PROCEEDINGS

International Europhysics Conference on HEP

Search for magnetic monopoles in the cosmic radiation with the MACRO detector at Gran Sasso

Ivan De Mitri[*] **(for the MACRO collaboration)**[†]

Dipartimento di Fisica dell'Università di Lecce and INFN, 73100 Lecce, Italy
E-mail: `ivan.demitri@le.infn.it`

Abstract: Supermassive GUT magnetic monopoles have been searched for in the penetrating cosmic radiation with the MACRO detector at the Gran Sasso National Laboratory. We present updated results obtained by several analyses by using the MACRO streamer tubes, scintillators and nuclear track subdetectors. Stringent upper limits, below the Parker bound, are imposed to the flux of GUT monopoles with velocity larger than 10^{-5} c. ehe described methods were also applied in the search for nuclearites.

PrHEP hep2001

1. Introduction

In the framework of Grand Unified Theories (GUT), Magnetic Monopoles (hereafter MMs) would have been produced in the very early Universe as supermassive ($M \sim 10^{17}\,\text{GeV}$) topological defects [1]. One of the primary aims of the MACRO experiment at the Gran Sasso underground Laboratories was the search for such particles with a sensitivity well below the Parker bound (i.e. 10^{-15} cm^{-2} s^{-1} sr^{-1} [2]) in a very wide velocity range $4 \cdot 10^{-5} < \beta < 1$, $\beta = v/c$. The detector, which took data until December 2000, was arranged in a modular structure of six "supermodules" (SM's) with global dimensions of $76.5 \times 12 \times 9.3\,\text{m}^3$ and a total acceptance of $\sim 10,000$ m^{2}sr to an isotropic flux of particles [3]. MACRO had three subdetectors: liquid scintillation counters, limited streamer tubes and nuclear track detectors (CR39 and Lexan), whose responses to slow and fast particles were experimentally studied [4, 5, 6, 7]. The use of three different subdetectors ensured redundancy of information, cross-checks and independent signatures for possible MM candidates. The analyses presented here, based on the various subdetectors in a stand-alone and in a combined way, refer to direct detection of bare MMs of one unit Dirac charge ($g_D = 137/2e$), nucleon decay catalysis cross section $\sigma_{cat} < 1$ mb [1] and isotropic flux.

Some of the methods used for the MM searches may also be applied to search for nuclearites [8, 9]. We quote upper flux limits for $\beta > 5 \cdot 10^{-5}$.

---

[*] Speaker.

[†] See [16] for the complete author list.

2. Searches with scintillators

The liquid scintillator subdetector was equipped with different specialized triggers searching for *low velocity* ($10^{-4} < \beta < 10^{-3}$), *medium velocity* ($10^{-3} < \beta < 10^{-1}$) and *high velocity* ($\beta > 0.1$) MMs respectively.

Low velocity monopole searches:
Previous searches using data collected with the Slow Monopole Trigger (SMT) and Waveform Digitizer (WFD) were reported in [10], see curves "A", "B" in Fig.1.

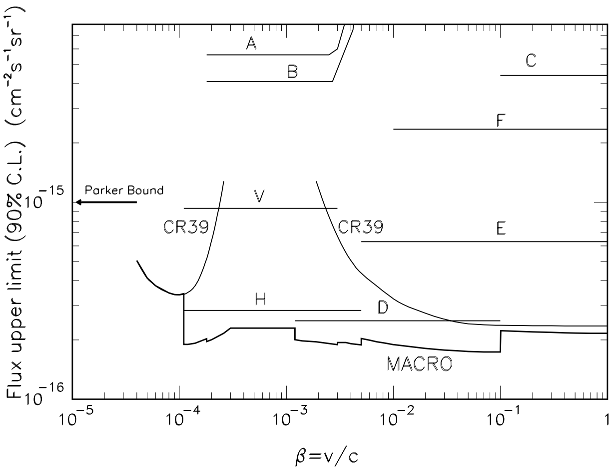

Figure 1: The 90% C.L. upper limits for an isotropic flux of supermassive magnetic monopoles obtained by using the three MACRO subdetectors (see text). The limit obtained from the combination of all the MACRO searches is also shown.

Medium and high velocity monopole searches:
The data collected by the PHRASE (Pulse Height Recorder and Synchronous Encoder) trigger are used to search for MMs in the range $1.2 \cdot 10^{-3} < \beta < 10^{-1}$ [10, 11]. The events are selected by requiring hits in a maximum of four adjacent scintillation 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 if their pulse width is smaller than the expected counter crossing time, while events with $5 \cdot 10^{-3} < \beta < 10^{-1}$ are rejected if the light produced is much lower than that expected for a MM. Events at the boundary of the two β-regions are studied using both the selection criteria. The analysis refer to data collected by the MACRO lower part from October 1989 to mid-June 2000 and also by the upper part from June 1995 to the end of 1999. No candidate survives; the 90% C.L. flux upper limit is $2.6 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} (curve "D" in Fig.1). The result of a previous search for MMs with $\beta > 10^{-1}$ based on the ERP trigger [10, 11] is also reported in Fig.1 (curve "C").

3. Search using the streamer tubes

Two different trigger circuits operated on the streamer tube system: one on the horizontal planes of the lower MACRO and one on the vertical planes [12, 13]. Accordingly, two analysis streams have been applyed which start from the two different triggers, while all the MACRO streamer tubes were used for the event reconstruction. In both cases the analysis is based on the search for single tracks and on the measurement of the particle velocity by using the time information provided by the tubes (maximum time jitter $\sim$ 600 ns). Triggers and analyses were checked to be velocity independent while the global efficiency was estimated by computing the ratio of single muons reconstructed by each of the analyses to the expected ones [14].

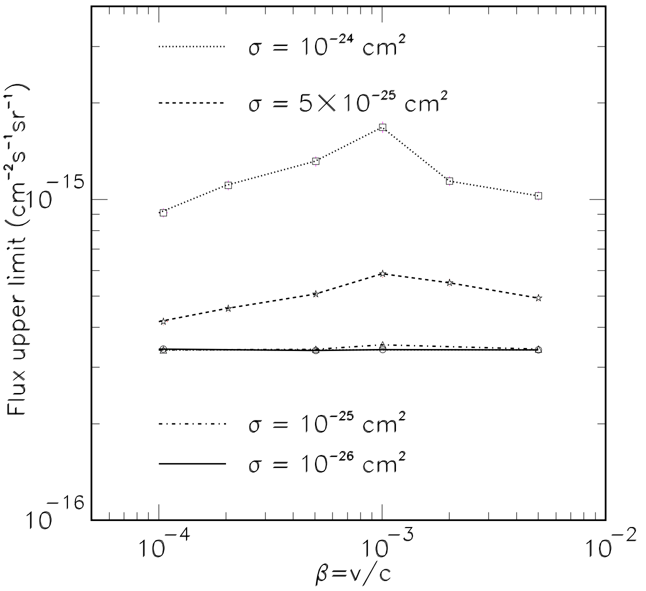

Figure 2: Flux limits from streamer tubes for 4 values of σ_{cat}, which is assumed to be the same on protons and neutrons.

The search performed with the horizontal trigger uses data collected from January '92 to September 2000, for a live time of 71193 hours. The overall efficiency was 74%. The detector acceptance, computed by a full simulation, including geometrical and trigger requirement, is 4250 $m^2\ sr$. No monopole candidate was found. For $1.1 \cdot 10^{-4} < \beta < 5 \cdot 10^{-3}$ the flux upper limit is $2.8{\cdot}10^{-16} cm^{-2} s^{-1} sr^{-1}$ at 90% C.L. (Fig.1, curve "H").

The search with the vertical trigger covers data from November '95 to September 2000 for a total live time of 31521 hours. The efficiency was 72% while the acceptance, estimated by Monte Carlo simulation, is $3118 m^2 sr$. The resulting β distribution is broader than the one obtained from the horizontal analysis. This limits the sensitivity of this search to the velocity range $1.1 \cdot 10^{-4} < \beta < 3 \cdot 10^{-3}$. Since no monopole candidate was found, an upper limit to the monopole flux has been established at $\Phi \leq 9.3 \cdot 10^{-16} cm^{-2} s^{-1} sr^{-1}$ (Fig.1, curve"V").

GUT magnetic monopoles may catalyze nucleon decay along their path [1]. Detailed Monte Carlo simulations were performed to study the effects of decay products on the streamer monopole trigger and on the related analysis. For instance, the tracking procedure might be confused, both in the space and time views. The physical process and the detector response were introduced in the code to a high degree of details, taking into account the theoretical predictions on the cross section and on the decay channels. Fig.2 shows the flux upper limit (for a given data sample) vs β for different values of the catalysis cross section. As can be seen for catalysis cross section as large as 100 mb the analysis is fully efficient.

4. Search using the nuclear track subdetector

The nuclear track subdetector covered a surface of 1263 m^2 with an acceptance for fast MMs of 7100 m^2 sr. The subdetector was used as a stand-alone detector and in a "triggered mode" by the scintillator and streamer tube systems. A detailed description of the method of seaching for MMs is given in [15]. On May 2000 we began the massive etching of the CR39 sheets using the Bologna and Gran Sasso etching facilities, at the rate of about 40 m^2/month. An area of 545 m^2 of CR39 has been analysed, with an average exposure time of 9.1 years. No candidate was found; the 90% C.L. upper limits on the MM flux are at the level of $2.4 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} at $\beta \sim 1$, and $3.4 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} at $\beta \sim 10^{-4}$ (Fig.1, curves "CR39").

5. Combined searches for fast monopoles

The analysis procedure is based on the scintillator and streamer tube data; the nuclear track detector is used as a final tool for rejection/confirmation of the selected candidates. The trigger requires at least one fired scintillation 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. After corrections for gain variations, geometrical and electronic non-linear effects, a 90% efficiency cut is applied on the average streamer charge. Possible candidates ($\sim$ 2/year) are analysed in the corresponding nuclear track detector modules.

The analysis refers to about 36,980 live hours with an average efficiency of 77%. The geometrical acceptance, computed by Monte Carlo methods, including the analysis requirements, is 3565 m^2 sr. Ultra relativistc monopoles (i.e. $\gamma \geq 10$) could induce showers in the apparatus. Such events could not be distinguished from those due to high energy showering muons. Therefore this analysis has full efficiency up to $\beta \simeq 0.99$. Since no candidate was found, the 90% C.L. flux upper limit is set at the level of $6.3 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} for MMs with $5 \cdot 10^{-3} < \beta < 0.99$ (curve "E" in Fig.1).

The result of a previous search for $\beta > 10^{-2}$ MMs, performed by combining the streamer tube and PHRASE triggers, is also reported in Fig.1, curve "F".

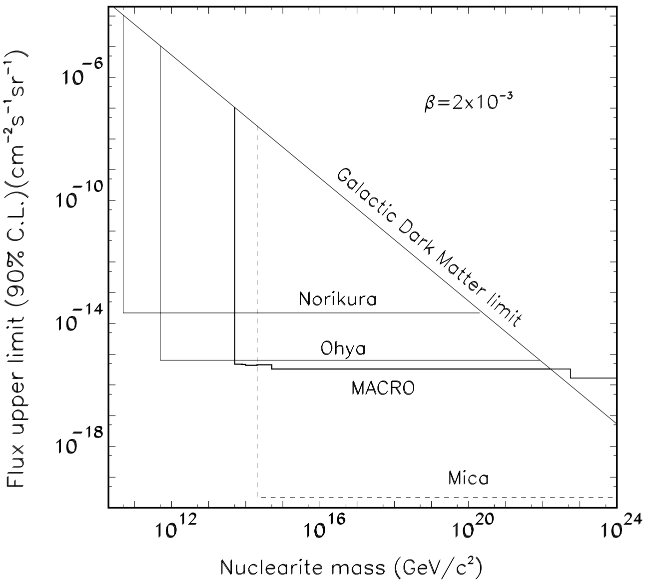

Figure 3: The global MACRO 90% C.L. flux upper limit for nuclearites with $\beta = 2 \cdot 10^{-3}$ at ground level, versus nuclearite mass, is compared with the limit obtained by other experiments and with the galactic DM bound.

6. Searches for nuclearites

Nuclearites are expected to have typical galactic velocities, i.e. $\beta \sim 10^{-3}$. At these velocities, the main energy loss mechanism for SQM passing through matter is that of atomic collisions [9]. Since their expected energy loss rate is large, they would be easily detected by MACRO. In particular, the scintillators are sensitive to the blackbody radiation emitted along the heated nuclearite paths down to $\beta \simeq 5 \cdot 10^{-5}$, while the CR39 is sensitive to nuclearites down to $\beta \sim 10^{-5}$ [16]. However, since the density of the gas mixture in the streamer tubes is too low to produce a detectable signal, this subdetector is not useful for nuclearite searches.

By taking into account their energy loss rate, it can be seen that nuclearites with $\beta \sim 10^{-3}$ and masses $M \leq 5 \cdot 10^{11}$ GeV could not reach MACRO. If $5 \cdot 10^{12} \leq M \leq 10^{21}$ GeV only downward going nuclearites could reach it, while for $M > 10^{22}$ GeV nuclearites could reach MACRO from all directions. Therefore data collected by the scintillator and CR39 subdetectors have been used to put stringent limits to the nuclearite flux in the proper mass range. At $\beta = 2 \cdot 10^{-3}$ the limit is $1.8 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1}. In Fig.3, it is compared with the limits obtained by other experiments [20, 22, 23, 24].

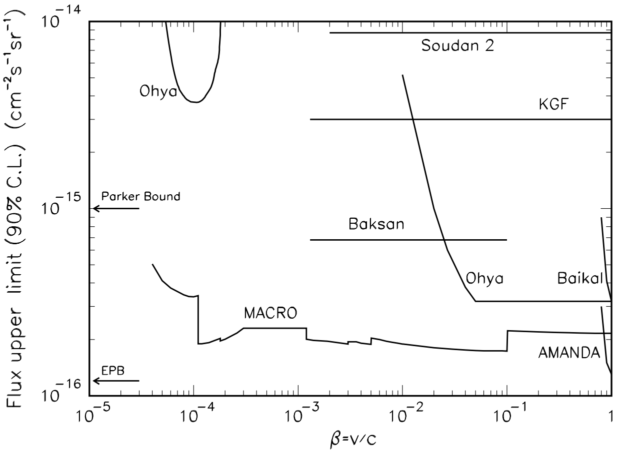

Figure 4: The global MACRO 90% C.L. upper limit for an isotropic flux of $g = g_D$ magnetic monopoles compared with the limits obtained by other experiments.

7. Conclusions

Several analysis techniques were used to search for supermassive GUT magnetic monopoles in the cosmic radiation with the MACRO detector at Gran Sasso. No monopole candidate was found in any of these searches. The 90% C.L. flux limits for MMs versus β are shown in Fig.1 for the different searches. The global MACRO limit was also computed as $2.3/X_{total}$, where $X_{total} = \sum_i X_i'$ and the X_i' are the independent time integrated acceptances of the different analyses. This limit is compared in Fig.4 with the limits obtained by other experiments which searched for bare MMs with $g = g_D$ and $\sigma_{cat} < 1$ mb [17, 18, 19, 20, 21]. As can be seen from the figure, the MACRO limit is the only one which is well below the Parker bound in the whole β range in which supermassive GUT monopoles are expected.

By following the same procedure used for MMs, we obtained also the 90% C.L. global MACRO limit for an isotropic flux of nuclearites.

References

[1] Preskill, J., *Phys. Rev. Lett.* **43** (1979) 1365 and references therein.

[2] Turner, M.S., Parker, E. M. & Bogdan, T. J.,*Phys. Rev.* **D 26** (1982) 1926.

[3] MACRO Coll., (Ahlen, S. P., et al.), *Nucl. Instrum. Meth.* **A324** (1993) 337.

[4] Ahlen, S. P. & Tarlé, G., *Phys. Rev.* **D 27** (1983) 668.

[5] Battistoni, G. et al., *Nucl. Instrum. Meth.* **A270** (1988) 185.

[6] Battistoni, G. et al., *Nucl. Instrum. Meth.* **A401** (1997) 309.

[7] Cecchini, S. et al., *Nuovo Cim.* **A109** (1996) 1119.

[8] Witten, E., *Phys. Rev.* **D 30** (1984) 272

[9] De Rújula, A. & Glashow, S. L., *Nature* **312** (1984) 734.

[10] MACRO Coll., (Ambrosio, M. et al.), *Phys. Lett.* **B 406** (1997) 249.

[11] MACRO Coll., (Ambrosio, M. et al.), *Astropart. Phys.* **1** (1992) 11.

[12] Auriemma, G. et al., *Nucl. Instrum. Meth.* **A263** (1988) 249.

[13] De Mitri, I. et al., *Nucl. Instrum. Meth.* **A360** (1995) 311.

[14] MACRO Coll., (Ambrosio, M. et al.), *Astropart. Phys.* **4** (1995) 33.

[15] Patrizii, L. for the MACRO Coll., Proc. of the XXth ICNTS, Rad. Meas. (in press), 2001.

[16] MACRO Coll., (Ambrosio, M. et al.), *Eur. Phys. J.* **C 13** (2000) 453.

[17] Alexeyev, E. N., et al.,("Baksan"), 21^{st} ICRC, Adelaide, vol. 10,83, 1990.

[18] Adarkar, H., et al., ("KGF"),21^{st} 21^{st} ICRC, Adelaide, vol. 10, 95, 1990.

[19] Thron, J. L., et al.,("Soudan"), *Phys. Rev.* **D 46** (1992) 4846.

[20] Orito, S., et al.,("Ohya"), *Phys. Rev. Lett.* **66** (1991) 1951.

[21] Balkanov, V.A. for the Baikal Coll. ("Amanda" and "Baikal"), *Nucl. Phys.* **B91** *(Proc. Suppl.)* (2001) 438.

[22] Nakamura, S., et al., ("Norikura"), *Phys. Lett.* **B 263** (1991) 529.

[23] Price, P. B.,("Mica"), *Phys. Rev.* **D 38** (1988) 3813.

[24] Ghosh, D. & Chatterjea, S.,("Mica"), *Europhys. Lett.* **12** (1990) 25.