Chapter 2

The MACRO Detector

2.1 Overview

The Monopole, Astrophysics, and Cosmic Ray Observatory experiment (MACRO) is a large underground detector primarily designed to look for magnetic monopoles. However, it also is very efficient at detecting muons and neutrinos. This dissertation treats MACRO as a muon telescope. MACRO has collected data since

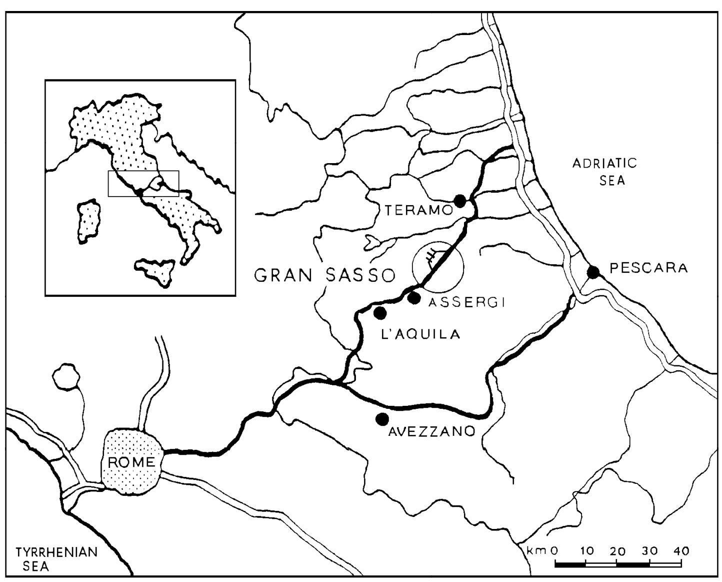

Figure 1: The location of the MACRO Experiment

February 1989, and is located at the Laboratori Nazionali del Gran Sasso (LNGS), near the city of L'Aquila in central Italy. This lab is managed by the Istituto Nazionali di Fisica Nucleare (INFN).

2.2 The Experimental Site

The experiment is in the underground section of the laboratory, underneath Corno Grande, the highest peak in the Appennine mountain range. These underground halls (Figure 2) are in a series of side tunnels near the middle of the 11 km long tunnel of the A24 Autostrada as it cuts through the mountains. MACRO occupies

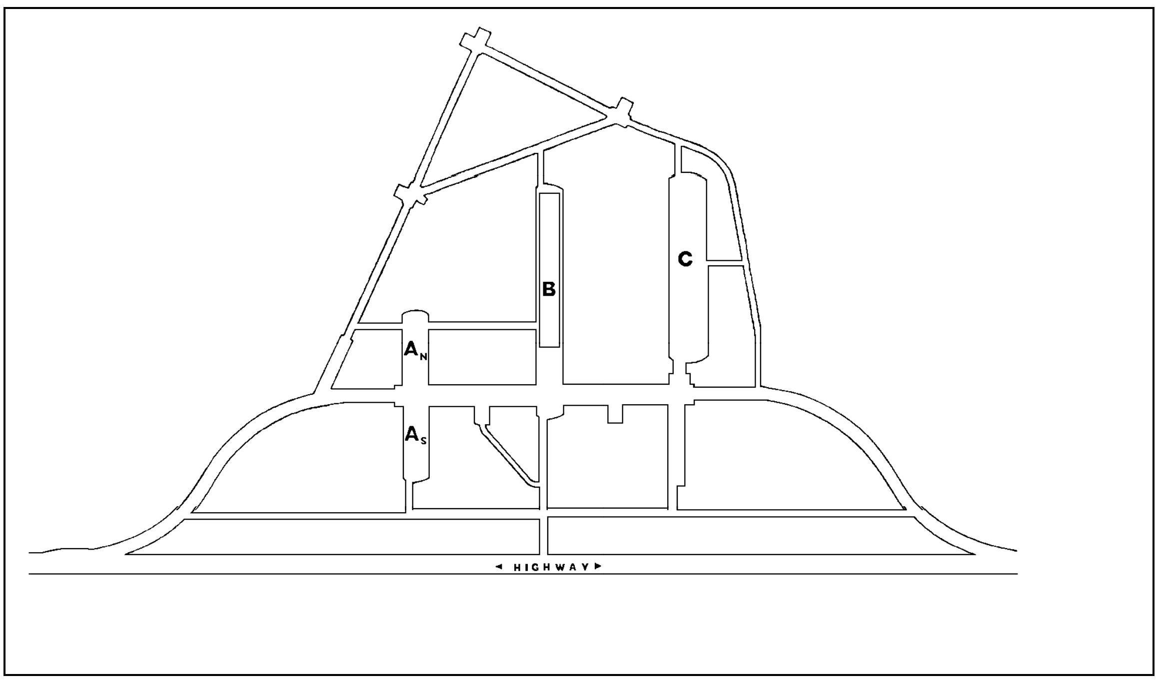

Figure 2: The underground laboratory at the Gran Sasso Lab.

most of Hall B in the underground lab. Hall A houses the LVD and Gallex experiments; Hall C houses the Borexino and Icarus experiments. In smaller connecting tunnels are smaller experiments also needing a low background environment, such as double β decay experiments. A laser interferometer used in a geological experiment is housed in a triangular set of small tunnels behind the main halls.

MACRO was placed deep underground to minimize processes that would produce background events for the monopole search. Primarily, this background comes from the penetrating muon component of the showers produced by primary cosmic rays impacting the Earth's atmosphere. The minimum depth of the rock overburden above Hall B is 1.1 km; the average depth is 1.4 km. Given the density of Gran Sasso rock of 2.7 g/cm^3 with a $\langle Z^2/A \rangle$ of 5.7, this corresponds to a minimum depth equivalent to 3100 meters of water and an average of 3800 mwe[1]. Since the range of a muon in rock is proportional to the muon's energy, this rock overburden eliminates lower energy muons; greater depths of rock stop higher energy muons. For the minimum depth above MACRO, the energy threshold for muons to pass through that much rock is 1.2 TeV[1], as discussed in Chapter 5. Since the spectrum of cosmic ray induced muons falls exponentially, the flux of muons at MACRO's depth is 10^6 times less than it is at the surface. Also contributing to the low background is the low radioactivity of the rock itself.

2.3 A Description of MACRO

The MACRO detector is 77 m long, 12 m wide and 9 m high. The active components of the detector are layers of Iarocci tubes operating in limited streamer mode and layers of liquid scintillator observed by photomultiplier tubes. In general, the streamer tubes provide tracking for particles that cross the detector, while the

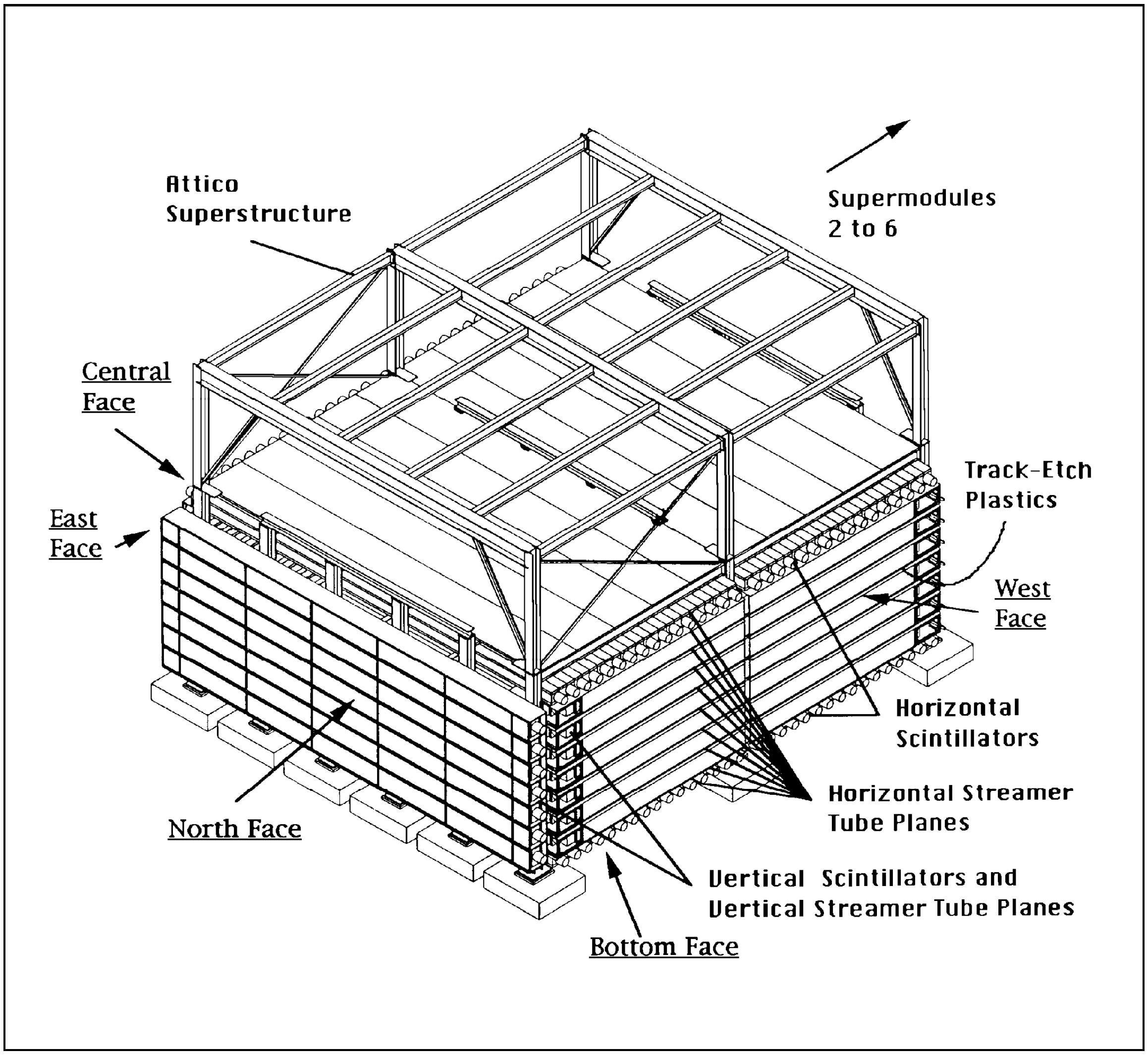

Figure 3: The first Supermodule of MACRO. Note the two modules of streamer tubes. The attico superstructure is also now laden with scintillator and streamer tube planes.

scintillator provides the timing information. There are also layers of CR39 plastic, for use in a track-etch based monopole search, and layers of crushed Gran Sasso rock, which act as absorber for low energy secondary particles.

MACRO is built in a modular fashion. A “module”, the organizational unit of the lower half of the streamer tube system, is 6 m x 12 m x 4.5 m. Two of these make up a “supermodule". A supermodule is the unit of organization for both the scintillator system and the attico (hollow upper half) streamer tubes. The final

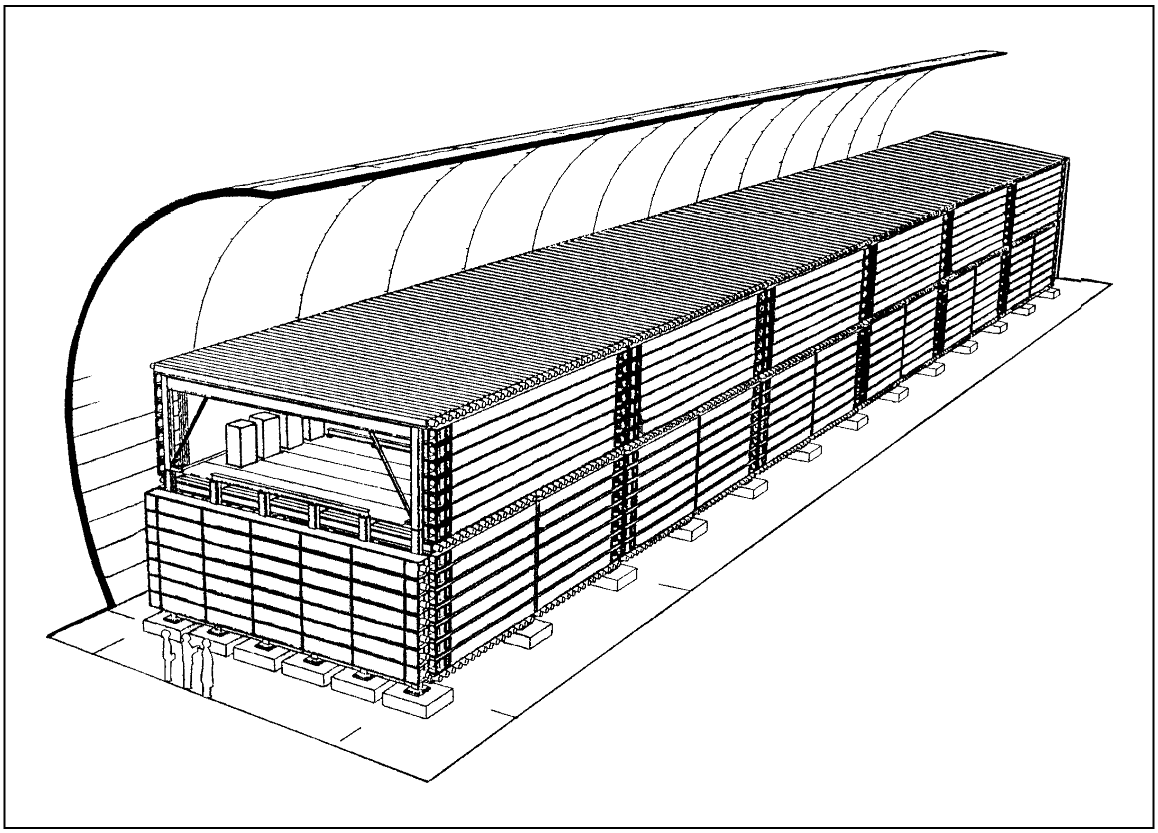

Figure 4: The complete MACRO, with all six supermodules, and the attico.

organizational unit is the “microVAX” (μVAX). This is a unit of two supermodules.

It takes its name from the fact that the data acquisition μVAXen each control two supermodules. Therefore note the 12 modules divided into six supermodules are controlled by three μVAXen. Because of this modular nature, the experiment took data with the supermodules first built, while construction of the later supermodules was still underway. The first supermodule went online February 29, 1989. Supermodules were added to the acquisition until June 1992, when the lower half of all six supermodules of streamer tubes was completed. The lower half of the scintillator system was completely turned on by December 1992. The “attico” is the hollow upper half of the detector, built after the lower half of MACRO was already in operation. The attico was turned on starting in mid 1994; the total detector was completed in early 1995.

2.4 The Streamer Tube System

The Iarocci (streamer) tubes are the most relevant subsystem for this dissertation because they provide the tracking ability to point the observed muons back onto the sky. A streamer tube is a long narrow chamber with grounded walls and a central anode wire running down the length of the tube. The space between the anode and the walls is filled with a 73% He and 27% n-pentane gas. The anode is held at a high voltage (around 4000 V). An ionizing particle which passes through the tube will ionize the gas along its path. This initiates a stream of electrons from the anode to the grounded walls of the chamber, producing an electrical signal. MACRO’s tubes operate in the “limited streamer” mode. This is the voltage regime below “Geiger” mode and above “proportional mode”. In Geiger mode, the voltage is high enough to cause an ionizing spark to jump from the anode to the walls, often inducing secondary discharges. Using lower voltages and including n-pentane in the gas mix to quench secondary streamers allows the free electrons created by the ionizing particle to reach the walls of the chamber without creating additional discharges. Operating in this mode has the advantage that the stream of electrons produced in the chamber is proportional to the ionization caused by the particle itself. At still lower voltages, in proportional mode, the charge discrimination is finer, but the signals are so small that many expensive pre-amplifiers would have been required.

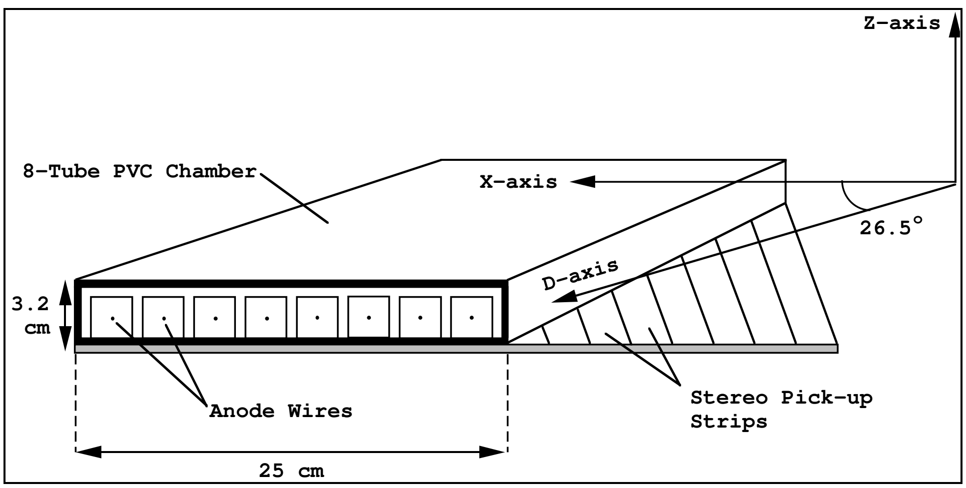

Figure 5: Schematic of a MACRO Streamer Tube Chamber.

An individual streamer tube chamber is 3.2 cm x 25 cm x 12 m in size. This chamber contains eight individual cells. Each cell has an anode wire and grounded walls. A layer of streamer tubes in a module consists of 24 of these chambers. Sandwiching each layer of tubes are aluminum strips, placed at a 26.5° angle to the anode wires. These induction strips pick up the streamer discharge and produce a signal. Because of this stereo angle, the position of a particle hit along the wire can be reconstructed within 4.5 cm, and to 9 cm along the strips[2].

In the lower part of the detector, there are ten horizontal planes of streamer tubes. Scintillator lies between the first and second, and ninth and tenth planes. Between the other planes are layers of crushed Gran Sasso rock. There is 32 cm of absorber in each layer, equivalent to a column depth of 60 g/cm^2 per strata.

The horizontal streamer tubes in the attico are 4.2 m above the tenth (and top) plane of the lower section. The space between the top streamer tube plane of the lower section is open; it is used for the readout, triggering, and data acquisition electronics. Consisting of three layers with no intervening material, the attico horizontal tubes have an additional three layers on top of a third plane of liquid scintillator.

MACRO also has vertical planes of streamer tubes consisting of three layers of streamer tubes on each side of a layer of scintillator. The streamer tubes in these planes are known as "lateral" tubes. Each layer of lateral tubes consists of 14 chambers, rather than the 24 chambers of the larger horizontal layers. The lateral tubes on the lower half of the detector lack stereo strips. This omission hampers the use of the lower lateral layers in track reconstruction. To correct this, the attico laterals do have stereo strips.

Finally, there are the north and south faces of the lower detector. They are identical to the vertical east and west lower faces. In order to allow access to the electronics inside the hollow shell of the attico, no north and south face attico walls were added.

2.5 The Scintillator System

The liquid scintillator is the other major active detector in MACRO. When a charged particle passes through the scintillator, the outer electrons of the scintillating chemicals are excited to a higher state. These electrons cascade to the ground state, emitting near ultraviolet photons in the process. The resulting photons are absorbed by waveshifting chemicals and re-emitted at a longer wavelength, which is readily observed by photomultiplier tubes (PMTs or phototubes). This produces a signal proportional to the amount of light released, which is in turn proportional to the amount of energy lost by the charged particle on its trip through the scintillation counter.

2.5.1 Scintillant

The scintillant itself is pseudocumene (1,2,4-trimethylbenzene). The carrier for this chemical is mineral oil of very high clarity (greater than 12 m attenuation length at 425 nm). Because pseudocumene is opaque to the light produced in the scintillation process, a balance had to be struck between too much pseudocumene blocking its own light and enough being present to produce a strong signal. For MACRO, the mixture is 96.4% mineral oil and 3.6% pseudocumene (except for the first supermodule, which has 6% pseudocumene). Included in this mix are small amounts (1.44g/l each) of waveshifting chemicals (PPO, 2,5-diphenyl-oxazole, and bis-MSB, p-bis[omethylstyryl]benzene), and a bit of vitamin E, which acts as an anti-oxidant. These waveshifters first convert the peak wavelength of the scintillation light from the 290 nm produced by the pseudocumene to 380 nm via absorption and re-emission in the PPO, and finally to 420 nm via the bis-MSB[3]. This is a wavelength to which both the scintillant mixture itself and the windows in the tank end are transparent. It also produces a greater response in the phototubes[4].

2.5.2 The Scintillator Counters

This mixture is kept in counters made of sheet PVC welded into long boxes. The interior of these boxes is lined with white vinyl-FEP. When filled with mineral oil (with an index of refraction of 1.48), the FEP lining (n = 1.33) allows the box to become totally internally reflective to rays of light traversing the box lengthwise. At the box ends are mirrors to focus the light onto the photomultiplier tubes which convert the scintillation light into electrical signals.

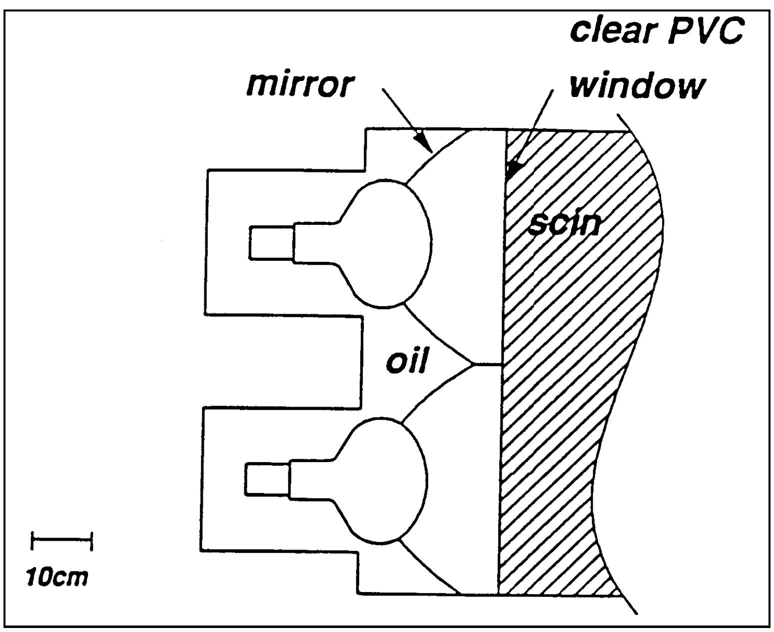

Figure 6: One end of a Horizontal Scintillator Box.

There are two different types of scintillation counters in MACRO. 75% of the ~600 metric tons of active mass is held in horizontal tanks. These counters take their name from the fact that they are laid side by side, forming horizontal planes of scintillator. These boxes are 11.86 m long, 75 cm wide, and 26 cm deep. Two PMTs are positioned at either end of the box, along the long axis of the box. The signals from the two PMTs at a tank end are ganged together.

The other style of counter is a vertical tank. These are the boxes stacked on top of each other to form the east and west vertical walls of the detector, and the north and south endcaps. They are 11.58 m long, 23 cm wide, and 49 cm deep. There is only one phototube at each end of a vertical tank.

2.5.3 **Photomultiplier Tubes**

The photomultiplier tubes are primarily 8" EMI model D642 tubes, although the attico vertical tubes (and all tubes used in the first run of the first supermodule) use older 8" Hamamatsu R1408 tubes. These tubes operate at near 1500 V, producing a nominal gain of 10^7. The gains are set so the single photoelectron peak of the PMT signal is four mV in amplitude. This gain was chosen so a slow monopole travelling through the scintillator produces a recognizable PMT signal from the train of single photoelectrons such a particle creates[5].

2.5.4 **Calibrations**

This system is calibrated in several ways. First, fiber optic cables are installed in each counter to deliver near ultraviolet (337 nm) nitrogen laser light pulses to the centers of the tanks. This light produces a similar path of excitation to that of a charged particle, which then gives a scintillation signal proportional to the intensity of the light. These pulses are used to map the low intensity end of the equipment (specifically the pedestals of the analog to digital converters (ADCs) which digitize the PMT signals) and to measure the changes in pulse rise time that occur with intensity or “timewalk”. The timewalk numbers characterize the change in the timing of the pulses with changing pulse amplitude; the pedestals affect the zero points for the energy reconstruction.

Another special piece of hardware for calibrating the scintillator system is the LED (Light Emitting Diode) system. There are low power red LEDs installed near the ends of every box. These diodes can be pulsed with good time control. By varying the time delays on the LED pulses, the behavior of the Time Digital Converter (TDC) circuits can be mapped.

Finally, the steady stream of cosmic ray muons coming through the detector is also used to calibrate the system. A minimum ionizing particle, such as a muon, loses energy while passing through the scintillator in a Landau spectrum peaked at 1.4 MeV/cm traversed. Since the path of the muon is known from the tracks produced in the streamer tubes, the size of the ADC signal can be normalized by pathlength for any individual muon. These values for many muons traversing a given box are gathered together and plotted. Fitting this plot to a Landau distribution peaked at 1.4 MeV/cm gives an absolute gain for the scintillator/PMT/electronics combination for a given tank. These muons also produce timing information. A relativistic muon travels very near to the speed of light and the muon’s pathlength across the detector is known. Thus, given no instrumental effects, simple geometry reveals when the signals should have been recorded. Subtracting the muon's actual time of flight from that measured with the scintillator gives the delays involved due to wiring and electronics. These delays can then be removed from future timing measurements.

With careful calibration, the scintillator system gives energy measurements good to about an MeV, and timing measurements good to several hundred picoseconds. This timing allows MACRO to distinguish between fast moving particles such as muons and more slowly moving particles such as monopoles, nuclearites, and other exotic massive particles. It also provides positional information good to about 10 cm which easily tells the direction the particle is traveling along the track. This is important for muons, since muons coming from below the detector are due to neutrino induced interactions in the rock below MACRO. Studying such muons is a probe of the properties of neutrinos.

2.6 The Track-Etch System

The third detector subsystem in MACRO is the track etch system. This is a passive system composed of sheets of CR39 plastic covering the outside of the detector, with an additional layer between the fifth and sixth horizontal streamer tube planes. A monopole or other massive particle would disrupt the structure of the plastic along its path in a unique way as it passes through the sheet. If the active systems (the streamer tubes and scintillator systems) were to detect a monopole candidate, the section of plastic hit by the candidate track would be pulled for analysis. The plastic would be soaked in an acid bath to preferentially etch the plastic damaged by the monopole. As measured by an electron microscope, the hole's size compared to the spectrum of holes caused by less exotic radiation, would discriminate between an actual monopole and something mimicking a monopole, perhaps a tight bundle of muons.

2.7 The Data Acquisition System

All of the signals produced by the active components of the detector need to be read out, organized, and stored for later analysis. This job is done by two classes of electronics. The front-end electronics watch the signals continuously and make triggering decisions. If a trigger is formed by the front end, the Data Acquisition System (DAS) is signaled. The DAS reads out the relevant data from the front end electronics, timestamps the event with time from an atomic clock, and stores this information together as an event. That event is then saved to disk for future analysis.

2.7.1 Data Acquisition System Computers

The DAS is composed of several μVAXen. Running the VAXELN operating system and living in VME crates, these computers talk to the electronics via a combination of Camac branches and VME pathways. When a trigger is formed, the atomic clock time is latched, the relevant electronics are alerted, and the system waits for a short interval. This wait allows a slow particle to fully traverse the detector and allows all electronics time to ready their data for read out. Then the μVAX reads out the data as specified by which triggers fired over the Camac branch and VME backplanes. Any given trigger will read out several sets of electronics. Usually a real event will set off more than one trigger, so a great deal of information is read out and stored in any given event.

2.7.2 **Triggers**

There are three general classes of triggers. The first class is the fast particle triggers activated when near light speed particles cross the detector. These particles are nearly all cosmic ray-induced muons. The second class is the slow particle triggers which watch for evidence of large, slow particles crossing the detector. To date no monopoles have been observed. The events causing these triggers have all been shown to be background coincidences. The third trigger class is for Gravitational Collapse (GC) detection. These watch for bursts of low energy events in the scintillator. Such bursts would be generated in if a nearby (10-20 kpc) star underwent a gravitational collapse. An example of this kind of an event was produced in the IMB and Kamiokande proton decay experiments by Supernova 1987A. Since no nearby stars have been kind enough to explode since MACRO came online (in February 1989), these triggers are also generally caused by background coincidences.

Two trigger systems contributed most to this dissertation, both muon triggers. The first is a scintillator trigger, the Energy Reconstruction Processor or “ERP” trigger, developed by Indiana University’s Jim Musser. The second is a streamer tube trigger, developed by the INFN group at the University of Bari and named “the Bari Trigger”.

The ERP trigger looks at the PMT signals from individual scintillator tanks. If both ends of any given tank produce signals above a 100 mV (75 mV for verticals) threshold in a 200 ns coincidence window, a "minimum bias trigger" is formed. This internal trigger causes the flash Analog to Digital Converters (ADCs) in the front end of the ERP to digitize the charge. These ADC values are compared with a look-up table to make a trigger decision. Constructed from previous calibrations, these tables return a simple answer: "no trigger, GC level trigger, or muon level trigger". If there is a trigger, the phototube signal is fed to precision ADCs and TDCs farther downstream, and an event is started in the DAS.

Low level background noise causes continuous firing of the streamer tube system at a rate of 200 Hz/wire. The streamer tubes are only read out when a trigger occurs to avoid getting many events composed of this background. These triggers are designed to select real events. When an ERP channel is triggered by a muon level event, the DAS will read out the streamer tubes in the modules near to the scintillator box hit. Since this trigger requires only a single box hit, it can be triggered by events that pass through only a small portion of the detector. These are often events that have not hit enough streamer tube planes to produce a standard Bari trigger. As a result, when comparing data runs both with and without the ERP trigger, runs including the ERP catch ~10% more muons than runs using the Bari trigger alone.

The Bari trigger activates when some number of streamer tubes all fire within a short (300 ns) time window. This trigger is a simple logic trigger. Any of the following combinations of planes firing will produce a Bari trigger:

Six of 10 horizontal planes;

Five of eight contiguous horizontal planes;

Three of 10 horizontal planes AND three of six vertical planes (in a vertical face);

Three of six vertical planes in both vertical faces;

Five of six vertical planes in one face.

When at least one of the conditions listed above is met, a Bari trigger occurs; all of the involved modules of streamer tubes, plus their nearest neighbors, are read out.

Once the event is triggered, time stamped, and read out, the DAS stores it to disk for later analysis. For this dissertation, the first task of the analysis is to track the muon through the detector. The tracking algorithm is fundamentally simple, with numerous additional horrendous clauses that deal with the complicated job of making sense of events involving many tracks. However, 90% of all muon events are single tracks; most of the rest are double tracks. For this analysis, single and double tracks are the important ones, by sheer weight of numbers.

2.7.3 **Tracking**

The tracking algorithm finds the best fit line in two two dimensional views: that of the wires, and the strips. There needs to be a minimum of four hits to make a good track. The two dimensional pictures in the strip and wire views are then combined. By virtue of the stereo angle between the strips and wires, a three dimensional track is produced. Information about which part of the detector was hit, the space location of the track, and the time of the event are recorded in a summary file, which will be used for the analysis in later chapters.

2.8 My Contributions to MACRO

MACRO is a large, complicated experiment. Many people have worked hard for many years to design, build, and operate the experiment. The names on the author list are those of the scientists involved. There are also many technicians. As such, this dissertation is different from the standard astronomy theses in which a much smaller group of people are involved with the work, with the candidate doing most of the total sum of the work. Due to the sheer size of MACRO, each individual works on smaller parts, all contributing to the whole.

2.8.1 Analysis

Due to the remote location of the apparatus itself, there is a dichotomy in the work I have done. While at my home institution of Indiana University, the main area of my work on MACRO has been in data analysis. Our group has been analyzing the muon signal as seen by MACRO since the experiment began, with Stuart Mufson leading John Petrakis, Lynn Miller and me. This dissertation expands upon many of the topics this group has investigated, but other aspects of the underground muon signal have also been examined. Several examples of such research are the study of muon arrival times to search for correlations with gamma ray bursts; looking at the muon intensity distribution for signs of "prompt" muons coming from charmed particle decays; looking for evidence of point sources of high energy neutrinos coming up from below MACRO.

2.8.2 **Hardware**

The other side of the work done is with the experimental hardware. While on site at the Gran Sasso, one must deal with an endless stream of construction and maintenance tasks. My work on the experiment itself began in the summer of 1990, after the lower half of the detector had been physically constructed. The American part of the collaboration's area of responsibility is the scintillator system, so that is where my hardware work has been directed.

Starting with a month's trip in October 1991, and continuing with a long stay from May 1992 until July 1993, I was involved with the installation and testing of the lower six supermodules worth of scintillator electronics. This came on line in December 1992 for a run of six months duration. During this run much work was done on monitoring and calibrating the detector, as well as maintaining the system. In addition to the general scintillator tank end maintenance and data acquisition system babysitting, I focused on the ERP system. With Ed Diehl (then at the University of Michigan), Jim Musser (father of the ERP, at Indiana University), and Alice Hawthorne (also at Indiana), the software used to calibrate the ERP trigger was refined and then used in general production of the calibration constants used by the whole collaboration. I also worked with Gary Ludlam and Alex Marin (from Boston University) on installing and maintaining the calibration hardware.

In the summer of 1993, I worked with Dan Levin (Michigan) on the Grand Sasso Air Čerenkov Experiment (GRAČE)[6]. This experiment was a prototype air Čerenkov array that detected air showers from the surface of the Gran Sasso. Its purpose was to establish the feasibility of such an array for the detection of coincident events with an underground detector such as MACRO. It succeeded in this goal[7]. Air Čerenkov experiments have a lower energy threshold than traditional air shower experiments such as EASTOP[8], thus providing another energy window on cosmic ray physics. I was heavily involved in the installation and operation of GRAČE.

With Kate Scholberg (CalTech) and Rich Baker (Michigan), I worked on the ERP gravitational collapse trigger. The initial version of the online supernova alarm monitor was written by me in Indiana in late 1992.

While the lower half of the detector was on its shakedown cruise in early 1992, construction on the upper half ("the attico") was underway. I was one of several students and technicians who completed the installation of the attico scintillators.

2.9 The MACRO Collaboration

MACRO is a collaboration of high energy physicists and astronomers from institutions in both the United States and Italy. This is the current list of authors including some people who are no longer with the experiment, but who worked on MACRO while the data for this dissertation was being compiled.

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<u>References</u>

1. Ambrosio, M. *et al.*, The MACRO Collaboration, 1995, “Vertical Muon Intensity Measured with MACRO at the Gran Sasso Laboratory”, *Physical Review D*, **52**, 3793.

2. Ahlen, S. *et al.*, The MACRO Collaboration, 1993, “The First Supermodule of the MACRO Detector at Gran Sasso”, *Nuclear Instruments and Methods in Physics Research A*, **324**, 337-362.

3. Isadore B. Berlman, 1971, **Handbook of Flourescence Spectra of Aromatic Molecules**, 2nd ed., Academic Press, New York.

4. Birks, J. B., 1964, **The Theory and Practice of Scintillation Counting**, The MacMillan Co., New York.

5.Ahlen, S. *et al.*, The MACRO Collaboration, 1994, “Search for Slow Moving Magnetic Monopoles with the MACRO detector”, *Phys. Rev. Lett.* **72**, 608.

6. Levin, D.S., Barish, B.C., Diehl, E., Habig, A.T., Handel, J., Kertzman, M., Mufson S., Musser, J., S., Nutter, S., Sembrowski, G., and Tarlè, G., 1992, “GRAČE: A prototype for the Gran Sasso Air Čerenkov Experiment”, *Nucl. Instr. and Methods A*, **322**, 101.

7. Levin, D.S., Barish, B.C., Diehl, E., Habig, A.T., Handel, J., Kertzman, M., Mufson, S., Musser, J., Nutter, S., Sembrowski, G., Tarlè, G., and the MACRO Collaboration, 1994, “Coincident Observation of Air Čerenkov Light by a Surface Array, and Muon Bundles by a Deep Underground Detector”, *Phys. Rev. D*, **50**, 3046.

8. Aglietta, M., *et al.*, The MACRO and EASTOP Collaborations, 1994, “Study of the Primary Cosmic Ray Composition Around the Knee of the Energy Spectrum”, *Phys. Lett. B*, **337**, 376.