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Search for magnetic monopoles and for nuclearites with the MACRO detector at Gran Sasso

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Abstract

We discuss the searches for massive magnetic monopoles (MM) and for nuclearites in the penetrating cosmic radiation performed with the MACRO detector at Gran Sasso. Independent analyses for MM were carried out using the scintillator, streamer tubes and nuclear track subdetectors in different ranges of velocities. No candidates were found in several years of data taking; present flux upper limits for monopoles are well below the Parker bound for monopole velocities $\geq 10^{-4}c$. For nuclearites, only the scintillator and nuclear track subdetectors were used; limits are at the level of $10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

1 INTRODUCTION

Magnetic Monopoles. Grand Unified Theories (GUTs) of the electroweak and strong interactions predict the existence of massive ($\sim 10^{17}$ GeV) magnetic monopoles [1]. One of the primary purposes of the MACRO detector at Gran Sasso is to perform a sensitive search for such monopoles, at a sensitivity level below the Parker bound (10^{-15} cm $^{-2}$ s $^{-1}$ sr $^{-1}$) [2], for a large range of velocities, $4 \times 10^{-5} < \beta = v/c < 1$.

The MACRO detector has a modular structure, with six “supermodules”, with total dimension of $77 \times 12 \times 9$ 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 interleaved with seven rock absorber layers and two scintillation counter planes (on the top and bottom). The east and west sides of each lower supermodule are closed by a sandwich of two sets of vertical streamer tube planes (three layers each), interleaved with one 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 scintillator 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; the experiment has enough redundancy of information to attain unequivocal and reliable interpretation on the basis of only few events. A detailed description of the apparatus has been given in [3, 4, 5].

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 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 few mb. An isotropic flux of M.M. 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 $\beta \sim 5 \times 10^{-5}$ and is lower (down to $\sim 10^{10}$ GeV for faster poles).

Nuclearites. Nuggets of strange quark matter (aggregates of u , d and s

quarks in equal proportions and electrons that ensure the electrical neutrality) that should be stable for all baryon numbers in the range between ordinary nuclei and neutron stars ($A \sim 10^{57}$) have been hypothesized [6]. They could be the ground state of QCD and could have been produced in the primordial Universe or in violent astrophysical processes.

The main energy loss mechanism for nuclearites passing through matter is that of atomic collisions. While traversing the medium the nuclearites should displace the matter in their path by elastic or quasi-elastic collisions with the ambient atoms [7]. For typical galactic velocities, nuclearites with masses larger than 0.1 g could traverse the Earth [7].

Nuclearites could contribute to the missing mass of the Universe. A limit on their local mass density may be estimated assuming that $\Phi_{max.} = \rho_{DM} v / (2\pi M)$, where $\rho_{DM} \simeq 10^{-24} \text{ g cm}^{-3}$ represents the local dark matter density [7].

It was shown [8] that the monopole searches based on the liquid scintillator subdetector are sensitive also to nuclearites; in [9] the response of the CR39 subdetector to nuclearites was analysed finding that it is efficient for any nuclearite with $\beta > 10^{-5}$. It was also shown that due to the low density of the filling gas, the limited streamer tube subdetector is not sensitive to nuclearites. Some earlier results of the search for strange quark matter in the penetrating cosmic radiation using the scintillator subsystem of the first MACRO module have been published [8].

No nuclearite candidate was found in any of these searches. We can place upper limits for each β -interval.

2 MAGNETIC MONOPOLES

2.1 Independent subdetector searches

Searches using the liquid scintillator. The use of 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 $10^{-4} < \beta < 5 \times 10^{-3}$ is inferred by the measurement of the light yield of protons with similar velocities in scintillators [10]. 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 [10, 4]. The established flux upper limits for $1.8 \times 10^{-4} < \beta < 3 \times 10^{-3}$ of 5.6 and $4.1 \times 10^{-15} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ 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

Figure 1: The 90% C.L. upper limits for an isotropic flux of $g = g_D$ magnetic monopoles, obtained using the various MACRO subdetectors

of monopole candidates the 90% C.L. upper limit of $6 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for $1.2 \times 10^{-3} < \beta < 10^{-1}$ is reported in Fig. 1 curve B.

3. The large energy loss of a fast magnetic monopole, $\beta > 10^{-1}$, 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 removed by checking that the measured energy loss in two scintillator layers is lower than that expected for monopoles. The resulting flux upper limit ($4.4 \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ 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) were 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 helium allows detection with 100 % efficiency of the passage of a magnetic monopole exploiting the Drell and Penning effects [5, 11]. 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 may be found in ref. [5]. Until now, 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 $4250 \text{ m}^2\text{sr}$ of the detector lower part. The trigger and the analysis procedures were checked to be velocity independent. The global efficiency was 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. For $1.1 \times 10^{-4} < \beta < 5 \times 10^{-3}$ a flux limit $\Phi_M < 5 \times 10^{-16} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ at 90% C.L. was obtained.

Search using the nuclear track subdetector. The nuclear track sub-detector (CR-39 and Lexan sheets) covers a surface of 1236 m^2 and the total acceptance for fast magnetic monopoles is about $7100 \text{ m}^2\text{sr}$. The subdetector is used as a stand alone detector and in a “triggered mode” by the scintillator and streamer tube systems. The CR-39 nuclear track detector was calibrated with slow and fast ions, checking that the response depends on the restricted energy loss only [12]. A total surface area of 88.86 m^2 of CR-39 has been analysed, with an average exposure time of 5.89 years. The 90% C.L. upper limit on the magnetic monopole flux is at the level of $2.7 \times 10^{-15} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ at $\beta \sim 1$, and $4.2 \times 10^{-15} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ at $\beta \sim 10^{-4}$, (see Fig. 1, curves “CR-39”).

2.2 Combined searches

A combined search for fast MM was also performed. The analysis procedure uses, at the same time, the data from scintillator and streamer subdetectors, while scanning of the nuclear track subdetector is used as a final tool for rejection/confirmation of the selected candidates. The events are triggered by requiring at least one fired scintillator 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 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 $\beta < 1$ 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 scintillators 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 $\beta = 5 \times 10^{-3}$ monopole [13] 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 [4], a three standard deviation cut is imposed.

A further selection is applied by using the logarithmic dependence of the

streamer tube pulse charge on the particle ionizing power [14, 15]. 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 nonlinear effects [16], a cut is applied on the mean streamer charge measured along the particle trajectory. A Monte Carlo simulation of the streamer response gives a 90% efficiency for monopoles with $\beta > 5 \times 10^{-3}$ for this analysis step. The few (~ 5 /year) selected candidates are analysed in the appropriate CR-39 - Lexan sheets by looking for a detectable track in this subdetector.

The analysis refers to 667 live days with an average global efficiency of 74%. The acceptance, computed by means of a Monte Carlo, including all the analysis requirements, is $3565 \text{ m}^2\text{sr}$. The 90% C.L. monopole flux upper limit is $1.5 \times 10^{-15} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ for $5 \times 10^{-3} < \beta < 0.1$.

3 NUCLEARITES

Scintillators. It was shown that the scintillator sub-detector is sensitive to nuclearites with masses $M \leq 1.5 \text{ ng}$ having velocities as slow as $v = 5 \times 10^{-5}c$ [8], as the light yield should be above the 90%-trigger-efficiency threshold of the scintillator slow-particle trigger system; thus the scintillators are sensitive not only to nuclearites of galactic or extragalactic origin, but also to those possibly trapped in our solar system. The nuclearite detection efficiency in the scintillation subdetector is assumed to be equal to that for magnetic monopoles. The analysis of the data collected during the completion of the detector and with the full detector did not find any nuclearite candidate; thus flux 90% C.L. upper limits could be established. Curves A - D in Fig. 2 summarize for $M < 0.1 \text{ g}$ the limits for a flux of down-going nuclearites obtained during the construction phase; curve E refers to data collected also with the complete detector.

For an isotropic flux of nuclearites ($M > 0.1 \text{ g}$) the limits are lower by a factor of two. The limit A in Fig. 2 were published in [8] while the other more recent limits in [9].

CR-39. For our CR-39 the “intrinsic” threshold is about $20 \text{ MeV g}^{-1} \text{ cm}^2$, in the condition of a chemical etching in 8 N NaOH water solution at 80° C . In order to reduce the background produced by neutron interactions, in the magnetic monopole searches the effective CR39 threshold was set at $50 \text{ MeV g}^{-1} \text{ cm}^2$, by requiring the observation of traversing tracks with a diameter of at least $100 \mu\text{m}$ [17]. The MACRO CR-39 is sensitive to nuclearites of any mass and with $\beta > 10^{-5}$. As a consequence, the 90% C.L. limits for $\beta \sim 1$ monopoles established by the nuclear track sub-detector ($2.2 \times 10^{-15} \text{ cm}^2 \text{ s}^{-1} \text{ sr}^{-1}$) apply to an isotropic flux of $M > 0.1 \text{ g}$ nuclearites. Lower mass nuclearites cannot traverse the earth; thus only nuclearites coming from above the detector are detected, the detection acceptance is half the previous value and the 90% C.L. flux limit is twice the previous value ($4.4 \times 10^{-15} \text{ cm}^2 \text{ s}^{-1} \text{ sr}^{-1}$) [4]. In the

Figure 2: 90% C.L. MACRO limits for a flux of down-going nuclearites with masses of $10^{-10} < M < 0.1$ g. See text for explanations

case of nuclearites with masses lower than $1 \mu\text{g}$ and velocities $\beta = v/c$ between 10^{-5} and 10^{-4} there is an additional loss of acceptance (from few percents to about 50%) arising from the limitation of the incidence angle for the formation of latent tracks in CR39. The present CR-39 limit is presented in Fig. 2 as curve F.

4 CONCLUSIONS

Magnetic monopoles. No candidate was 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 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 E'_i are the independent time integrated acceptances. This procedure ensures the 90% C.L. significance of the global limits.

Figure 3: 90% C.L. flux limit obtained by MACRO for an isotropic flux of bare magnetic monopoles with $g = g_D$ and $\sigma_{cat} < \text{few mb}$ compared with those obtained by other experiments

The present MACRO limit is compared in Fig. 3 with the limits obtained by other experiments which searched for bare M.M. with $g = g_D$ and $\sigma_{cat} < \text{few mb}$ [18, 19, 20, 21, 22, 23, 24]

Nuclearites. No nuclearite candidate was found in any of our searches. The present global MACRO limit for nuclearites is taken as the “OR” combination of separate limits. Using the M.M. procedure based on the summation of the independent parts of the individual exposures, we obtain the global limit denoted as “MACRO” in Fig. 2.

The limits presented in Fig. 2 refer to the flux of nuclearites at the level of the MACRO detector, i.e. below an average rock thickness of 3700 hg cm^{-2} . In order to compare our limits with the limits published by different experiments and with the dark matter limit, we integrated the energy loss equation for a path corresponding to the average rock thickness and for different assumed velocity values at the detection level.

Fig. 4 presents the MACRO global 90% C.L. nuclearite flux limit assuming a nuclearite velocity at the detector level of $\beta = 2 \times 10^{-3}$. We include for comparison two other limits, from papers [25, 22], obtained by experiments using the CR39 nuclear track detector; in [25] the experiment was performed at mountain altitude, while the experiment of reference [22], was performed at a depth of 100 mwe; so the conditions that a nuclearite should fulfill in order to reach the detectors are different. These differences explain the different

Figure 4: The 90% C.L. MACRO global limit for a flux of down-going nucle-
arites, compared with other published limits and with the dark matter limit,
assuming a nuclearite velocity of $v = \beta c = 2 \times 10^{-3}c$

astrophysical limits computed for different experiments.

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