

Search for Magnetic Monopoles with MACRO

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Abstract

Data from the complete MACRO detector have been used to search for magnetic monopoles (MMs) of all expected velocities. Scintillator, streamer tube (instrumented with specialized electronics) and nuclear track detectors have been used to search for signatures coming from MMs; the scintillator and nuclear track subdetectors were used also for searches for other rare particles (nuclearites, charged Q-balls). Based on no observation of such signals, we establish stringent flux limits, for MMs as slow as a few $10^{-5}c$.

1 Introduction:

Grand Unified Theories (GUTs) of the electroweak and strong interactions predict the existence of massive ($\sim 10^{17}$ GeV) magnetic monopoles, Preskill (1979). One of the primary aims of the MACRO detector at the Gran Sasso underground lab (in Italy, at an average depth of 3700 hg/cm²) is the search for such MMs 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, $4 \cdot 10^{-5} < \beta < 1$, $\beta = v/c$.

MACRO uses three different types of detectors: liquid scintillators, limited steamer tubes and nuclear track detectors (CR39 and Lexan) arranged in a modular structure of six “supermodules” (SM’s). Each SM is divided into a lower and an upper (“Attico”) part. The overall dimensions of the apparatus are $76.6 \times 12 \times 9$ m³, Ahlen et al. (1993). The response of the three types of detectors to slow and fast particles was experimentally studied by Ahlen & Tarlé (1983), Battistoni et al. (1988, 1997b) and Cecchini et al. (1996). The 3 subdetectors ensure redundancy of information, cross-checks and independent signatures for possible MM candidates.

The analyses reported here, obtained using the various subdetectors in a stand-alone and in a combined way, refer to direct detection of bare MMs of one unit Dirac charge ($g_D = 137/2e$), catalysis cross section $\sigma_{cat} < 1$ mb (we ignore monopole induced nucleon decay), and isotropic flux (we consider MMs with enough kinetic energy to traverse the Earth); this last condition sets a β dependent mass threshold ($\sim 10^{17}$ GeV for $\beta \sim 5 \cdot 10^{-5}$, and lower for faster MMs).

We also discuss the limits obtained for nuclearites and charged Q-balls.

2 Searches for MMs with Individual Subdetectors:

2.1 Searches with Scintillators: The searches with the liquid scintillator subdetector use different specialized triggers covering different velocity regions; the searches are grouped into searches for low velocity ($10^{-4} < \beta < 10^{-3}$), medium velocity ($10^{-3} < \beta < 10^{-1}$) and high velocity ($\beta > 0.1$).

2.1.1 Low Velocity Monopole Searches: Previous searches using data collected with the Slow Monopole Trigger (SMT) and Waveform Digitizer (WFD) were reported in Ambrosio et al. (1997), see curves “A”, “B” in Fig. 1a. A new 200 MHz WFD system was implemented which improves by at least a factor of two the sensitivity to very slow monopoles ($\beta \sim 10^{-4}$) and by over a factor of five the sensitivity to relativistic monopoles with respect to previous conditions. The sensitivity of the SMT/WFD was tested with LED pulses, of ~ 6.3 μ s duration, corresponding to $\beta \sim 10^{-4}$, down to the level of few tens of single photoelectrons (spe’s), which is the signature of a slow monopole. A waveform analysis procedure scanned off-line the corresponding wave forms and simulated in software the function of both the analog and digital part of the SMT circuitry on an event-by-event basis. The

trigger+analysis efficiency is $> 95\%$ for a light yield > 10 spe's over $\sim 6.3 \mu\text{s}$. The same waveform methods used to determine the efficiency of the system are also used to search for slow monopole signatures in the most recent data. Applying simple cuts to reject background from muons and to guarantee proper functioning of the hardware, we employ redundant waveform methods to search for slow MMs. We plan to report on this search in the near future.

2.1.2 Medium and High Velocity Monopole Searches: The data collected by the PHRASE trigger are used to search for MMs in the range $1.2 \cdot 10^{-3} < \beta < 10^{-1}$, Ambrosio et al. (1992, 1997). The events are selected requiring hits in a maximum of four adjacent counters, with a minimum energy deposition of 10 MeV in two different scintillator layers. Events with $1.2 \cdot 10^{-3} < \beta < 5 \cdot 10^{-3}$ are rejected because their pulse width is smaller than the expected counter crossing time; events with $5 \cdot 10^{-3} < \beta < 10^{-1}$ are rejected because the light produced is much lower than that expected for a MM. The analysis refers to data collected by the MACRO lower part from October 1989 to the end of 1998 and by the Attico from June 1995 to the end of 1998. No candidate survives; the 90% C.L. flux upper limit is $3.2 \cdot 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (curve “D” in Fig. 1a).

A previous search for MMs with $\beta > 10^{-1}$ based on the ERP trigger, Ambrosio et al. (1992,1997) is included in Fig. 1a (curve “ C”).

2.2 Search Using the Streamer Tubes: This search was described in Ahlen et al. (1995), Ambrosio et al. (1997). The analysis is based on the search for single tracks in the streamer tubes and on the measurement of the velocity with the “time track”. Only the horizontal streamer planes of the lower MACRO are used in the trigger; the Attico and the vertical planes are used for event reconstruction. Data were collected from 1992 to January 1999 for a live-time of 59,712 hours. The trigger and the analysis chain were checked to be velocity independent. The overall efficiency was $\sim 73\%$. The detector acceptance, computed by a Monte Carlo simulation including geometrical and trigger requirements, is $4250 \text{ m}^2 \text{ sr}$. No monopole candidate was found. For $1.1 \cdot 10^{-4} < \beta < 5 \cdot 10^{-3}$ the flux upper limit is $3.4 \cdot 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at 90% C.L.

2.3 Search Using the Nuclear Track Subdetector: The nuclear track subdetector covers a surface of 1263 m^2 and the acceptance for fast MMs is $7100 \text{ m}^2 \text{ sr}$. The subdetector is used as a stand alone detector and in a “triggered mode” by the scintillator and streamer tube systems. The method of searching for MMs and the determination of the geometrical and detection efficiencies are given in Ahlen et al. (1994). An area of 227 m^2 of CR39 has been analysed, with an average exposure of 7.6 years. No candidate was found; the 90% C.L. upper limits on the MM flux are at the level of $6.8 \cdot 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at $\beta \sim 1$, and $10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at $\beta \sim 10^{-4}$ (Fig. 1a, curves “CR39”).

3 Combined Searches for Fast Monopoles:

3.1 A search for fast MMs with scintillators or streamer tubes is affected by the background due to energetic muons with large energy losses. A combined use of the three subdetector systems can achieve the highest rejection by imposing looser requirements. The trigger requires at least one fired scintillator counter and 7 hits in the horizontal streamer planes. Candidates are selected on the basis of the scintillator light yield and of the digital (tracking) and analog (pulse charge) information from the streamer tubes. A further selection is then applied on the streamer tube pulse charge. After corrections for gain variations, geometrical and electronic non-linear effects (Battistoni et al. (1997a)), a 90% efficiency cut is applied on the average streamer charge. Selected candidates ($\sim 5/\text{year}$) are analysed in the corresponding nuclear track detector modules. The analysis refers to about 30,508 live hours with an average efficiency of 77%. The geometrical acceptance, computed by Monte Carlo methods, including the analysis requirements, is $3565 \text{ m}^2 \text{ sr}$. No candidate survives; the 90% C.L. flux upper limit is $7.6 \cdot 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for MMs with $5 \cdot 10^{-3} < \beta < 0.99$ (curve “E” in Fig. 1a).

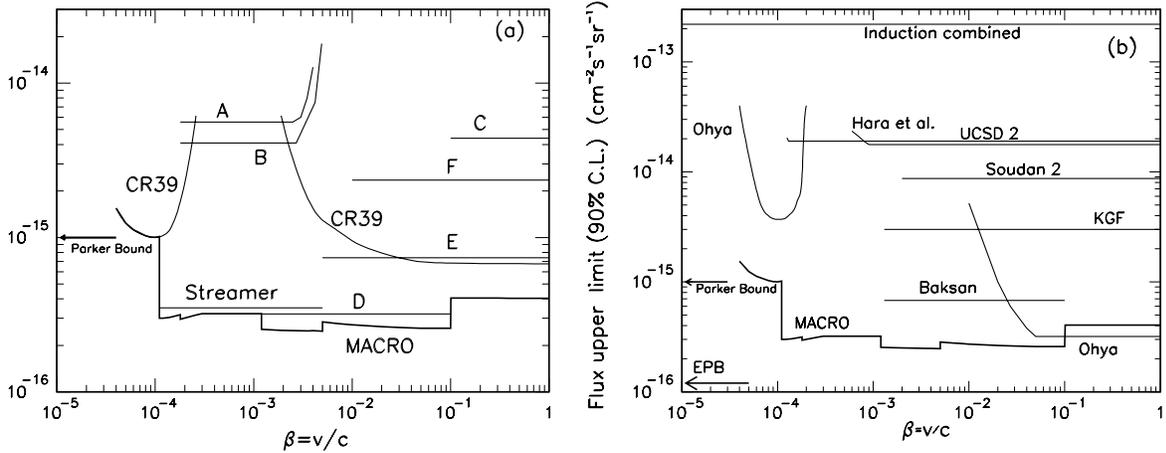


Figure 1: The 90% C.L. upper limits obtained (a) using various MACRO subdetectors and the MACRO global limit and (b) by other experiments.

3.2 MMs with $\beta > 10^{-2}$ are searched combining the streamer tube and PHRASE triggers. Streamer tubes are used to reconstruct the trajectory and pathlength, scintillators are used to measure the velocity and the light yield. Selected events ($\sim 50/\text{year}$) have a single track and an energy deposition > 200 MeV in three scintillator layers. The event energy loss is compared to that expected for a monopole with the same velocity. The analysis refers to about 8528 live hours from May, 1997 to June, 1998. No candidate survives. The geometrical acceptance, including analysis cuts, is $3800 \text{ m}^2 \text{ sr}$. The 90% C.L flux upper limit is $2.3 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (curve “F” in Fig. 1a).

4 Searches for Nuclearites and Q-balls:

The searches for MMs based on the scintillator and nuclear track subdetectors may also be applied to search for nuclearites, hypothesized nuggets of strange quark matter and possible candidates for Dark Matter (DM), Witten (1984). Scintillators are sensitive to nuclearites down to $\beta \simeq 5 \cdot 10^{-5}$ and the CR39 down to $\beta \sim 10^{-5}$, Ambrosio et al. (1999). Individual limits from scintillators and CR39 are presented in Fig. 2a (curves “a-e” and “f”, respectively).

As recently suggested by Kusenko et al. (1997), the MACRO limits for nuclearites may also apply to charged Q-balls (supersymmetric coherent states of squarks, sleptons and Higgs fields). Relic Q-balls are also candidates for cold DM.

5 Conclusions:

No MM candidates were found in any search. The 90% C.L. flux limits versus β are shown in Fig. 1a. The global 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 of different analyses. This limit is compared in Fig. 1b with the limits of other experiments which searched for bare MMs with $g = g_D$ and $\sigma_{cat} < 1 \text{ mb}$, Bermon (1990), Buckland (1990), Thron (1992), Alexeyev (1990), Orito (1991), Adarkar (1990), Hara (1990).

Following the same procedure used for MMs, we obtain the 90% C.L. global MACRO limit for an isotropic flux of nuclearites (masses $> 6 \cdot 10^{22} \text{ GeV}/c^2$, Fig. 2a); at $\beta = 2 \cdot 10^{-3}$ the limit is $2.4 \cdot 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The MACRO limit for a flux of downgoing nuclearites is compared in Fig. 2b with the limits of other experiments, Nakamura (1991), Orito (1991), Price (1988), Ghosh & Chatterjea (1990), and with the DM bound.

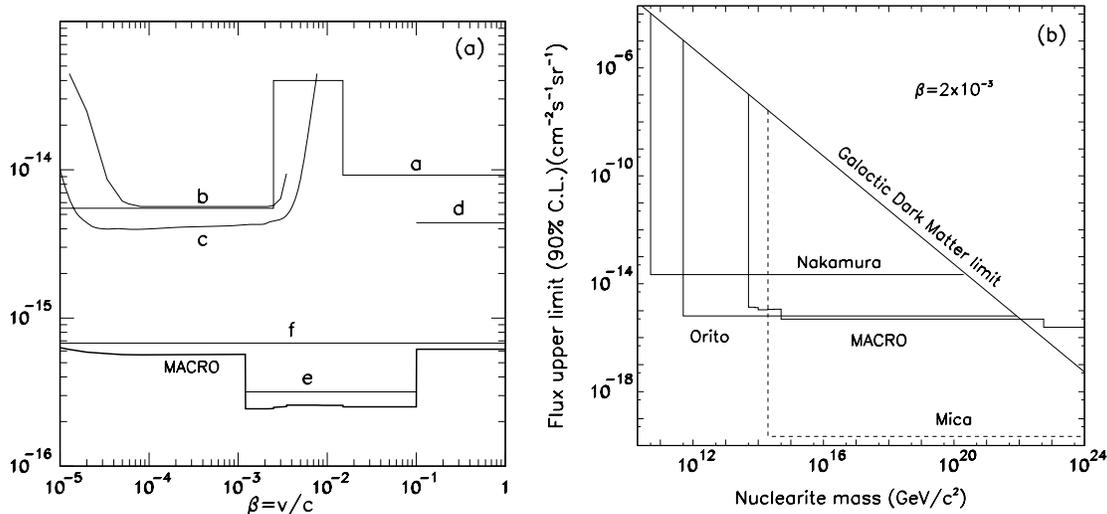


Figure 2: 90% C.L. upper limits for an isotropic flux of nuclearites (a) versus β for different MACRO searches with scintillators (curves “a - e”) and CR39 (curve “f”); (b) versus mass obtained by MACRO and by other experiments, for downgoing nuclearites with $\beta = 2 \cdot 10^{-3}$ at ground level. The MACRO limit for $M_N > 6 \cdot 10^{22}$ GeV/c^2 has been extended above the DM bound and corresponds to an isotropic flux.

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