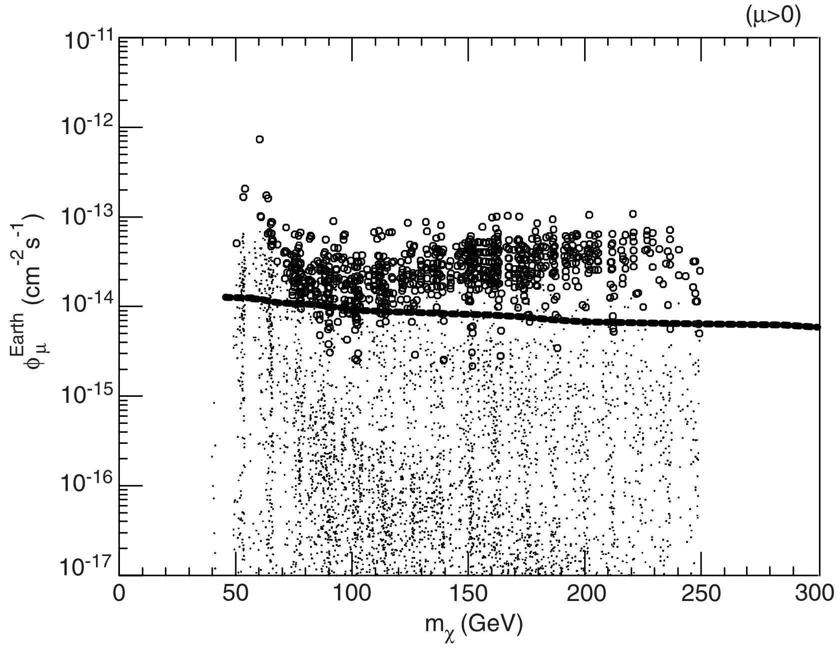

Fig. 7. – Upward-going muon flux *vs.* neutralino mass m_χ for $E_\mu{}^{\rm th} = 1$ GeV from the Earth. Each dot is obtained varying model parameters. The solid line is the MACRO flux limit (90 % CL); the line for the no-oscillation hypothesis is essentially indistinguishable in the log scale from the one for the $\nu_\mu \to \nu_\tau$ oscillation hypothesis (it could be about two times lower). The open circles indicate models *excluded* by direct measurements (particularly the DAMA/NaI experiment) and assume a local dark matter density of 0.5 GeV cm^{-3}.

4. – Indirect searches for WIMPs

Weakly Interacting Massive Particles (WIMPs) could be part of the galactic dark matter; they could be intercepted by celestial bodies, slowed down and trapped in their centers. WIMPs and anti-WIMPs could annihilate and yield pions, kaons and then neutrinos of GeV or TeV energy coming from a small angular window from the celestial body centers. The 90 % CL limit for the flux from the Earth center is $\sim 0.8 \cdot 10^{-14}$ cm^{-2} s^{-1} for a 10° cone around the vertical. The limit from the Sun is $\sim 1.4 \times 10^{-14}$ cm^{-2} s^{-1}. If the WIMPs are identified with the lowest mass neutralinos, the MACRO limit constrains the stable neutralino mass, following the models of Bottino *et al.*, see fig. 7 [8].

5. – Neutrinos from stellar gravitational collapses

A stellar gravitational collapse (GC) is expected to produce a large burst of all types of neutrinos and antineutrinos with energies of 7–30 MeV for a duration of ~ 10 s. The $\bar\nu_{\rm e}$'s can be detected via the reaction $\bar\nu_{\rm e} + {\rm p} \to {\rm n} + {\rm e}^+$ in the liquid scintillator. About 100–150 $\bar\nu_{\rm e}$ events would be detected in our 580 t of scintillator for a stellar collapse at the center of our Galaxy. We use two electronic systems for detecting $\bar\nu_{\rm e}$'s from stellar gravitational collapses [9]. Both systems have an energy threshold of ~ 7 MeV and record pulse shape, charge and timing information. Immediately after a trigger, the dedicated system lowers its threshold to about 1 MeV, for a duration of 800 μs, in order to detect (with $\simeq$ 25 % efficiency) the 2.2 MeV γ released in the reaction n + p $\rightarrow$ d + $\gamma_{2.2\ \mathrm{MeV}}$ induced by the neutron produced in the primary process. A redundant supernova alarm system is in operation: we have defined a general procedure to alert the physics and astrophysics communities in case of an interesting alarm [9]. A procedure to link the various supernovae observatories around the world (MACRO, SuperK, LVD, SNO, etc.) was set up. Our lifetime fraction in the last four years was $\simeq$ 97.5 %. No stellar gravitational collapses were observed in our Galaxy since 1989.

6. – Conclusions

We presented new MACRO data on upgoing muons of low and high energy. These data are relevant for the study of neutrino oscillations, in particular $\nu_\mu \rightarrow \nu_\tau$ [10].

We discussed the limits obtained from the searches for astrophysical sources of H.E. neutrinos, for WIMPs and for low energy neutrinos from gravitational stellar collapses.

REFERENCES

[1] De Marzo C. *et al.*, *Nuovo Cimento C*, **9** (1986)281; Calicchio M. *et al.*, *Nucl. Instrum. Methods A*, **264** (1988) 18; Ahlen S. *et al.*, *Nucl. Instrum. Methods A*, **324** (1993) 337.
[2] Ambrosio M. *et al.*, *Phys. Lett. B*, 434 (1998) 451; **357** (1995) 481; **478** (2000) 5.
[3] Ambrosio M. *et al.*, *Astropart. Phys.*, **9** (1998) 105.
[4] Feldman G. and Cousins R., *Phys. Rev. D*, **57** (1998) 3873.
[5] Lipari L. *et al.*, *Phys. Rev. Lett.*, **74** (1995) 384.
[6] Ambrosio M. *et al.*, *Phys. Rev. D*, **59** (1999) 012003.
[7] Ambrosio M. *et al.*, Neutrino astronomy with the MACRO detector, astro-ph/0002492.
[8] Ambrosio M. *et al.*, *Phys. Rev. D*, **60** (1999) 082002.
[9] Ambrosio M. *et al.*, *Astropart. Phys.*, **8** (1998) 123.
[10] Giacomelli G., Closing lecture at the 1999 S. Miniato Workshop, hep-ex/0001008.