Search for Rare Particles with the MACRO Detector

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We present the results of the search for rare particles (magnetic monopoles, nuclearites, WIMPs and LIPs) with the MACRO detector. For magnetic monopoles (the main goal of the experiment) our limit is \( \sim 0.4 \) times the Parker bound for \( 10^{-4} \leq \beta \leq 10^{-1} \).

1 Introduction

MACRO\(^\text{a}\) at the Gran Sasso Laboratory is a large area underground detector devoted to the search for rare events in the cosmic radiation. It is optimized to search for GUT magnetic monopoles (MM), but can also perform many observations relevant to astrophysics, nuclear, particle and cosmic ray physics. The main MACRO physics items are the study of atmospheric neutrinos and oscillations, the search for MMs, the study of the high energy underground muons, the primary cosmic ray composition, the measurement of the muon residual energy spectrum, the search for low energy stellar collapse neutrinos and the high energy neutrino astronomy.

Here we present the results of the search for rare particles: magnetic monopoles and nuclearites, weakly interacting massive particles and lightly ionizing particles. All these searches gave (until now) null results, setting significant limits on the fluxes of these rare particles.

2 The MACRO detector

The MACRO detector consists of six supermodules (total sizes \( 77 \times 12 \times 9 \text{ m}^3 \)), each one divided in a lower and an upper part. The lower part is made by ten horizontal planes of limited streamer tubes, interleaved with seven rock absorber layers, and two liquid scintillation counter planes of limited streamer tubes, interleaved with seven rock absorber layers, and two liquid scintillation counter planes of limited streamer tubes.

The lateral walls are closed by four “vertical detectors”, formed by a liquid scintillator layer sandwiched between two sets of streamer tubes (three planes each). The upper part is made by two “vertical detectors” on the East and West faces and by a roof with one layer of scintillators sandwiched between two planes of tubes; this part is left open on the North and South faces to house the electronics. A nuclear track detector\(^\text{b}\) is located horizontally in the middle of the lower part and vertically on the East and North walls.

The scintillation counters are equipped with specific triggers for rare particles, muons and stellar gravitational collapse neutrinos and by 200 MHz WFDs. The streamer tubes are read by 8-channel cards which discriminate the signals and send the analog information (time development and total charge) to an ADC/TDC system; the discriminated signals form two different chains of TTL pulses, which are the inputs for the streamer tube Fast and Slow Particle Triggers.

3 Magnetic Monopoles

Massive \( (M_M \sim 10^{17} \text{ GeV}/c^2) \) magnetic monopoles arise spontaneously in Grand Unified Theories (GUTs)\(^\text{c}\) of electroweak and strong interactions. Magnetic monopoles of such a large mass cannot be produced with accelerators and must be searched in the cosmic radiation. The MACRO experiment was designed to be sensitive to monopoles at a flux level well below the Parker Bound \( \Phi_M \lesssim 10^{-15} \text{ cm}^{-2} \text{s}^{-1} \text{ sr}^{-1} \) in the monopole velocity range \( 4 \times 10^{-5} < \beta < 1 \). The use of three subdetectors (liquid scintillators, streamer tubes and nuclear track detector) ensure redundancy of information, multiple cross-checks and independent signatures for possible monopole candidates. The results reported here are obtained using the various subdetectors in a stand-alone and in a combined way. All the limits refer to monopoles with unit Dirac magnetic charge \( (g = 137/2 \ e) \), catalysis cross section \( \sigma < 10 \text{ mb} \) (we do not consider the monopole induced nucleon decay) and isotropic flux (we consider monopoles with enough kinetic energy to traverse the Earth); the last condition sets a \( \beta \)-dependent mass threshold of \( \sim 10^{17} \text{ GeV} \) for \( \beta \sim 5 \times 10^{-5} \) and lower (down to \( 10^{10} \text{ GeV} \)) for faster monopoles.

3.1 Searches with the scintillator subdetector

The energy loss, arrival time and velocity of a particle passing in the scintillator system are measured by using the total charge and shape of the photomultiplier pulses.

In the low velocity region \( (1.8 \times 10^{-4} < \beta < 3 \times 10^{-3}) \) we studied the photomultiplier waveform, looking for the wide, flat and small amplitude signals (or long trains of single photoelectrons) expected for a monopole. No candidates were found in two independent analy-
ses, the flux upper limits (90 \% C.L.) are 5.6 and 4.1 \times 10^{-15} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} (curves “A” and “B” in fig. \textbf{1}).

In the medium velocity range (1.2 \times 10^{-3} < \beta < 10^{-1}) the monopoles are searched using the data collected between October 1989 and March 1998 by the stellar gravitational collapse trigger PHRASE. The events selected in this \beta range are rejected since their pulse width is smaller than the expected counter crossing time or since the light produced is lower than that expected for a monopole. The flux upper limit at 90 \% C.L. is 4.3 \times 10^{-16} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} (curve “D” in fig. \textbf{1}).

The technique is fully discussed in \textbf{14}.

Finally, in the high velocity range (\beta > 0.1) the data collected by the muon trigger ERP are used. All events are rejected since the measured energy deposit in two counter layers is much lower than the energy loss expected for a fast monopole. The 90 \% C.L. flux upper limit is 4.4 \times 10^{-15} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} (curve “C” in fig. \textbf{1}).

3.2 Search with the streamer tubes subdetector

The MACRO streamer tubes are filled with a mixture of He (73 \%) and n-pentane (27 \%); the Helium was chosen to allow the detection of slow (\beta \lesssim 10^{-3}) monopoles by the Drell-Penning effect. The hits on the streamer tubes system and the charge collected on each tube provide measurements of track, velocity and energy loss of an ionizing particle. The data were collected from February 1992 to October 1997. The monopole analysis is based on the search for clean single tracks of well reconstructed velocity; it was checked that the trigger selection and analysis procedure are velocity independent. No candidates survived; the flux upper limit (90 \% C.L.) is $\Phi < 4.5 \times 10^{-16} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ for $1.1 \times 10^{-4} < \beta < 5 \times 10^{-3}$ (curve “Streamer” in fig. \textbf{1}).

3.3 Search with the nuclear track subdetector

The MACRO nuclear track subdetector is made by three layers of LEXAN and three layers of CR39; its total surface is 1263 m$^2$ and its acceptance for fast monopoles is $\approx 7100$ m$^2$ sr. A calibration of the CR39 with slow and fast ions showed that its response depends on the restricted energy loss only. The track-etch subdetector is used in a stand-alone or in a “triggered” mode by the streamer tubes and the scintillator systems. A total surface of 181 m$^2$ was etched, with an average exposure time of 7.23 years; the flux upper limits (90 \% C.L.) are $\sim 0.88$ and $\sim 1.3 \times 10^{-15} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ at $\beta \sim 1$ and $\beta \sim 10^{-4}$ respectively (curves “CR39” in fig. \textbf{1}).

3.4 Combined search

The fast monopoles are expected to release a huge amount of energy by ionization/excitation without producing showers for $\beta < 0.99$. A monopole search based on the energy deposition only can be seriously affected by a large background due to showering cosmic rays, but such a background is efficiently rejected by a combined analysis. This analysis uses at the same time the data collected by the scintillators and by the streamer tubes, requiring large photomultiplier pulses, an isolated single track and a high streamer charge per unit path length. Only few ($\sim 5$/year) events survive and are looked for in the appropriate track-etch sheets. In 667 days of live time no candidates were found; the 90 \% C.L. flux upper limit is $1.5 \times 10^{-15} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ for $5 \times 10^{-3} < \beta < 0.99$ (curve “E” in fig. \textbf{1}).

3.5 Conclusions about magnetic monopoles

We show in fig. \textbf{1} the flux upper limits obtained using the various MACRO subdetectors. Since each subdetector can rule out, within its acceptance and sensitivity, a potential candidate from the others, we obtain a global MACRO limit (curve “GLOBAL” in fig. \textbf{1}), as an “OR” combination of the separate results. The prescriptions used for this combination are described in \textbf{1}.

In fig. \textbf{1} we compare the MACRO combined result with that obtained by other experiments and with the Parker Bound. Our limit is at the level of 0.3 times the Parker Bound for $\beta > 10^{-4}$ and is the best existing for $10^{-4} < \beta < 5 \times 10^{-2}$.

4 Nuclearites

The results obtained using the liquid scintillator and the nuclear track subdetectors can be, at least in part, extrapolated to the search for nuclearites, hypothesized...
nuggets of strange quark matter (the streamer tubes are not sensitive to nuclearites because of the low density of the filling gas\(^2\)). By studying the mechanism of nuclearite energy loss\(^2\) it was shown that the scintillators are sensitive to nuclearites\(^2\) down to \(\beta < \sim 10^{-4}\) and the CR39\(^2\) down to \(\beta \approx 10^{-5}\). The MACRO flux upper limits are \(\sim 4 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) for \(M_N > 0.1\) g and about 2 times higher for \(M_N < 0.1\) g (the lighter nuclearites cannot traverse the Earth and then only the down-going flux must be considered). Assuming a nuclearite velocity at the ground level \(\beta = 2 \times 10^{-3}\) we compared our limit with the results of other experiments\(^{19,24,25}\) and with the dark matter bound; our results look competitive in a large range of nuclearite masses \((10^{14} \text{ GeV}/c^2 < M_N < 10^{22} \text{ GeV}/c^2)\) (see fig. 3b). For further details on this search see\(^2\).

5 WIMPs

The Weakly Interacting Massive Particles (WIMPs) are important candidates for the Cold non-baryonic part of the Dark Matter in the Universe\(^2\). Between the various Cold Dark Matter candidates subject to weak interactions one of the most promising is the supersymmetric neutralino \(\tilde{\chi}\)\(^{29}\).

In supersymmetric theories where the \(R\) parity is conserved there exists a lightest stable supersymmetric particle (LSP), which is the natural candidate for the Dark Matter since its expected density is close to the critical one: \(\Omega_{\text{LSP}} \sim 1\). In many theories the LSP is the neutralino \(\tilde{\chi}\), the simplest linear combination of the gaugino and higgsino eigenstates. The \(\tilde{\chi}\) mass depends on the supersymmetric parameters, as, for instance, the gaugino and higgsino mass parameters \(M_1, M_2\) and \(\mu\) and the ratio of the Higgs doublet vacuum expectation values \(\tan \beta\). These parameters are constrained by accelerator searches and a lower limit on \(m_{\tilde{\chi}}\) was set by LEP\(^2\) data: \(m_{\tilde{\chi}} > 20 \div 30 \text{ GeV}\)\(^\text{30}\). The search for WIMPs in underground detectors can probe complementary regions of the parameter space.

5.1 WIMP searches in MACRO

The WIMPs are indirectly searched in MACRO by using upward going muons. A WIMP intercepting a celestial body can lose its energy and be trapped in the core of this body and annihilate with an other WIMP; the decay of the annihilation products produces high-energy \(\nu\)'s which can be detected in an underground detector as upward going muons. Then, a statistically significant excess of upward going muons from the direction of a celestial body can be a hint for a WIMP-WIMP annihilation in the core of that body. Some possible traps were proposed and some calculations of the WIMP annihilation rate in the Earth and Sun and of the corresponding upward going muon fluxes were performed\(^{29,31,32}\). This indirect search achieves a better signal to noise ratio for high WIMP masses, since the higher the WIMP mass,

Figure 2: Magnetic monopole flux upper limits obtained by MACRO and by other experiments.

Figure 3: Nuclearite flux upper limits obtained by MACRO and by other experiments; the dark matter bound is also shown.
the more the upgoing muon follows the parent neutrino direction. The technique was already used by other experiments.\cite{31,32}

The upward going muons in MACRO are selected by the time-of-flight technique, requiring a track in the streamer tubes and a time of flight between the scintillation counter layers consistent with a $\beta \sim 1$ particle from below. Details on the selection criteria can be found in [33].

5.2 Search for WIMP annihilation in the Earth

Upward going muons from WIMP annihilation in the Earth core are searched in angular cones ($3 \div 30^\circ$ wide) around the vertical. We used 517 events, collected in 3.1 years of live time, requiring a minimum crossing of 200 g cm$^{-2}$ of rock absorber. After background subtraction the number of selected events is $487 \pm 22_{\text{stat}}$, to be compared with $653 \pm 111_{\text{theor}}$ expected from a Monte Carlo calculation. Most of the deficit lies around the vertical, where the WIMP annihilation signal is expected, but also where the efficiency and acceptance of the apparatus are best known. To set a conservative limit on the WIMP flux we assumed that the number of measured and expected events are equal and normalized the expected distribution to the factor 0.85, corresponding to the ratio between measured and expected events for $\theta > 30^\circ$. With this prescription our limits on the WIMP flux from the Earth range from 0.4 to $2.3 \times 10^{-14}$ cm$^{-2}$ s$^{-1}$ for angular windows from 3 to $30^\circ$.

5.3 Search for WIMP annihilation in the Sun

In the search for WIMPs from the Sun, since the background for moving sources is lower than for steady sources, we used an enlarged sample (762 events) which includes also muons partially contained in the apparatus (produced by neutrino interactions in the absorber in the MACRO lower part) and muons crossing $< 200$ g cm$^{-2}$ of rock absorber. The simulation was obtained by the data themselves to include properly the effects of the partially contained events and the arrival times were extracted randomly during the whole measurement time to take into account possible drifts of detection efficiency. The angular distribution of the upward going muon events do not show any significant excess around the Sun direction. Then, we set upper limits on the WIMP flux from the Sun ranging from $1.7 \div 6.0 \times 10^{-14}$ cm$^{-2}$ s$^{-1}$ in the angular window $3 \div 30^\circ$.

5.4 Limits on the WIMP fluxes and $\tilde{\chi}$ mass from the angular distributions

As already stated, the angle between the upward going muon and the neutrino from the WIMP annihilation depends mainly on the WIMP mass. We performed a full Monte Carlo calculation of the expected angle between the upward going muon and the Earth or Sun directions for neutralino masses from 60 GeV to 1000 GeV. This calculation uses the shape of the upward going muon signals from $\chi \chi$ annihilation in the Earth and the Sun computed in \cite{34}, propagates the muons through the rock to the apparatus (with the cross sections given in \cite{35}) and includes the angular smearing produced by the experimental resolution. As expected, the angle becomes narrower when $m_{\tilde{\chi}}$ increases, but also in the less favourable case more than 90% of the signal is contained in an angular cone $\theta < 15^\circ$ around the selected direction. For each $m_{\tilde{\chi}}$ we determine the cone which collects the 90% of the expected signal and define a corresponding 90% C.L. limit on the upward going muon flux from $\chi \chi$ annihilation. These limits for the Sun are shown in fig. 4 and compared with the fluxes computed in \cite{36}, varying some supersymmetric parameters ($M_1, \mu, \tan\beta$ etc.).

![Figure 4: Upward going muon flux from the Sun vs $m_{\tilde{\chi}}$ computed in $^{31}$. The solid line is the 90% C.L. MACRO flux limit.](image)

Fig. 4 shows that, thanks to the improved statistics and exposure, our data start to constrain the supersymmetric theoretical models.\cite{37}

6 LIPs

Fractionally charged particles have been actively searched for since many years, but without success; the detection of such particles would be a proof of their existence and/or of a lack of the confinement hypothesis under some circumstances. The family of the possible fractionally charged particles includes the quarks (with charge $|e|/3$ and $2/3$ $|e|$) and a variety of other particles predicted by Grand Unified Theories, with charges rang-
ing from $1/5 \, |e|$ up to $2/3 \, |e|$. Particles with fractional charge deposit less energy than particle with unit charge since the energy loss is proportional to the square of the charge; such particles are called Lightly Ionizing Particles (LIPs).

A specialized trigger was developed in MACRO for the LIP search; this trigger uses the low energy events collected by the PHRASE system and performs a four-fold coincidence between the signals coming from three counters (each one in a different scintillator layer) and from the streamer tubes. The LIP trigger is sensitive down to $|Q/e| = 1/5$; the corresponding energy loss in the MACRO counters is $\Delta E \approx 1.6 \, \text{MeV}$. The LIP trigger gives the stop to the WFD system; the WFD data provide high quality measurements of the energy and timing of the events. For each LIP event, the maximum energy loss in the three scintillator layers is computed and compared with that expected for a fractionally charged particle. The efficiency as a function of the charge is obtained by a Monte Carlo simulation which takes into account the trigger behaviour close to the threshold and the cosmic muon background. No candidate survived out of 1.2 million triggers; the 90% C. L. upper limit for an isotropic flux is $\Phi \leq 9.2 \times 10^{-15} \, \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. This limit is shown in fig. 5 (solid line) and compared with that set by other collaborations in Kamiokande. This search is discussed in detail in.

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