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Search for massive rare particles with MACRO

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We present the latest results obtained by the MACRO experiment in the search for massive rare particles. The data coming from the streamer tubes, scintillators and nuclear track subdetectors were used to search for GUT magnetic monopoles, with several dedicated hardware systems. This ensured both redundancy and complementarity. The MACRO unique features made possible to reach, for the first time, a sensitivity to fluxes well below the Parker bound in the whole velocity range in which GUT monopoles are expected. The results were also applied to the search for nuclearites in the cosmic radiation.

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 ($M \sim 10^{17}$ 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 $76.5 \times 12 \times 9.3\,\mathrm{m}^3$ 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 [4–7]. 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 can also be applied to search for nuclearites [8,9]. We quote upper flux limits for $\beta > 5 \cdot 10^{-5}$.

2. Monopole searches with scintillators

Low velocity ($10^{-4} < \beta < 10^{-3}$). A search which uses the data coming from a system of 200 MHz waveform digitizers is now in progress. Previous searches using data collected with a different system were reported in [10].

Medium ($10^{-3} < \beta < 10^{-1}$) *and high* ($\beta > 0.1$) *velocity.* The data collected by the PHRASE (Pulse Height Recorder and Synchronous Encoder) trigger are used to search for MMs in the range $1.2 \cdot 10^{-3} < \beta < 10^{-1}$ [10–12]. 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}.

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3. Monopole searches with 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 [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 [14]. 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).

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 Monte Carlo simulation, including geometrical and trigger requirement, is 4250 m^2sr. 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.

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^2sr. 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 $\Phi \leq 9.3 \cdot 10^{-16}$ $cm^{-2}s^{-1}sr^{-1}$.

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 searching for MMs is given in [15]. After detector decommissioning, up to now 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 $\beta \sim 10^{-4}$.

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 [16]. 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. Possible left 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. 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 $5 \cdot 10^{-3} < \beta < 0.99$. A search for $\beta > 10^{-2}$ MMs, was also performed by combining the streamer tube and PHRASE triggers.

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, with the scintillator and nuclear track subdetector, while the density of the gas mixture in the streamer tubes is too low to produce a detectable signal [17].

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} [18].

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 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.1 with the limits obtained by other experiments which searched for bare MMs with $g = g_D$ and $\sigma_{cat} < 1$ mb [19–23]. 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.

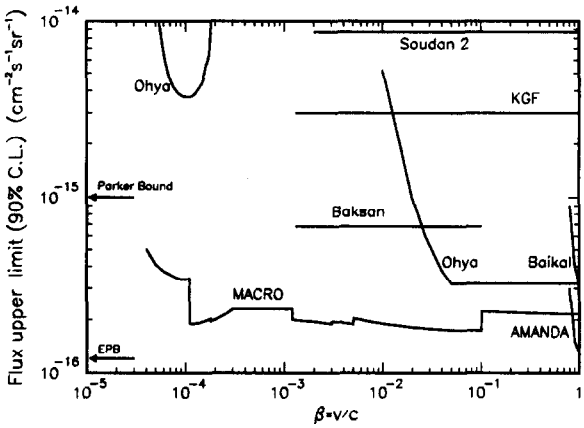

Figure 1. The global MACRO 90% C.L. upper limit for an isotropic flux of $g = g_D$ magnetic monopoles compared with the limits obtained by other experiments.

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