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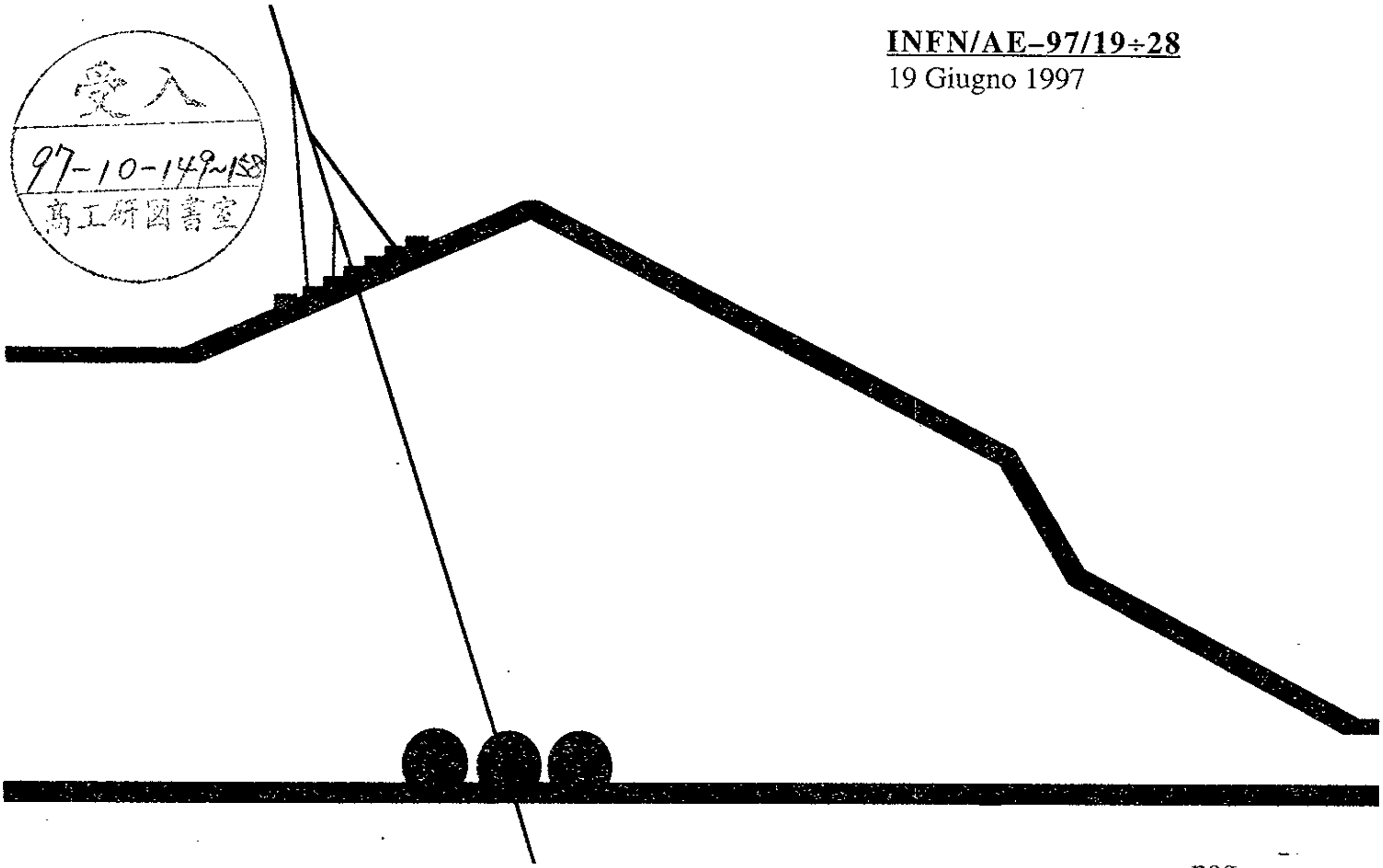

Contributions of the MACRO Collaboration to the 1997 Summer Conferences

INFN – Laboratori Nazionali del Gran Sasso

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The MACRO Collaboration

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MAGNETIC MONOPOLE SEARCH WITH THE MACRO DETECTOR AT GRAN SASSO

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ABSTRACT

We present the results of the search for massive magnetic monopoles in the penetrating cosmic radiation performed with the MACRO detector. Independent analyses were carried out by using the scintillator, streamer tubes and track-etch subdetectors in different ranges of the monopole velocities. Since no candidates were found in several years of data taking, present flux upper limits are below the Parker bound for monopole velocities $\geq 10^{-4}c$.

INTRODUCTION

Grand Unified Theories (GUTs) of the electroweak and strong interactions predict the existence of massive ($\sim 10^{17}$ GeV) magnetic monopoles (Preskill, 1979).The MACRO detector at Gran Sasso was conceived to be effective in the search for such monopoles at a sensitivity level well below the Parker bound (10^{-15}cm^{-2} s^{-1} sr^{-1}) (Turner et al., 1982), for a large range of velocities, $4 \times 10^{-5} < \beta < 1$.

MACRO consists of six supermodules with total dimension $77 \times 12 \times 9$ m^3. Each supermodule is divided into a lower and an upper part. The lower part consists of two separate modules made of ten horizontal streamer tube planes (6×12 m^2) interleaved with seven rock absorber layers and two scintillation counter planes (on the top and bottom). The east and west sides (12×5 m^2) of each lower supermodule are closed by a sandwich of two sets of vertical streamer tube planes (three layers each), interleaved with a scintillation counter plane. Two other "vertical detector systems" close the north and south walls. The upper part of each supermodule consists of two vertical detector systems and of a roof made of two sets of two horizontal streamer tube planes interleaved with a scintillation counter plane, without any absorber. The nuclear track subdetector is located horizontally in the middle of the lower MACRO structure, and vertically on the east wall and on the lower part of the north wall.

Special care was taken to ensure that the three types of detectors and the readout electronics were sensitive to low β particles. A single candidate event may provide distinctive and multiple signatures in the three subdetectors, so the experiment has enough redundancy of information to attain unequivocal and reliable interpretation on the basis of only few or even one event. A more detailed description of the apparatus with particular emphasis on monopole detection has been given in (Ahlen et al., 1993, Ambrosio et al., 1997 and Ahlen et al., 1995).

Single subdetector searches with scintillator or streamer tubes are very effective in the low β region, where the background is due to uncorrelated noise and the required rejection power is not too high. Searches for fast magnetic monopoles are heavily affected by the background due to energetic muons with large energy losses in the detector. Although single subdetector searches for fast monopoles have been effectively performed on limited data samples, a combined use of the three redundant systems can achieve the needed rejection by imposing looser requirements.

Present analyses refer only to direct detection of bare monopoles with unit magnetic Dirac charge. Magnetic monopole induced nucleon decay is not considered; the results are then valid for catalysis cross sections smaller than 10 mb. An isotropic flux of magnetic monopoles was also assumed. This applies to monopoles with enough kinetic energy to traverse the Earth. This condition sets a β dependent mass threshold which is $\sim 10^{17}$ GeV for $\beta \sim 5 \cdot 10^{-5}$ and is lower (down to $\sim 10^{10}$ GeV) for faster poles.

SINGLE SUBDETECTOR SEARCHES

Searches Using the Liquid Scintillator

The use of three different triggers, electronics and analysis procedures allows us to cover the entire β range with maximum efficiency.

1. The light yield of magnetic monopoles with $10^{-4} < \beta < 5 \cdot 10^{-3}$ is inferred by the measurement of the light yield of protons with similar velocities in plastic scintillators (Ahlen et al., 1994). The waveform of the photomultiplier output is analysed looking for the long and flat light pulse expected from a monopole. Two independent searches have been performed and published (Ahlenet al., 1994 and Ambrosio et al., 1997). The established flux upper limits for $1.8 \times 10^{-4} < \beta < 3 \times 10^{-3}$ of 5.6 and 4.1×10^{-15} cm^{-2} s^{-1} sr^{-1} are reported in Fig. 1 in curves A and D.

2. In the medium velocity interval the light produced per unit pathlength and the time of flight across the apparatus are used at the same time. In this way the background, mainly due to natural radioactivity and atmospheric muons stopping in the detector, is completely rejected. The analysed data were collected between October 1989 and January 1997. ¿From the absence of monopole candidates the 90% C.L. flux upper limit of 6.0×10^{-16} cm^{-2} s^{-1} sr^{-1} for $1.2 \cdot 10^{-3} < \beta < 10^{-1}$ is reported in Fig. 1 curve B.

3. The huge energy loss of a fast magnetic monopoles ($\beta > 10^{-1}$) tags candidates by searching for events with large amounts of light recorded by photomultipliers. High energy showering muons are the main background for this kind of analysis. Such events are completely removed by checking that the measured energy loss in two scintillator layers is lower than expected for monopoles. The resulting flux upper limit (4.4×10^{-15} cm^{-2} s^{-1} sr^{-1} for $\beta > 10^{-1}$) is reported in curve C of Fig. 1.

In the present analyses the upper part (including the top horizontal layer and the side top vertical layers) was not used. Trigger and analysis efficiencies were checked by pulsing the counters with LED and nitrogen laser light. The 90% flux upper limits are reported in Fig. 1.

Search Using the Streamer Tube Subdetector

The tubes are filled with a 73% He and 27% n-pentane gas mixture and are operated in the limited streamer mode. The presence of the helium allows detection with 100 % efficiency of the passage of a magnetic monopole exploiting the Drell and Penning effects (Ahlen et al., 1995 and Drell et al., 1983). The analysis is based on the search for single tracks and on the measurement of the velocity of the candidates, a complete description of the employed hardware and analysis procedures has been given (Ahlen et al., 1995). Only the horizontal streamer planes of the lower MACRO have been used in the trigger; the upper part and the vertical planes have been used for event reconstruction. The analyzed data sample was collected from February 1992 to April 1997 for a live-time of 1823 days. Since the construction of the apparatus was not yet completed, during the first year of this period the acceptance was only a fraction of the total 4250 m^2 sr of the full lower part of the detector. The trigger and analysis were checked to be velocity independent. The global efficiency was then estimated by computing the ratio of the rate of single muons reconstructed by this analysis to the expected one. The typical overall efficiency was over 90%. A Monte Carlo simulation including all the geometrical and trigger requirements was used to compute the detector acceptance. No candidate remained. For $1.1 \times 10^{-4} < \beta < 5 \times 10^{-3}$ a flux limit $\Phi_M < 5.0 \times 10^{-16}$ cm^{-2} s^{-1} sr^{-1} at 90 % C. L. was obtained.

Search Using the Nuclear Track Subdetector

The nuclear track-etch subdetector (CR39 and LEXAN sheets) covers a surface of 1263 m^2 and the total acceptance for fast magnetic monopoles is about 7100 m^{2}sr. The subdetector is used as a stand alone detector and in a "triggered mode" by the scintillator and streamer tube systems. The CR39 nuclear track detector was calibrated with slow and fast ions, checking that the response depends on the restricted energy loss only (Ambrosio et al., 1997a). In the last years about 24 m^2/year of track-etch detector were extracted. The method of searching for monopoles and the determination of the geometrical and detection efficiencies are reported in detail in (Ambrosio et al., 1997a). A total surface area of 88.86 m^2 of CR39 has been analysed, with an average exposure time of 5.89 years. No candidate was found; the 90% C.L. upper limits on the magnetic monopole flux are at the level of 2.7×10^{-15} $cm^{-2}s^{-1}sr^{-1}$ at $\beta \sim 1$, and 4.2×10^{-15} $cm^{-2}s^{-1}sr^{-1}$ at $\beta \sim 10^{-4}$, (see Fig. 1, curves "CR39").

COMBINED SEARCHES

As stated before, a combined search for fast magnetic monopoles was also performed. For such velocities the three subdetector responses directly result from the Bethe-Bloch formula applied to a moving magnetic charge. As a consequence a combined search (i.e. a three-fold detector coincidence) can be exploited to reduce the large cosmic ray background.

The analysis procedure uses, at the same time, the data coming from scintillator and streamer subdetectors, while scanning of the track-etch is used as a final tool for rejection/confirmation of the selected candidates. The events are triggered by requiring at least one fired scintillator counter and 7 hit horizontal streamer planes. The fast monopole signature is its large ionizing power with respect to minimum ionizing particles. The event selection criteria are therefore based on the amount of light recorded by the photomultipliers and by both digital (tracking) and analog (pulse charge) information coming from the streamer tubes. Since monopoles with $\beta < 0.99$ lose their energy by means of continuous excitation/ionization processes of the traversed medium, a non-showering single particle is searched for in the tracking system. A pathlength of at least 10 cm in the scintillator volume is imposed in order to guarantee a good measurement of the produced light. The signal detected in each crossed counter is then required to exceed the minimum amount of light produced by a $\beta = 5 \cdot 10^{-3}$ monopole (Ahlen and Tarlé, 1983) with the shortest pathlength accepted in the analysis. Taking into account the 5% resolution and the 10% non-linearity of the detector response at that light level (Ambrosio et al., 1997), a three standard deviation cut is imposed.

A further selection is then applied by using the logarithmic dependence of the streamer tube pulse charge on the particle ionizing power (Battistoni et al., 1988 and Battistoni et al., 1996). Fluctuations resulting from gas mixture and pressure variations are taken into account by calibrating the streamer response with cosmic muons on a run by run basis. After correction for geometrical and electronic non-linear effects (Battistoni et al., 1997), a cut is applied on the mean streamer charge measured along the particle trajectory. As a result of a detailed Monte Carlo simulation of the streamer response, 90% of monopoles with $\beta > 5 \cdot 10^{-3}$ are ensured to pass this analysis step. The few ($\sim$ 5/year) selected candidates are analysed in the appropriate CR39-LEXAN sheets by looking for large restricted energy loss producing a detectable track in this subdetector.

The analysed data refers to 667 live days with an average global efficiency of 74%. The acceptance, computed by means of a full Monte Carlo including all the analysis requirements, is 3565 m^2sr. No candidates survived, the 90% C.L. monopole flux upper limit is $1.5 \cdot 10^{-15} cm^{-2}sr^{-1}s^{-1}$ for $5 \cdot 10^{-3} < \beta < 0.99$.

DISCUSSION AND CONCLUSIONS

No candidates were found in any of the aforementioned searches. The corresponding 90% C.L. flux limits are shown in Fig. 1 as function of β.

As any one of the subdetectors may rule out, within its own acceptance and sensitivity, a potential candidate from the others, the present global MACRO limit may be taken as a combination of separate limits. When two or more analyses were coincident in time, in space and in β, we considered only the one with the larger acceptance in that β range. In the more general case the β-interval was divided into subintervals sufficient to characterize the changes in individual acceptances. In each β-subinterval the

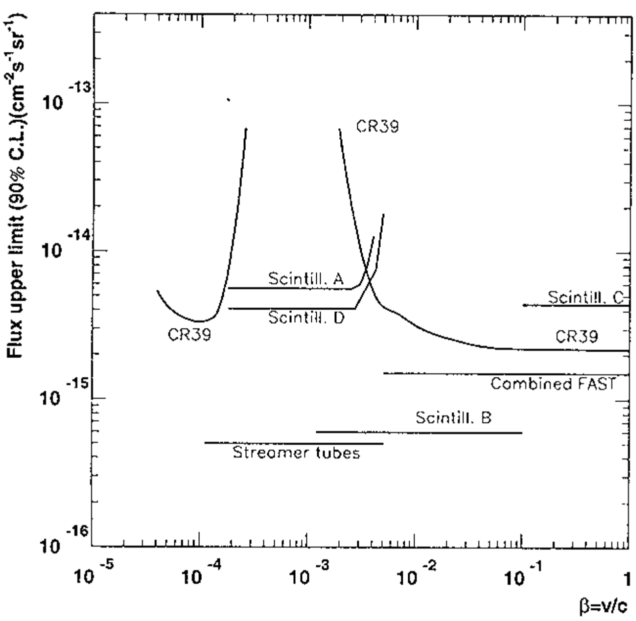

Fig. 1 The 90% C.L. upper limits obtained using the various MACRO subdetectors

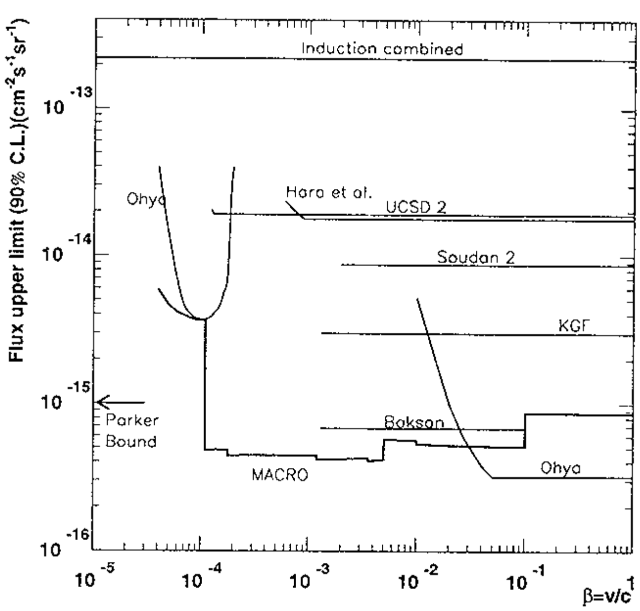

Fig. 2 The 90% C.L. obtained by MACRO (global limit) and by other experiments

MACRO time integrated acceptance was computed as the sum of the independent portions.

The total MACRO limit is computed as $2.3/E_{total}$ where $E_{total} = \sum_i E_i'$, and the E_i' are the independent time integrated acceptances.

This limit is compared in Fig. 2 with the results obtained by other experiments which searched for bare magnetic monopoles with $g = g_D$ and $\sigma_{cat} < 10$ mb (Bermon, 1990, Buckland, 1990, Thron, 1992, Alexeyev, 1990, Orito, 1991, Adarkar, 1990, Hara, 1990).

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