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# THE MACRO DETECTOR AT THE GRAN SASSO LABORATORY

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The MACRO detector is presently under construction, its installation at Gran Sasso being planned to start in September 1987. It is a large area detector, the acceptance for isotropic particle fluxes being around 10000 $m^2$ sr, designed to search for rare phenomena in the cosmic radiation. It makes use of three detection techniques: liquid scintillator counters, plastic streamer tubes, and track-etch. It will perform a search for GUT monopoles (or any supermassive charged penetrating particle), a survey of cosmic point sources of HE gammas and neutrinos, a systematic study of the penetrating cosmic ray muons, and will be sensitive to neutrino bursts from gravitational stellar collapses in the Galaxy.

## 1. Introduction

The MACRO detector will be installed at hall B of the Gran Sasso Laboratory, starting in September 1987, at the depth of 3600 mwe (meter water equivalent).

The general purpose of the experiment (monopoles, astrophysics, and cosmic ray observatory) is to search for rare constituents or phenomena in the cosmic radiation penetrating deep underground. The detector is designed to have a large acceptance for isotropic particle fluxes (above 10000 $m^2$ sr) and to measure particle trajectory, velocity, and ionization.

Its distinctive design features aim at a sensitive search for GUT monopoles, well beyond the astrophysical bounds. That sensitivity extends to any other charged supermassive penetrating particle.

The muon tracking capability of the detector includes angle accuracy optimized for the survey of very high energy gammas and neutrinos coming from Cyg X3 or similar objects in the sky, respectively above or below the horizon at Gran Sasso. The detector will be sensitive to neutrino bursts from supernovas in the Galaxy. It will perform a systematic study of the penetrating cosmic ray muons and multimuons.

## 2. The detector

The MACRO detector is designed as a modular array of liquid scintillation counters, plastic streamer tubes, and track-etch detectors, which fill a box-shaped volume with $12 \times 78$ $m^2$ base and 9 m height.

As shown in fig. 1, most of the detector volume consists of a horizontal sandwich of three scintillation counter layers, 18 streamer tube layers, and one track-etch multilayer. Passive absorbers (iron and $CaCO_3$) are in between the sensitive layers, to identify penetrating particles, setting a threshold for through-muons at 1 GeV. The four vertical sides of the detector are closed by one layer of scintillation counters and five layers of streamer tubes. Fig. 2 shows a general view of one of the 12 MACRO "supermodules", with dimensions $12 \times 12 \times 4.5$ $m^3$. An enlarged detail of the detector array is shown in fig. 3.

The liquid scintillation counters (see fig. 4) are 75 cm wide, 26 cm thick, and 12 m long. A PVC box, lined with FEP teflon, contains the liquid: pseudocumene dissolved in low-paraffin mineral oil. At each end light is viewed by a couple of 20 cm PMTs, immersed in nonscintillating mineral oil, to get rid of the relatively large light pulses due to very near soft electrons produced by radioactivity gammas. The total number of counters is 484, the total mass of liquid is around 1 kton. Their main features, as measured on full scale prototypes, are: light attenuation length above 7 m (see fig. 5); trigger energy threshold 5 MeV (10% of muon

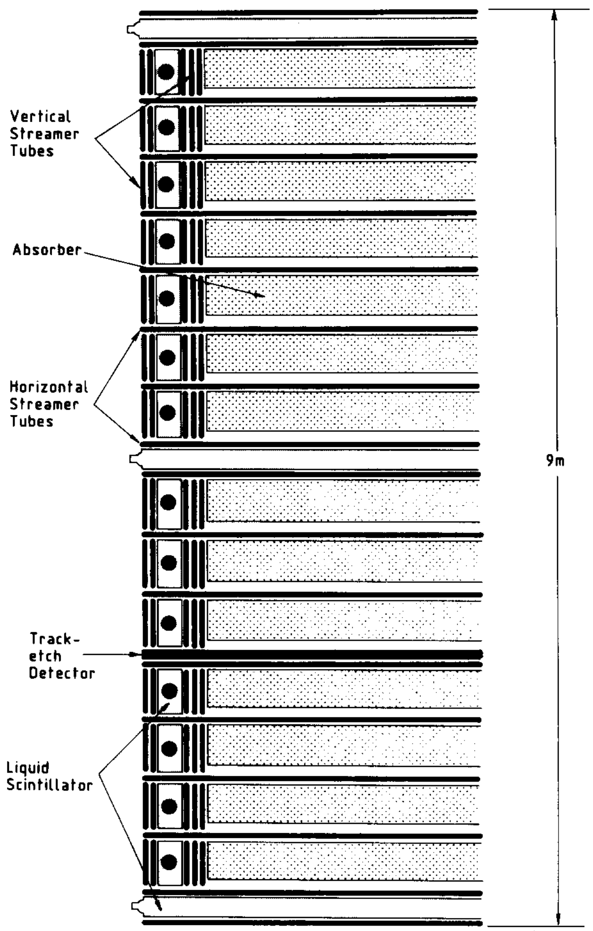


Fig. 1. Detector cross section.

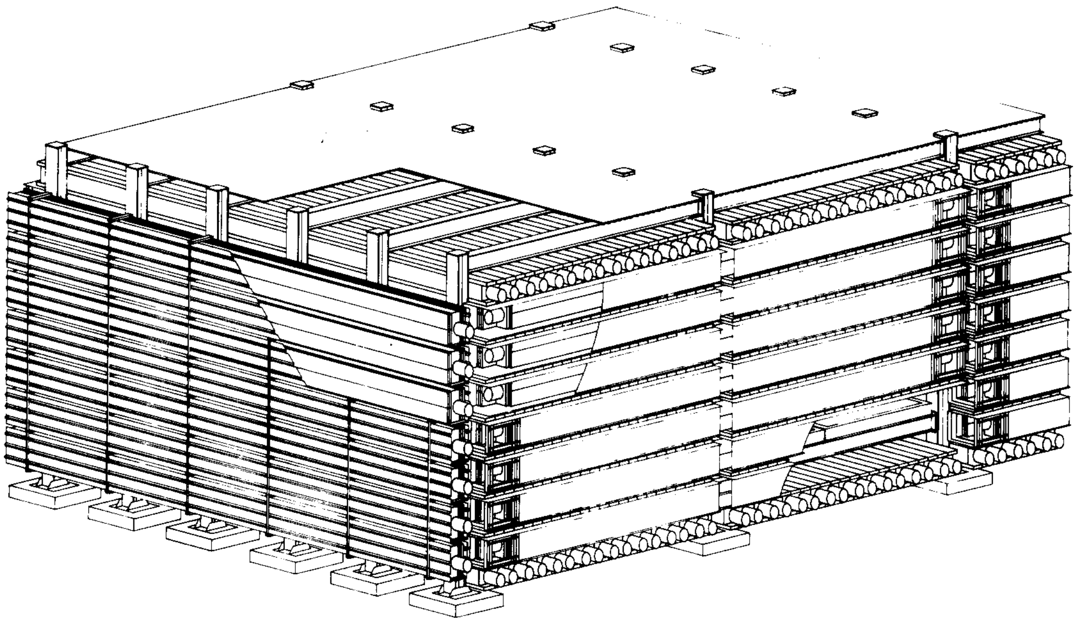

Fig. 2. General view of one of the 12 MACRO supermodules ($12 \times 12 \times 5$ m$^3$).

loss); and time accuracy 1 ns (necessary for the upward-going muon selection).

The streamer tube layers consist of 8-tube PVC chambers, with dimensions $25 \times 3$ cm$^2 \times 12$ m. The individual cell cross section is $3 \times 3$ cm$^2$, with 100 $\mu$m anode wire and graphite cathode (see fig. 6). Two-dimensional localization is performed by 3 cm wide pickup strips at an angle of 30°. The gas is a mixture of He, $CO_2$, and n-pentane. Space accuracy is about 1 cm, time accuracy for a through-track is 50 ns, while the ionization threshold is below 1% min. ion.

The track-etch layer is a sandwich of Lexan and CR39 plastic sheets, with an aluminum absorber in between (fig. 9).

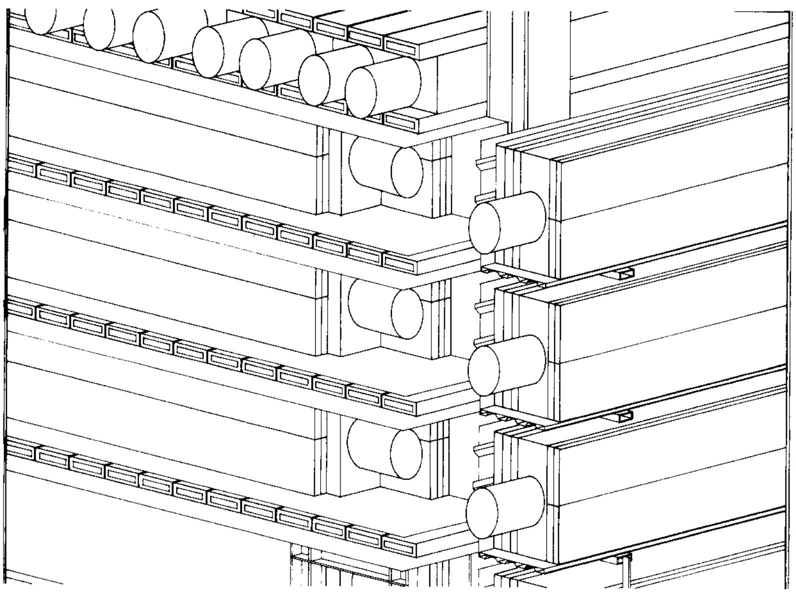

Fig. 3. An enlarged detail of the scintillation counter and streamer tube array.

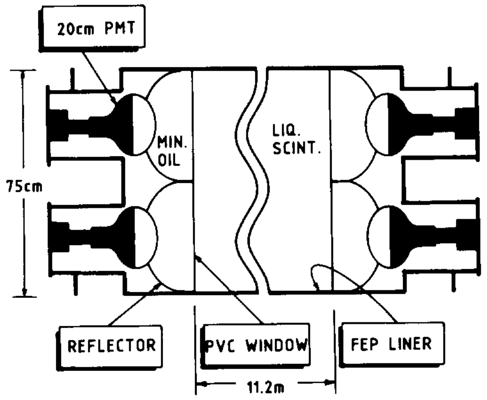


Fig. 4. A schematic drawing showing the scintillation counter design.

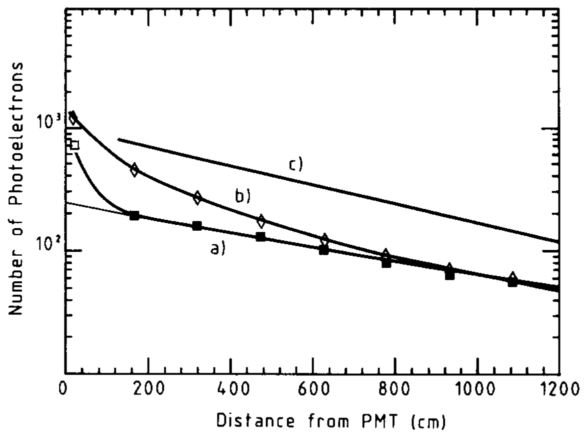


Fig. 5. Scintillation counter response. (a) and (b): single PMT response on full scale prototype with different light collection arrangements; (c): inferred response for the final counter design.

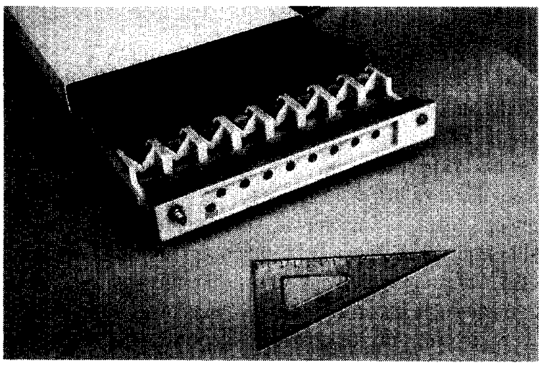

Fig. 6. Streamer tube chamber shown open at one end.

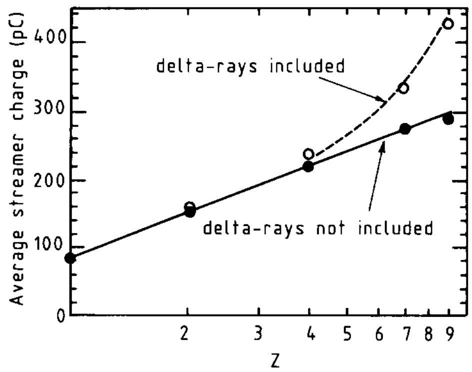


Fig. 7. Streamer charge response as a function of $Z$ of relativistic ions. The response obtained by cutting delta ray contribution allows to infer the response to slow ionizing particles.

## 3. Detection of supermassive particles

The search for supermassive GUT monopoles (as well as any other charged slow penetrating particle) will be performed independently by the three detection techniques, in order to exploit different excitation–ionization mechanisms of energy loss.

A crucial detector parameter is the monopole velocity threshold, above which it is detectable. The scintillation counters have a conservative velocity threshold around $6 \times 10^{-4}c$ [1]. The recent measurement of scintillation light emission by protons with velocity as low as $3 \times 10^{-4}c$ [2], sets there the threshold for monopoles carrying an electric charge, intrinsic or due to attached protons. The velocity threshold for the streamer tubes, for the conventional ionization mechanism, is at $10^{-3}c$, due to the n-pentane fraction of the gas mixture. The helium fraction, through excitation by the Drell mechanism [3] and consequent ionization by the Penning effect, lowers the threshold down to $10^{-4}c$, for bare monopoles and negative dyons. In the track-etch detector the CR39 covers the widest velocity range, with the threshold at $2 \times 10^{-5}c$, except for bare monopoles which are expected to go below the detection threshold around $10^{-3}c$ [4].

In the scintillators a slow particle is univocally identified by the long light pulse emitted at the passage through the thick counter. That is recorded on waveform digitizers, with a time granularity to 1% of the total pulse duration. In the streamer tubes a slow particle appears as a track in space of uniformly delayed hits. Streamer pulse height is also recorded, since tests on relativistic ion beams [5] have shown they can measure large ionization losses (fig. 7), which are expected to occur for monopole velocity above the threshold. The overall streamer charge response to ionization losses is summarized in fig. 8: it is substantially flat from the threshold (1% min. ion.) through the minimum ioniza-

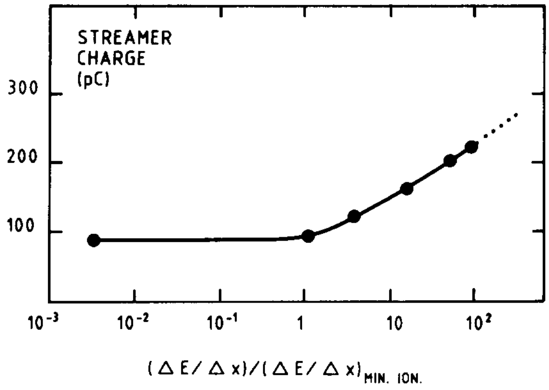


Fig. 8. Streamer charge response as a function of ionization loss in the $3 \times 3$ cm$^2$ tube. The experimental points have been obtained with (from the left) single photoelectrons, muons, relativistic ions.

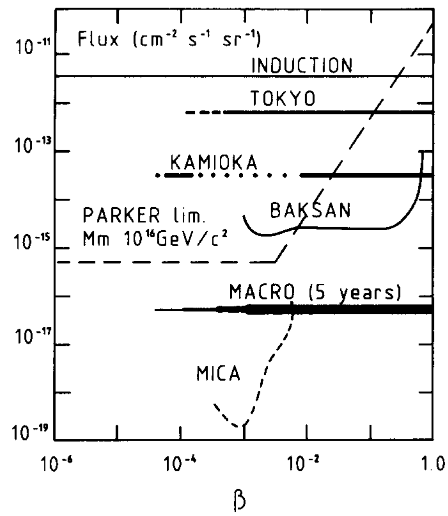


Fig. 10. MACRO 90% c.l. limit on monopole flux after 5 years of operation. The different thickness of the line is to indicate the redundancy of information from the different detectors. The most significant existing results are also shown. The mica track-etch experiment is very sensitive, but relies on a number of restrictive assumptions.

tion loss, and is logarithmic above it. This characteristic response suits in an optimal way the extremely wide energy loss range that a slow monopole can cover, from the very low level of the Drell mechanism near threshold, to the very large one of the conventional ionization process. The track-etch detector is thought to be used in a "triggered" mode, that is removing, etching, and looking for a track in the module crossed by a candidate track in the active detectors. Its monopole identification concept is shown in fig. 9.

The detector expected performance in the search for monopoles is shown in fig. 10, together with the most significant existing results as obtained with the various detection techniques. With an acceptance for isotropic particle fluxes of 10 000 m$^2$ sr, in a few years of operation MACRO will push the search well beyond the Parker bound (for monopole mass around $10^{16}$ GeV/$c^2$) covering the velocity range where monopoles are effectively expected to exist. More in general MACRO will search for any charged supermassive penetrating constituent of dark matter, with a sensitivity, at the same mass scale, of a few percent of the critical density of the universe.

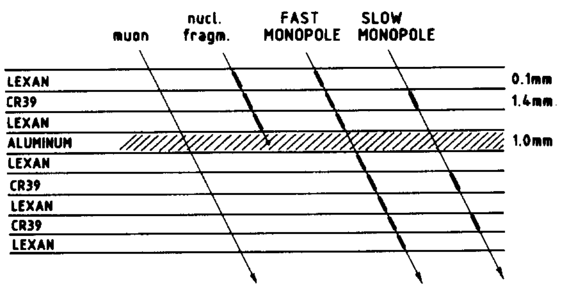


Fig. 9. The track-etch detector sandwich, with a schematic description of its response to different particles.

## 4. Astrophysical observation

Since the observation of multi-TeV gammas from Cyg X3 and other point sources, muon tracking underground is a new tool for viewing the sky.

For sources above the horizon at Gran Sasso, like Cygnus, MACRO will track the penetrating muons produced in the atmospheric showers. In that it will be complementary to surface arrays. Assuming the apparently high muon content of the Cygnus gamma showers, about 300 muons per year would be detected in Cyg X3 direction. That rate would be one order of magnitude above the background muon rate, assuming a duty factor of 1% in the time modulated signal, and exploiting the fine detector angle accuracy of 0.2°, which allows to narrow the observation window down to the limit set by the multiple scattering in the rock ($\Delta\theta = 0.6°$).

The basic idea about the operation of Cygnus-like particle accelerators is as follows. The emitting object consists of a neutron star revolving around a large ordinary companion star. Free protons around the collapsed star are accelerated in its intense e.m. field and interact with the matter around the companion star, producing pions. The decay gammas (and also neutrinos in this scheme) which emerge from the system, propagate undisturbed through space (but for gamma interaction with the microwave background, for very long propagation distances). Now the narrow range of material thickness necessary for both $\pi^0$ production and gamma transmission, can only occur for particle trajectories starting at the neutron star and grazing the large companion. Therefore gammas are emitted along a conical surface (with apex at the neutron star and tangential to the companion) rotating in space and so producing the characteristic time modulated signal at earth.

The intense HE neutrino emission implied in the hypothesis of intermediary pions would be also enhanced by the easy transmission through the matter of the large companion star. Neutrino sources below the horizont at Gran Sasso, can be visible looking for directional signals in the upward-going muon flux through the detector. Those muons are produced by neutrino interactions in the rock below the detector. The hard neutrino spectrum (a differential spectral index of 2 is inferred from the observed gamma spectrum), the increase with energy of the neutrino interaction cross section, and the high muon penetration through the rock, result into a very large effective fiducial mass of the detection system. A Monte Carlo calculation has given a muon energy at the MACRO detector in the TeV range and, most important, an angular spread with respect to the incoming neutrino direction such that 90% of the muons would be contained in a cone of 1° aperture. Looking at a candidate source in the sky, like LMC X4 or Vela X1, within that angular window, implies a negligible background (0.1 events/yr) due to atmospheric neutrinos, to be compared with an estimated signal from those sources of several events per year.

## 5. Supernova neutrinos

The large mass of liquid scintillator, about 1 kton, makes the detector sensitive to neutrino bursts from gravitational stellar collapse in the Galaxy.

MACRO will be able to detect the anti-$\nu_e$ component of the neutrino flux, produced at the cooling stage of the collapse and lasting several seconds, through charged current interactions with the protons in the organic liquid.

The average energy of the secondary positrons is expected to be above 10 MeV. Background measurements with full scale prototypes at Gran Sasso, equipped with specially designed fast energy-reconstructing triggers, show that it will be possible to operate the detector with 5 and 10 MeV thresholds, respectively at the trigger and final event selection level.

## 6. Cosmic rays

MACRO with its large acceptance and tracking capability will also allow an accurate and systematic study of the penetrating component of the cosmic ray muons.

The large detector acceptance first of all implies large statistics ($10^7$ events/yr). But most important it implies large "acceptance" for the high multiplicity events, in the sense of their containment, since the minimum detector dimension is more than twice the multimuon average size. That will make possible to perform an accurate measurement of the multiplicity distributions and a detailed study of the transverse structure of the muon bundles.

Various subjects will be covered in the field of cosmic ray physics (the composition of the primary spectrum, anisotropies, etc.) and also of particle physics (anomalously high $p_t$'s, "delayed" tracks, etc.).

## 7. Outlook

The detector parts are under construction. Installation of the first supermodule at hall B of the laboratory will start by september 1987. After some time dedicated to assessing backgrounds and fixing triggers, installation will continue, with the objective of having the full detector operational by 1989.

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