MACRO, a Large-Area Detector at the Gran Sasso Laboratory.

THE MACRO COLLABORATION (*)
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Summary. — MACRO is a large-area detector to be installed in hall B of the Gran Sasso Laboratory. Making use of scintillation counters, plastic streamer tubes, and track-etch detectors, it is designed to search for superheavy magnetic monopoles beyond the Parker bound, high-energy gamma and neutrino cosmic sourcs, and, more in general, exotic phenomena in the cosmic radiation.

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(*) MACRO is an acronym for Monopole, Astrophysics and Cosmic Ray Observatory. The present collaboration:

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1. – Introduction.

The Gran Sasso Laboratory is a unique facility in the world: its impressively large halls, easy access and powerful support facilities make possible to design a new generation of sophisticated underground detectors, dedicated to various fields of investigation.

MACRO is a large-area detector, designed to be installed in the hall B of the Laboratory, and dedicated to the study of rare phenomena in the natural penetrating radiation. The detector has a planar structure covering a surface of $\approx 1400\ m^2$, with an acceptance for isotropic particle fluxes of $\approx 12\,000\ m^2\,sr$.

Its design is optimized to search for magnetic monopoles, and for high-energy neutrino and gamma astronomy via the detection of the secondary penetrating muons.

The search for monopoles is based on excitation-ionization methods. The large detector acceptance allows the search significantly beyond the astrophysical bounds. Furthermore, all the three techniques used in existing experiments (scintillation light, gas ionization, and track-etch detectors), are simultaneously used here, aiming at unambiguous and convincing results.

The MACRO detector is a sensitive observatory to search for and to study cosmic objects, like Cygnus X3, which are powerful emitters of very-high-energy neutral particles (gammas, neutrinos, or new particles), detectable through the secondary penetrating muons. Gamma sources can be identified by narrow anisotropies observed in the downward-going muon flux, in the celestial co-ordinate frame. The Gran Sasso location and detector geometry give a good exposure to Cyg X3. The neutrino sources can be identified by similar narrow anisotropies observed in the upward-going muon flux, which is relatively small and due to atmospheric neutrinos. The detector has a good exposure for two interesting sources, Vela X1 and LMC X4, already identified as VHE gamma emitters by surface detectors in the southern emisphere. The sensitivity estimates give a high expectation for this experiment to open this new observation window. Due to the high particle energies involved, this field of investigation can be of outmost interest not only for astrophysics but also for particle physics.

This connection between astrophysics and particle physics is true in a very general sense for this detector. It can observe rare new forms of matter among the radiation filtered by the mountain, being generally sensitive to exotic penetrating superheavies. Exotic phenomena can be discovered in the multi-muon events, which are both a source of information about very-high-energy particle processes (the primary particle interactions in the atmosphere) and of astrophysical phenomena (the origin of the cosmic-ray primaries).

2. – Detector description.

The detector has been designed to be installed in hall B of the Gran Sasso Laboratory. It has a planar structure with active dimensions of 111.4 m along the hall, 12 m across, and 4.7 m high. Since in the vertical dimension it takes only about one half of the useful hall volume, its general mechanical design provides a concrete floor at a height of 5.7 m from the original floor, which can be used for other experiments.

According to the physics objectives, the basic detector concept is that of a penetrating particle identifier. The main part, shown in fig. 1, consists of a horizontal sandwich of two layers of liquid scintillation counters, ten layers

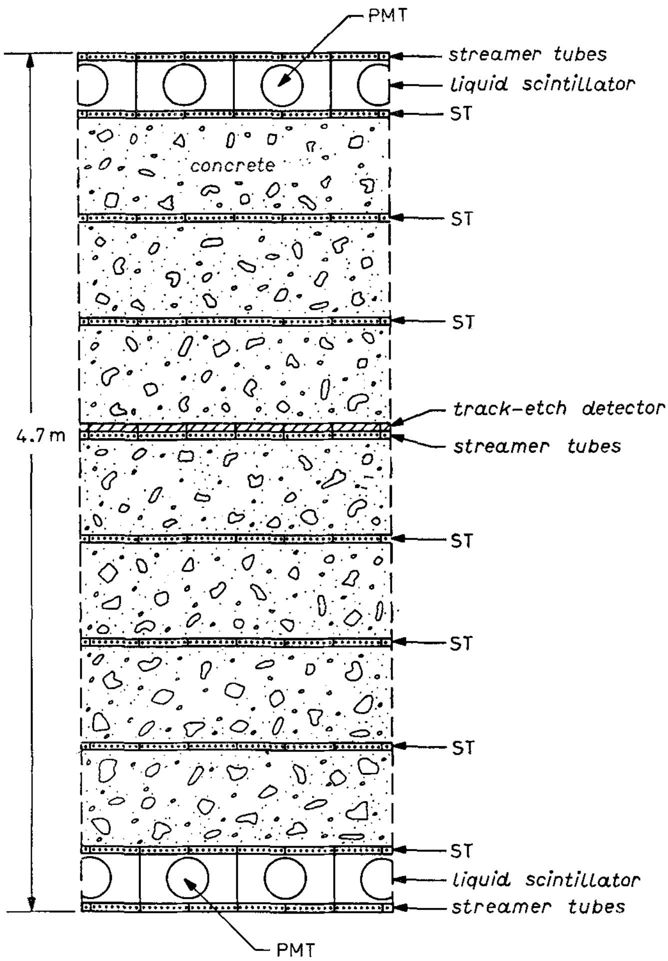

Fig. 1. – Cross-sectional sketch of the detector, showing the relative position of the various components.

of plastic streamer tubes, and a sandwich of plastic track-etch detectors. These sensitive elements are distributed throughout a thick concrete structure, to provide the positive identification of penetrating particles (muons). All the sides of the main horizontal structure are closed by the same sensitive elements, as shown in fig. 2. The acceptance of the closed structure for an isotropic particle flux is $\approx 12000\ m^2\ sr$.

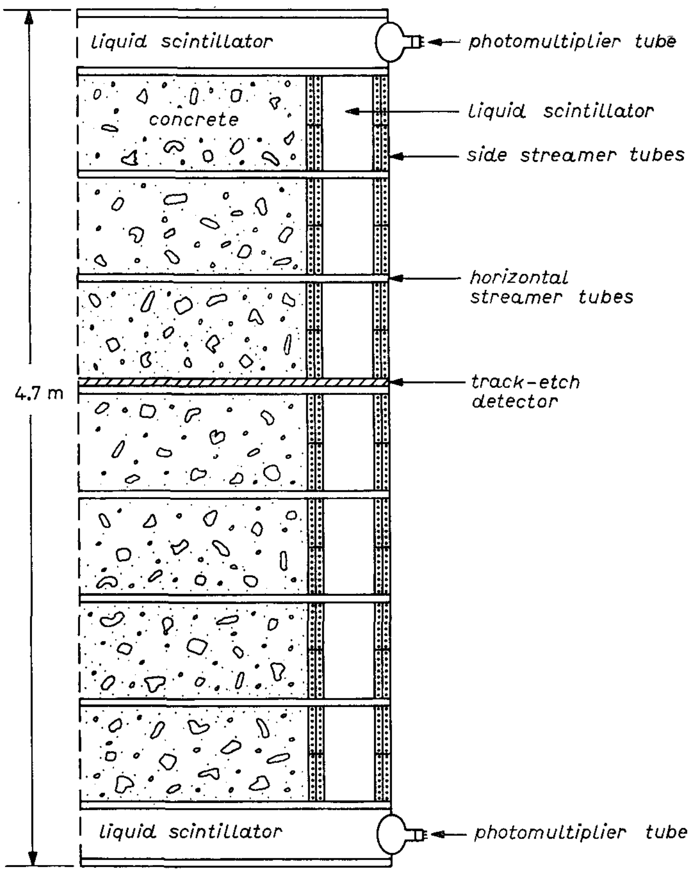

Fig. 2. – Cross-sectional sketch showing the active components which close the sides of the detector.

The liquid-scintillator counter layers are 25 cm thick, providing accurate energy loss and timing information, in particular particle velocity and direction. The streamer tube layers provide tracking with high angle accuracy and ionization information. The track-etch sandwich records the track of highly ionizing penetrating particles.

The whole detector structure results from the simple arrangement of a single modular unit for each of its constituents.

The scintillator counters (572 total) consist of PVC boxes $((50\times25)\,\text{cm}^2\times\times12\,\text{m})$, filled with a safe, stable and highly transparent mineral oil-based liquid scintillator. Each box is lined with low index of reflection ($n=1.35$) FEP TEFLON, providing total reflecting optics. Each counter is viewed by two phototubes, one at each end. The major part of the read-out electronics is the pulse-height digitization of each phototube signal, with wide dynamic range, fine time resolution and long memory.

The plastic streamer tubes consist of single cells of $(3\times3)\,\text{cm}^2\times12\,\text{m}$, filled with a helium and n-pentane mixture, and with a $60\,\mu\text{m}$ anode wire. The single-cell cathode structure has low resistivity graphite side walls and electrodeless top and bottom walls. The modular unit consists of an extruded PVC chamber $((25\times3)\,\text{cm}^2\times12\,\text{m})$ containing an open 8-cell profile, extruded PVC also. Two 8-tube chambers fit one scintillation counter. Two-dimensional localization in one layer of streamer tubes is provided by one set of external pick-up strips placed along the wires, and one set of pick-up strips placed at a stereo angle of $\approx30°$, both with ≈3 cm pitch.

The track-etch detector module is a thin sandwich of Lexan and CR39 sheets, separated by an aluminum absorber.

The combined detector will give a spatial accuracy in the streamer tubes of

$$\Delta x\approx\Delta y\approx\Delta z\approx1\ \text{cm}\,.$$

The ten track points of through-going particles yield an angular accuracy

$$\Delta\theta\approx0.2°\,.$$

The scintillator counters in a single layer using phototubes at each end have spatial and timing accuracy

$$\Delta x\approx15\ \text{cm}\qquad\text{and}\qquad\Delta t\approx1\ \text{ns}\,,$$

while the streamer tubes give

$$\Delta t\approx50\ \text{ns}\,.$$

The ionization loss for minimum ionizing particles crossing both scintillators is measured with an accuracy

$$\frac{\Delta(\Delta E/\Delta x)}{(\Delta E/\Delta x)}\approx5\%\,.$$

The ionization threshold for fully efficient detector triggering by the streamer tubes is

$$(\Delta E/\Delta x)_{\text{min}}\approx10^{-2}(\Delta E/\Delta x)_{\text{min. ion. part}}\,,$$

while for scintillators the corresponding threshold is

$$\approx 10^{-1}(\Delta E/\Delta x)_{\text{min. ion. part}} .$$

The threshold for an individual scintillator counter to detect electrons with good background rejection is

$$E_e \approx 10 \text{ MeV} .$$

The average minimum energy for muons to cross the whole detector is

$$E_\mu \approx 3 \text{ GeV} .$$

3. – Monopole detection.

Grand unified theories require the existence of monopoles. Also they can predict their properties, but not their abundance in the Universe, which at present is completely uncertain.

Actually the only guidance to the experimentalists comes from the astrophysical bounds to their flux. The persistence of the galactic magnetic field and the maximum allowed invisible matter in the universe, both set a limit to the flux of superheavy monopoles ($m_M \approx 10^{16}$ GeV/c²), which is roughly the same in the two cases, $\approx 10^{-15}$ cm^{-2} s^{-1} sr^{-1}.

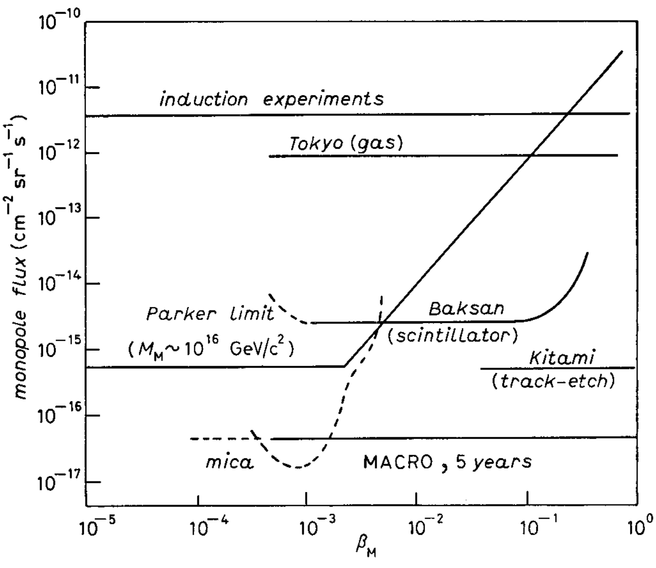

Fig. 3. – Summary of results from main monopole search experiments using the techniques described in the text.

The MACRO acceptance allows a search significantly beyond this limit. Recent theoretical and experimental work allows us to rely on the detector sensitivity in the $10^{-3}\,c$ velocity range (galactic trapping) which is reasonably expected for monopoles.

The expected detector performance, compared to other representative experiments for each technique, are shown in fig. 3. In case of a negative result, the experiment will be the first to set a significant limit on the contribution of monopoles to the dark matter in the Universe.

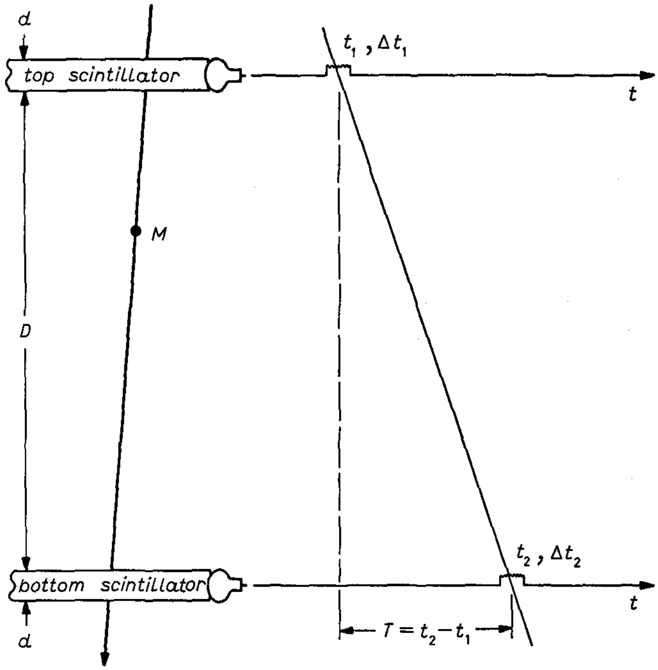

Fig. 4. – The concept for slow particle detection in the scintillator system is shown. A long pulse due to the slow passage of the particle is observed in both the top and the bottom layers.

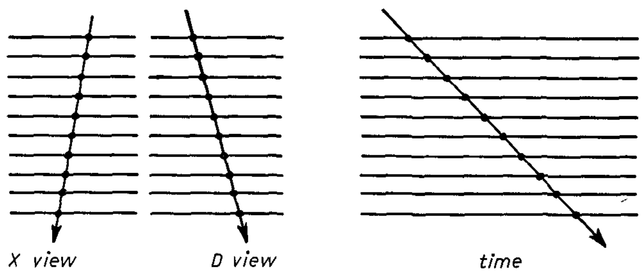

Fig. 5. – The concept of monopole detection in the streamer tube system is shown. A track in space is observed, with a linear distribution in time of the ten streamer tube hits (time track).

The concept of monopole identification for each of the three complementary methods are shown in fig. 4-6.

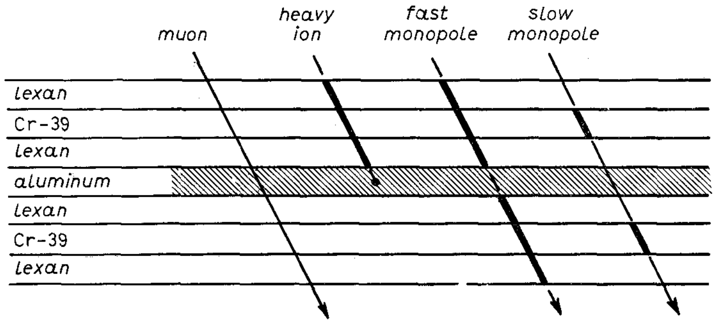

Fig. 6. – The concept of monopole detection in the track-etch detector.

The monopole velocity acceptance and the type of information involved for the various techniques are shown in fig. 7.

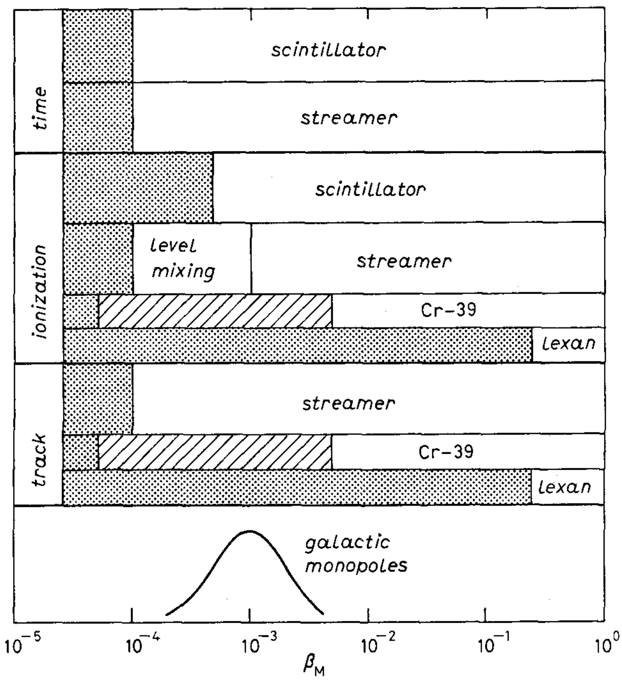

Fig. 7. – Summary of the response of the various detector elements for monopole detection.

4. – VHE neutrino and gamma astronomy.

The observation by surface detectors of intense emission from Cyg X3 of very-high-energy gammas (up to 10^{16} eV) has opened an exciting new field of investigation. Similar phenomena have been observed as originating from Vela X1 and LMC X4 (fig. 8). Due to the high energies involved, both at production at the extraterrestrial source and at the final terrestrial interaction, this new phenomenology can be of relevance not only for astrophysics, but also for particle physics.

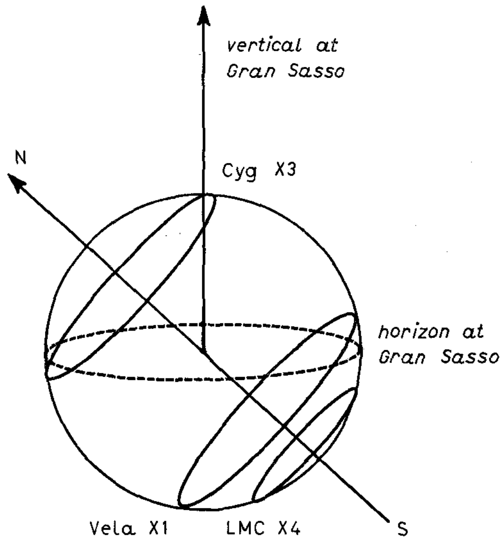

Fig. 8. – Exposure at the Gran Sasso latitude to Cyg X3, Vela X1 and LMC X4.

These objects are Binary X systems, consisting of a pulsar revolving around a large companion star. In fact the characteristic feature of the observed high-energy emission is its time modulation with the binary revolution period, as measured in the X-ray observations. The duty factors are small, around 1 %. Also of relevance is the relatively smooth differential flux shape ($\approx E^{-2}$).

The high energies observed suggest that the primary accelerated particles are protons. In a simple model these are accelerated and emitted isotropically out of the pulsar. The gammas arriving at earth are originated from π^0 decays produced by protons interacting in the star «atmosphere». This mechanism can occur only when the pulsar comes out of or enters the eclipse, and naturally explains the small duty factor of the emission.

The MACRO detector has a good acceptance to observe photons from Cyg X3 (fig. 8), through the penetrating muons produced in the atmospheric gamma showers. From the gamma fluxes observed at high energy ($\geqslant 10^{-15}$ eV), assuming a differential power law E^{-2}, and a duty factor of 1 %, the detector sensitivity has been evaluated by Monte Carlo in two hypotheses. In the first case a conservative extrapolation has been considered for the photoproduction cross-section at high energy, leading to an expected signal of 20 events/year, over a background of 10 events/year, in an angular window of $\pm 0.5°$.

In the second case, according to the apparent experimental observation, the muon content of the gamma showers has been assumed equal to that of hadron showers. This would lead to the observation of 300 events/year.

The mechanism described above for gamma emission from these sources is expected to produce also neutrinos, from the decay chain of charged pions. Assuming two charged produced for each one neutral pion, one expects twice as many muon neutrinos and antineutrinos, with about one half the gamma energies. However, due to the much larger absorption length of neutrinos into matter, there can be several mechanisms which can give a neutrino flux at earth much larger then the observed photon fluxes. For instance LMC X4 is an extragalactic source which is 50 kpc far from the Earth, so that only due to the interaction with the microwave background the observed primary gamma spectrum is expected to be attenuated by a factor of ≈ 3. More in general, with the gamma emission mechanism depicted above, a large relative gain in the neutrino luminosity is expected to come from a much larger duty factor, which in the limit can be 50 %, with neutrinos coming out of the system during the whole pulsar eclipse.

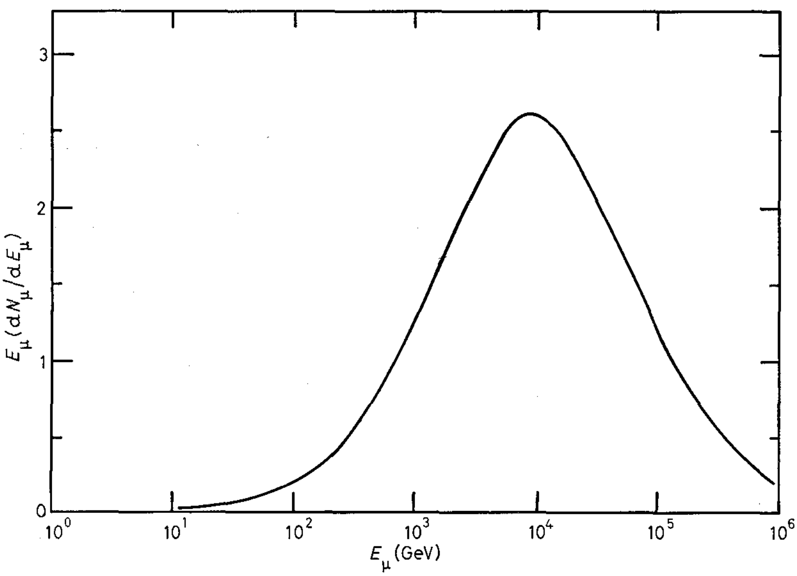

Fig. 9. – Expected energy spectrum at the detector, for muons produced by neutrino interactions in the surrounding rock. A differential flux shape E^{-2} has been assumed for neutrinos.

The MACRO detector has a good sensitivity for the observation of Vela X1 and LMC X4 through the upward-going muons produced by the neutrino interactions in the rock (fig. 8). Neutrino fluxes have been considered, resulting from the observed gamma luminosities, and then assuming a duty factor gain of 20, an attenuation gain of 3 for LMC X4, and an E^{-2} differential power law. The detectable muon flux has been calculated considering neutrino and antineutrino inelastic interactions in the rock, and muon propagation in the rock, including the e.m. losses for the high-energy muons.

In this way MACRO is expected to detect ≈ 6 events/year from Vela X1 and ≈ 20 events/year from LMC X4.

It is worthwhile noticing the hard muon spectrum expected at the detector (fig. 9), which in turn implies a very narrow angular distribution ($\Delta\theta \approx 0.5°$) of the observed muons with respect to the incoming neutrinos (fig. 10). This allows for a narrow angular selection of events ($\pm 1°$), which makes negligible the atmospheric neutrino background (≈ 0.1 events/year for a given direction).

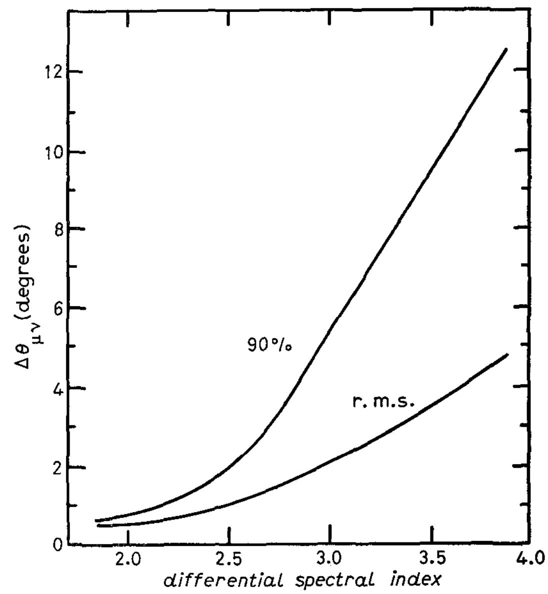

Fig. 10. – Expected angular deviation of the detected muons with respect to the incoming neutrinos, as a function of the differential spectral index of the neutrino flux. Both the kinematics of the interaction and the multiple scattering of muons in the rock are included.

Atmospheric neutrinos on their own will allow to perform a muon neutrino disappearance experiment, based on the measurement of the modulation of the angle distribution of upward-going muon neutrinos (see the paper by GRILLO and VALENTE at this same conference).

5. – Multimuon physics.

The detector, designed to search for the rare phenomena discussed before, turns out to be a powerful instrument for the study of the standard cosmic-ray muons. It will detect $\approx 2 \cdot 10^7$ single muons and $\approx 6 \cdot 10^5$ multimuons per year.

This large amount of data will allow to address, with significant contributions, some classical themes of cosmic-ray physics, such as the primary energy spectrum and chemical composition at high energy $((10^{13} \div 10^{17})$ eV).

The large detector dimensions with respect to the typical multimuon event size, will allow us to measure unbiased multiplicity distributions and also to study their transverse structure. These events can give hints of new phenomena arising in hadron collisions at very high energies, such as anomalously large transverse momenta (far away muons), or the production of new stable heavies (delayed muons).

6. – Conclusion.

The MACRO detector to be installed at the Gran Sasso Laboratory is a multipurpose device optimized for monopoles, astrophysics and cosmic-ray investigations. The quality and redundancy of information make it in general sensitive to search for rare exotic phenomena in the penetrating cosmic radiation. The device is modular in construction with a proposed schedule of having the first module (about 12 % of the total detector) operational in 1986 and the full detector completed in 1988.

● RIASSUNTO

MACRO è un apparato a grande area, che installare nella sala B del laboratorio dei Gran Sasso. Basato sull'uso di contatori a scintillazione, tubi a streamer e rivelatorl a track-etch, esso è progettato per la ricerca di monopoli magnetici superpesanti oltre il limite di Parker, di sorgenti cosmiche di neutrini e gamma d'alta energia e, piú in generale, di fenomeni esotici nella radiazione cosmica.

Резюме. — MACRO представляет собой детектор с большой площадью, который будет установлен в подземной выработке В лаборатории Гран Сассо. Конструкция детектора, в котором используются сцинтилляционные, стримерные и трековые счетчики, разработана с целью поиска сверхтяжелых магнитных монополей в области ниже Паркеровского предела, космических источников гамма-квантов и нейтрино высоких энергий, и в целом — экзотических явлений в космическом излучении.