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Search for massive rare particles with MACRO

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Abstract. Using the MACRO detector, we have searched for massive rare particles in the penetrating cosmic radiation. We present updated results on the search for magnetic monopoles and nuclearites obtained using MACRO scintillators, streamer tubes and nuclear track detectors. The most stringent limits are established in the range of velocities $v >$ few $10^{-5}c$.

1 Introduction

One of the primary aims of the MACRO experiment at the Gran Sasso underground Laboratories was the search for Magnetic Monopoles (MMs) at the mass scale of Grand Unified Theories (GUTs) of the electroweak and strong interactions (Preskill, 1979) with a sensitivity well below the Parker bound (10^{-15} cm^{-2} s^{-1} sr^{-1}) (Turner et al., 1982) in the velocity range $4 \cdot 10^{-5} < \beta < 1$, $\beta = v/c$.

MACRO had three subdetectors: liquid scintillation counters, limited streamer tubes and nuclear track detectors (CR39 and Lexan) arranged in a modular structure of six "supermodules" (SMs). Each SM was divided into a lower and an upper ("Attico") part and came with separate mechanical structure and electronics readout. The detector global dimensions were $76.6 \times 12 \times 9.3$ m^3 (MACRO Coll., 1993) with a total acceptance for an isotropic flux of particles of $\sim 10,000$ m^{2}sr. The response to slow and fast particles of the scintillators, streamer tubes and nuclear track detectors was experimentally studied (Ahlen and Tarlé, 1983; Battistoni et al., 1988, 1997; Cecchini et al., 1996). The three 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 ($g_D = 137/2e$), catalysis cross section $\sigma_{cat} < 1$ mb 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). Since no MM candidate was found we quote new flux upper limits at the level of $2 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} for $\beta > 5 \cdot 10^{-5}$.

Strange Quark Matter (SQM) should consist of aggregates of comparable amounts of u, d and s quarks; it might be the ground state of QCD (Witten, 1984). If bags of SQM were produced in a first-order phase transition in the early universe, they could contribute to the cold Dark Matter (DM), and might be found in the cosmic radiation reaching the Earth. SQM in the cosmic radiation is commonly known as "nuclearite" and "strangelet" (De Rújula and Glashow, 1984). Some of the methods used for the MM searches may also be applied to search for nuclearites; we quote nuclearite upper limits for $\beta > 5 \cdot 10^{-5}$.

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2 Searches for magnetic monopoles

The searches discussed in the following sections exploit the MM energy loss mechanisms in each of the three MACRO subdetectors.

In scintillators the fraction of energy loss which is effective for detection is the excitation energy loss which leads to the emission of light; in streamer tubes it is the ionization energy loss in the gas; in nuclear track detectors it is the Restricted Energy Loss (REL), i. e. the energy deposited within ~ 10 nm from the MM trajectory.

Independent and combined monopole analyses were performed using the scintillator, streamer tube and nuclear track subdetectors in different ranges of velocity.

2.1 Searches with scintillators

The liquid scintillator subdetector was equipped with different specialized triggers covering specific 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 ($\beta > 0.1$) MMs.

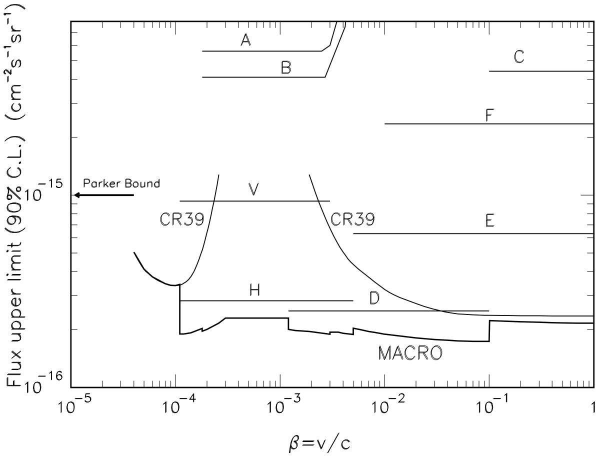

Fig. 1. The 90% C.L. upper limits for an isotropic flux of supermassive magnetic monopoles obtained using the three MACRO subdetectors. See text for explanations.

Low velocity monopole searches. Previous searches using data collected with the Slow Monopole Trigger (SMT) and Waveform Digitizer (WFD) were reported in (MACRO Coll., 1997), see curves "A", "B" in Fig. 1.

Medium and high velocity monopole searches. The data collected by the PHRASE (Pulse Height Recorder and Synchronous Encoder) trigger were used to search for MMs in the range $1.2 \cdot 10^{-3} < \beta < 10^{-1}$ (MACRO Coll., 1992, 1997). 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; 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 refers to data collected by the MACRO lower part from October 1989 to mid-June 2000 and also by the upper part (Attico) 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).

A previous search for MMs with $\beta > 10^{-1}$ based on the ERP trigger (MACRO Coll., 1997, 1992) is included in Fig. 1 (curve "C").

2.2 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. Accordingly two different analysis streams have been applied. In both cases the analysis is based on the search for single tracks and on the measurement of their velocity by using the time information provided by the streamer tubes. All MACRO streamer tubes were used for event reconstruction. Triggers and analyses were checked to be velocity independent. The global efficiency was estimated by computing the ratio of single muons reconstructed by each of the two analyses to the expected ones (MACRO Coll., 1995).

The search performed with the horizontal trigger sample uses data collected from January 1992 to September 2000, for a live time of 71193 hours. The overall efficiency is 74%. The detector acceptance, computed by a Monte Carlo simulation which included geometrical and trigger requirement, is 4250 m^{2}sr. No monopole candidates were 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 sample covers data from November 1995 to September 2000 for a total live time of 31521 hours. The efficiency is 72%. The acceptance, estimated by Monte Carlo simulation, is 3118 m^{2}sr. The resulting β distribution, shown in Fig. 2, is broader than the one obtained from the horizontal analysis. This limits the sensitivity of this search to the velocity range $1.1 \cdot 10^{-4} < \beta < 3 \cdot 10^{-3}$. No monopole candidate was found. We establish an upper limit to the monopole flux at $\Phi \leq 9.3 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} (Fig. 1, curve "V").

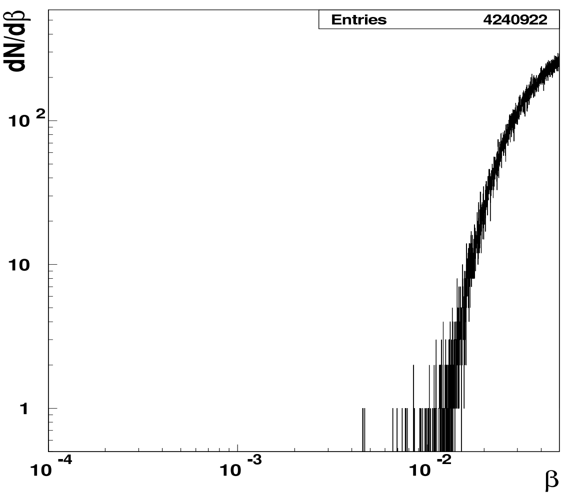

Fig. 2. The beta distribution for events reconstructed with the streamer tube vertical analysis.

2.2.1 Catalysis of nucleon decay

Detailed Monte Carlo simulations were performed to study the effects of nucleon decay catalyzed by a GUT magnetic monopole on the streamer monopole trigger and on the analysis. The presence of catalysis hits may confuse the tracking procedure, both on the space and time views. The physical process and the detector response were introduced in the code to a high degree of detail, taking into account the theoretical predictions on the cross section and on the decay channels. Two different theoretical models for the catalysis cross section were chosen, one which considers it to have the same β dependence for both protons and neutrons and a second one which assumes it to be β–enhanced in the case of protons.

Figure 3 shows the streamer tube upper limit vs β for different values of the catalysis cross section, obtained by applying the standard horizontal analysis to the simulated samples and computing the inefficiency due to this process.

A dedicated analysis is in progress searching for catalysis events in the real data.

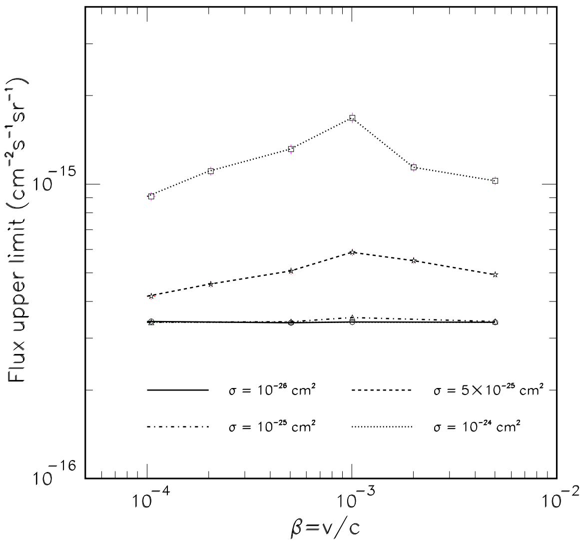

Fig. 3. Flux limits from streamer tubes for 4 values of σ_{cat}, which is assumed to be the same on protons and neutrons. The simulation was performed at fixed β; the lines are only drawn to guide the eye.

2.3 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 searching for MMs is given in (MACRO Coll., 2001). 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 analyzed, 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").

2.4 Combined searches for fast monopoles

This analysis 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 analyzed 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 relativistic 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 $\beta \simeq 0.99$. No candidate survives; the 90% C.L. flux upper limit is $6.3 \cdot 10^{-16}$ 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 reported in Fig. 1, curve "F".

3 Searches for nuclearites

Nuclearites are expected to have typical galactic velocities, $\beta \sim 10^{-3}$. At these velocities, the main energy loss mechanism for SQM passing through matter is that of atomic collisions (De Rújula and Glashow, 1984). The energy loss rate is large; therefore nuclearites should be easily detectable by detectors (like scintillators and CR39 nuclear track detectors) used for MM searches.

Scintillators are sensitive to the blackbody radiation emitted along the heated nuclearite paths down to $\beta \simeq 5 \cdot 10^{-5}$. The CR39 is sensitive to nuclearites down to $\beta \sim 10^{-5}$ (MACRO Coll., 2000). The density of the gas mixture in the streamer tubes is too low to produce energy losses yielding ionization, so the streamer tubes are not useful for nuclearite searches.

Nuclearites with $\beta \sim 10^{-3}$ and masses $\leq 5 \cdot 10^{11}$ GeV couldn't reach MACRO; for $5 \cdot 10^{12} \leq M \leq 10^{21}$ GeV only downward going nuclearites could reach it; for $M > 10^{22}$ GeV nuclearites could reach MACRO from all directions.

Individual flux limits for nuclearites from the scintillator and CR39 subdetectors are presented in Fig. 4; curves "a - d" refer to earlier searches with scintillators (MACRO Coll., 2000); curves "e" and "f" are the updated limits obtained using the PHRASE system and CR39 nuclear track detectors, respectively.

4 Conclusions

No MM and no nuclearite candidates were found in any of these searches.

The 90% C.L. flux limits for MMs versus β are shown in Fig. 1. The global MACRO limit (labeled MACRO) is computed as $2.3/X_{total}$ where $X_{total} = \sum_i X'_i$, and the X'_i are the independent time integrated acceptances of different analyses. This limit is compared in Fig. 5 with the limits of other experiments which searched for bare MMs with $g = g_D$ and $\sigma_{cat} < 1$ mb (Alexeyev et al., 1990; Adarkar et al., 1990; Thron et al., 1992; Orito et al., 1991; Baikal Coll.,

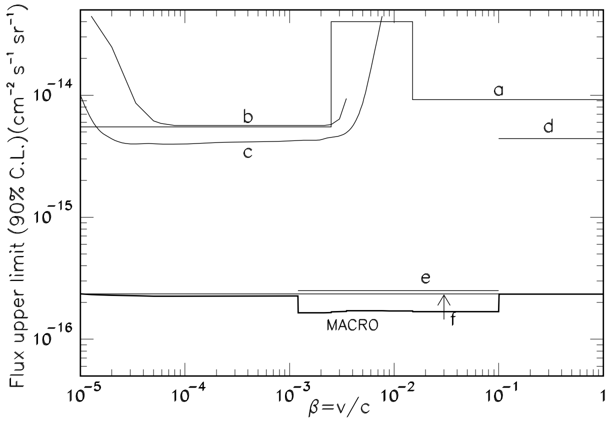

Fig. 4. The 90% C.L. upper limits for an isotropic flux of nuclearites using the liquid scintillator ("a" - "e") and the CR39 nuclear track ("f") subdetectors; the bold line is the MACRO global limit.

2000). The limits from superconducting induction devices are at the level of $2 \cdot 10^{-13}$ cm^{-2} s^{-1} sr^{-1}.

Following the same procedure used for MMs, we obtain the 90% C.L. global MACRO limit for an isotropic flux of nuclearites (with masses $> 6 \cdot 10^{22}$ GeV/c^2, Fig. 4); at $\beta = 2 \cdot 10^{-3}$ the limit is $1.8 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1}. The MACRO limit for a flux of downgoing nuclearites is compared in Fig. 6 with the limits of other experiments (Orito et al., 1991; Nakamura et al., 1991; Price, 1988; Ghosh and Chatterjea , 1990). The Galactic Dark Matter (DM) limit in Fig. 6 was estimated assuming that $\Phi_{max} = \rho_{DM} v/(2\pi M)$, where $\rho_{DM} \simeq 10^{-24}$ g/cm^3 is the local DM density, and M and v are the mass and the velocity of nuclearites, respectively.

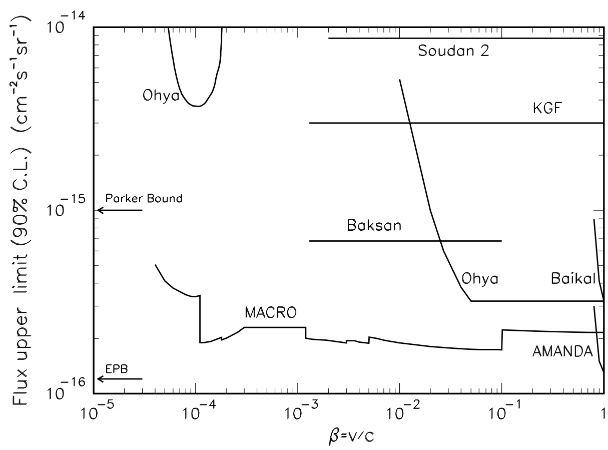

Fig. 5. The global MACRO 90% C.L. upper limit for an isotropic flux of $g = g_D$ magnetic monopoles compared with the limits obtained by other experiments.

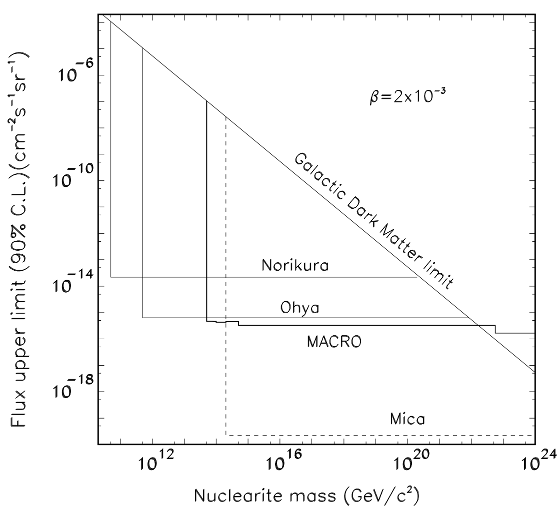

Fig. 6. The global MACRO 90% C.L. flux upper limit for nuclearites with $\beta = 2 \cdot 10^{-3}$ at ground level, versus nuclearite mass, is compared with the limit obtained by other experiments and with the galactic DM bound. The limit above $M_N > 6 \cdot 10^{22}$ GeV corresponds to an isotropic flux; for $M_N < 6 \cdot 10^{22}$ GeV the limit corresponds to nuclearites reaching the detectors only from above.

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