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Magnetic Monopole Searches

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Abstract

In this lecture notes will be discussed the status of the searches (i) for classical Dirac Magnetic Monopoles (MMs) at accelerators, (ii) for GUT superheavy MMs in the penetrating cosmic radiation and (iii) for Intermediate Mass MMs in the cosmic radiation underground, underwater and at high altitude. An outlook and a discussion on future searches follows.

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1 Introduction

In 1931 Dirac introduced the magnetic monopole in order to explain the quantization of the electric charge, which follows from the existence of at least one free magnetic charge [1]. He established the basic relationship between the elementary electric charge e and the basic magnetic charge g

$$eg = n\hbar c/2 \tag{1}$$

where n is an integer, $n = 1, 2, ...$ The magnetic charge is $g = ng_D$; $g_D = \hbar c/2e = 68.5e$ is called the unit Dirac charge. The existence of magnetic charges and of magnetic currents would symmetrize in form the Maxwell's equations, but the symmetry would not be perfect since $e \neq g$. But the couplings could perhaps be energy dependent and they could merge in a single common value at very high energies [2].

There was no prediction for the MM mass; from 1931 searches for "classical Dirac monopoles" were carried out at every new accelerator using mainly relatively simple set-ups, and recently also large collider detectors [3-9]. Searches at the Fermilab collider seem to exclude MMs with masses up to 850 GeV. Experiments at the LEP2 collider exclude masses below 102 GeV [8].

Electric charge is naturally quantized in GUT gauge theories of the basic interactions; such theories imply the existence of MMs, with calculable properties. The MMs appear in the Early Universe at the phase transition corresponding to the spontaneous breaking of the unified group into subgroups, one of which is U(1) [10]. The MM mass is related to the mass of the carriers X, Y of the unified interaction, $m_M \geq m_X/G$, where G is the dimensionless unified coupling constant at energies E $\simeq m_X$. In GUTs with $m_X \simeq 10^{14} - 10^{15}$ GeV and $G \simeq 0.025$, $m_M > 10^{16} - 10^{17}$ GeV. This is an enormous mass: MMs cannot be produced at any man–made accelerator, existing or conceivable. They could only be produced in the first instants of our Universe and can be searched for in the penetrating Cosmic Radiation (CR).

Larger MM masses are expected if gravity is brought into the unification picture, and in some SuperSymmetric models.

Intermediate mass monopoles (IMMs) may have been produced in later phase transitions in the Early Universe, in which a semisimple gauge group yields a U(1) group [11]. IMMs with masses $10^5 \div 10^{12}$ GeV may be accelerated to relativistic velocities in the galactic magnetic field, and in several astrophysical sites. It has been speculated that very energetic IMMs could yield the highest energy cosmic rays [12].

The lowest mass MM should be stable, since magnetic charge is conserved like electric charge. Therefore, the MMs produced in the Early Universe should still exist as cosmic relics, whose kinetic energy has been affected first by the expansion of the Universe and then by their travel through galactic and intergalactic magnetic fields.

GUT poles in the CR should have low velocities and relatively large energy losses; they are best searched for underground in the penetrating cosmic radiation. IMMs could be relativistic and may be searched for at high altitude laboratories, in the downgoing CR and, if very energetic, also in the upgoing CR.

In this lecture we shall review the present experimental situation on MM searches with emphasis on classical Dirac monopoles and on Intermediate Mass MMs. Recently there has

been renewed interest in the search for relatively low–mass Dirac MMs. In fact there seem to be no a priori reasons that Dirac MMs (or dyons) might not exist [9].

2 Main properties of magnetic monopoles

The main properties of MMs are obtained from the Dirac relation (1), and are summarized here. We recall that the Dirac relation may be easily obtained semiclassically by considering the system of one monopole and one electron, and quantizing the radial component of the total angular momentum.
- *Magnetic charge.* If n =1 and if the basic electric charge is that of the electron, then the basic magnetic charge is $g_D = \hbar c/2e = 137e/2 = 3.29 \times 10^{-8}\ cgs = \ 68.5e$. The magnetic charge should be larger if $n > 1$ and also if the basic electric charge is $e/3$.
- *Coupling constant.* In analogy with the fine structure constant, $\alpha = e^2/\hbar c \simeq 1/137$, the dimensionless magnetic coupling constant is $\alpha_g = g_D^2/\hbar c \simeq 34.25$; notice that it is very large, much larger than 1, and thus perturbative methods cannot be used.
- *Energy W acquired in a magnetic field B*: $W = ng_D B\ell = n$ 20.5 keV/G cm. In a coherent galactic–length ($\ell \simeq 1$ kpc, and $B \simeq 3\ \mu$G), the energy gained by a monopole is $W \simeq 1.8 \times 10^{11}$ GeV. Classical poles and IMMs in the cosmic radiation could be accelerated to relativistic velocities. Instead GUT poles have large masses and are expected to have relatively low velocities, $10^{-4} < \beta < 10^{-1}$.
- *Trapping of MMs in ferromagnetic materials.* MMs may be trapped in ferromagnetic materials by an image force, which could reach the value of $\simeq 10$ eV/Å.
- Electrically charged monopoles (dyons) may arise as quantum–mechanical excitations or as M–p, M-nucleus composites.
- There is no real prediction of the mass of classical Dirac MMs. One may have a rough estimate assuming that the classical monopole radius is equal to the classical electron radius: $r_M = \frac{g^2}{m_M c^2} = r_e = \frac{e^2}{m_e c^2}$, from which $m_M = \frac{g^2 m_e}{e^2} \simeq n\ 4700\ m_e \simeq n\ 2.4\ GeV/c^2$. Thus the mass should be relatively large and even larger if the basic charge is $e/3$ and if $n > 1$.

Also the interactions of MMs with matter are connected with the electromagnetic properties of MMs and thus are consequences of the Dirac relation. It is also important to know whether the quantity and quality of energy lost by a MM in a particle detector is adequate for its detection. The interaction of the MM magnetic charge with nuclear magnetic dipoles could lead to the formation of M–nucleus bound systems. This may affect the energy loss in matter and the cross–section for MM catalysis of proton decay. A monopole–proton bound state may be produced via radiative capture, $M + p \rightarrow (M + p)_{bound} + \gamma$. Monopole–nucleus bound states may exist for nuclei with a large gyromagnetic ratio.
- *Energy losses of fast poles.* A fast MM with magnetic charge g_D and velocity $v = \beta c$ behaves like an equivalent electric charge $(ze)_{eq} = g_D\beta$; the energy losses of fast monopoles are thus very large.
- *Energy losses of slow monopoles* ($10^{-4} < \beta < 10^{-2}$). For slow particles it is important to distinguish the energy lost in ionization or excitation of atoms and molecules of the medium ("electronic" energy loss) from that lost to yield kinetic energy to recoiling atoms or nuclei ("atomic" or "nuclear" energy loss). Electronic energy loss predominates for electrically or magnetically charged particles with $\beta > 10^{-3}$. The dE/dx of MMs with $10^{-4} < \beta < 10^{-3}$ is

mainly due to excitations of atoms. In an ionization detector using noble gases there would be, for $10^{-4} < \beta < 10^{-3}$, an additional energy loss due to atomic energy level mixing (Drell effect, see Section 3).
- *Energy losses at very low velocities.* MMs with $v < 10^{-4}c$ cannot excite atoms; they can only lose energy in elastic collisions with atoms or with nuclei. The energy is released to the medium in the form of elastic vibrations and/or infra–red radiation [13].

Fig. 1 shows a sketch of the energy losses in liquid hydrogen of a $g = g_D$ MM vs its β [4].

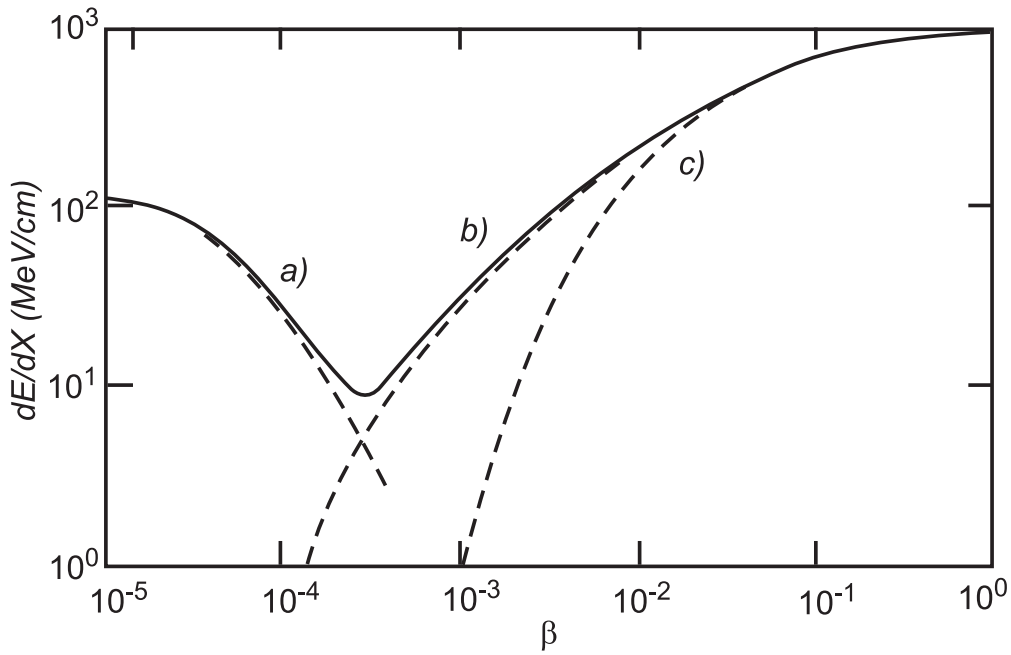

Figure 1: The energy losses, in MeV/cm, of $g = g_D$ MMs in liquid hydrogen as a function of β. Curve a) corresponds to elastic monopole–hydrogen atom scattering; curve b) corresponds to interactions with level crossings; curve c) describes the ionization energy loss.

- *Energy losses in superconductors.* If a pole passes through a superconducting ring, there will be a magnetic flux change of $\phi_B = 2\pi\hbar c/e$, yielding $dE/dx \simeq 42$ MeV/cm, $\beta-$independent (see Section 3).
- *Energy losses of MMs in celestial bodies.* For $\beta < 10^{-4}$ the main energy losses in the Earth are due to : i) pole–atom elastic scattering, ii) eddy current losses, iii) nuclear stopping power. Poles may be stopped by celestial bodies if they have
Moon: $\beta \leq 5 \times 10^{-5}$, Earth: $\beta \leq 10^{-4}$, Jupiter: $\beta \leq 3 \times 10^{-4}$, Sun: $\beta \leq 10^{-3}$.

3 Monopole detectors

Monopole detectors are based on the properties of MMs determined from Dirac's relation.
- *Superconducting induction devices.* This method of detection is based only on the long–range electromagnetic interaction between the magnetic charge and the macroscopic quantum state of a superconducting ring. A moving MM induces in the ring an electromotive force

and a current (Δi). For a coil with N turns and inductance L, $\Delta i = 4\pi N n g_D/L = 2\Delta i_o$, where Δi_o is the current change corresponding to a change of one unit of the flux quantum of superconductivity. A superconducting induction detector, consisting of a detection coil coupled to a SQUID (Superconducting Quantum Interferometer Device), should be sensitive to MMs of any velocity [3].
- *Scintillation counters.* Many searches have been performed using excitation loss techniques. The light yield from a MM traversing a scintillator has a threshold at $\beta \sim 10^{-4}$, above which the light signal is large compared to that of a minimum ionizing particle. For $10^{-3} < \beta < 10^{-1}$ there is a saturation effect. For $\beta > 0.1$ the light yield increases because of the production of many delta rays [14, 15].
- *Gaseous detectors.* Gaseous detectors of various types have been used. MACRO used limited streamer tubes equipped with readouts for the wires and pickup strips, for two–dimensional localization [16]. The gas was 73% helium and 27% n–pentane. This allows exploitation of the Drell [17] and Penning effects: a magnetic monopole leaves the helium atoms in a metastable excited state (He*) with an excited energy of $\simeq 20$ eV. The ionization potential of n–pentane is about 10 eV; the Penning effect converts the excited energy of the He* into ionization of the n–pentane molecule [3, 18].
- *Nuclear track detectors.* Nuclear track detectors (NTD) can record the passage of heavily ionizing particles like magnetic monopoles [19]. The formation of an etchable track in a nuclear track detector is related to the Restricted Energy Loss (REL), which is the fraction of the total energy loss which remains localized in a cylindrical region with about 10 nm diameter around the particle trajectory. Both the electronic and the nuclear energy losses contribute to REL. In Ref. [20] it was shown that both are effective in producing etchable tracks in the CR39 nuclear track detector. The CR39 has a threshold at $z/\beta \simeq 5$; it is the most sensitive NTD and it allows to search for magnetic monopoles with one unit Dirac charge (g=g_D) for β around 10^{-4} and for $\beta > 10^{-3}$, the whole β-range of $4 \times 10^{-5} < \beta < 1$ for MMs with $g \geq 2g_D$ [14]. The Lexan and Makrofol polycarbonates have a threshold at $z/\beta \sim 50$; thus they are sensitive only to relativistic MMs.

4 Searches for "classical Dirac monopoles"

We shall consider "classical" Dirac monopoles those MMs which have relatively low masses and could possibly be produced at accelerators.
- *Accelerator searches.* If MMs could be produced at high–energy accelerators, they would be relativistic and would ionize heavily. They would thus be easily discriminated from minimum ionizing particles. Examples of direct searches are scintillation counter searches and the experiments performed with nuclear track detectors for which data taking is integrated over periods of months. Experiments at the Fermilab $\overline{p}p$ collider established cross section upper limits of $\sim 2 \times 10^{-34}$ cm^2 for MMs with masses up to 850 GeV [18, 21]. Searches at e^+e^- colliders excluded masses up to 45 GeV [18] and later also the 45-102 GeV mass range (the cross section upper limits are at $\sigma \sim 5 \times 10^{-37}$ cm^2) [8], Fig. 2. Recently several large purpose detectors at high energy colliders have used some of their subdetectors (mainly the tracking subdetectors) to search for classical Dirac monopoles.

Fig. 3 summarizes the direct limits as a function of the monopole magnetic charge $g = ng_D/q$ (the value of 1 corresponds to the electric charge of the electron and $n = 1$); if the

basic electric charge is that of a quark with $q = 1/3$, then the magnetic charge would be 3 times larger.

An example of an indirect search is an experiment at the CERN SPS: the 450 GeV protons interacted in targets made of ferromagnetic tungsten powder. Later on the targets were placed in front of a pulsed solenoid with a field $B \sim 200$ kG, large enough to extract and accelerate the MMs, to be detected in nuclear emulsions and in CR39 sheets [3]. A more recent indirect experiment was performed at the $\overline{p}p$ Tevatron collider at Fermilab, assuming that the produced MMs could stop, be trapped and bound in matter surrounding the D0 collision region [5]. Beryllium and Aluminium samples of the materials having dimensions of ≤ 7.5 cm diameter and 7.5 cm long, were repeatedly passed through the 10 cm diameter warm bore centered on and perpendicular to two superconducting coils. The induced charge (current) in the superconducting coil could be measured by DC SQUIDs. Monopole mass limits $m > 285$ GeV were established for $g = g_D$ poles. It is difficult to establish the validity of several hypotheses which have to be used in order to interpret these negative results.

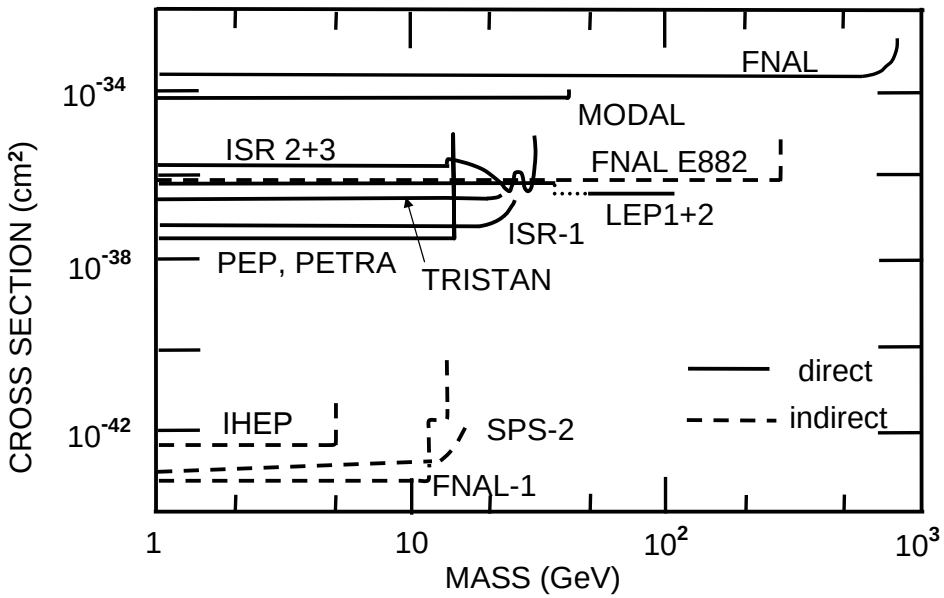

Figure 2: Cross section upper limits vs MM mass obtained from direct accelerator searches (solid lines) and indirect searches (dashed lines).

- *Multi–γ events.* Five peculiar photon shower events, found in nuclear plates exposed to high–altitude cosmic rays, were characterized by an energetic narrow cone of tens of photons, without any incident charged particle [22]. The total energy in the photons was of the order of 10^{11} GeV. The small radial spread of photons suggested a c.m. $\gamma = (1 - \beta^2)^{-1/2} > 10^3$. The energies of the photons in the overall c.m. system were small, too low to have π^o decays as their source. One possible explanation of these events could be the following: a high–energy γ–ray, with energy $> 10^{12}$ eV, produced in the plate a pole–antipole pair, which then

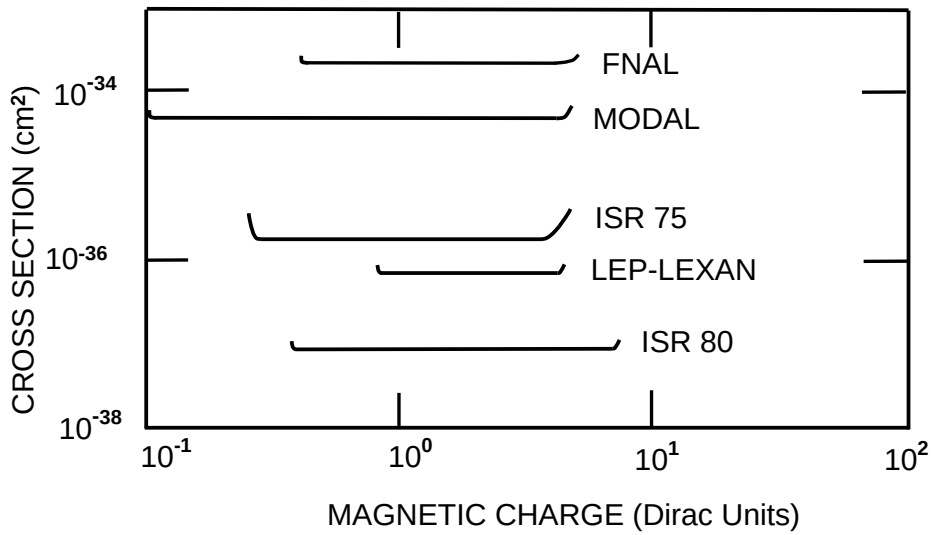

Figure 3: Upper limits (95% C.L.) for classical–monopole production for some direct experiments plotted versus magnetic charge.

suffered bremsstrahlung and annihilation producing the final multi–γ events.

Searches for multi-γ events were performed in pp collisions at the ISR at $\sqrt{s} = 53$ GeV [18], in $\overline{p}p$ collisions at the 1.8 TeV collider at Fermilab and in e^+e^- collisions at LEP. The ISR experiment placed a cross–section upper–limit of $\sim 10^{-37}$ cm^2. At Fermilab the D0 experiment searched for pairs of photons with high transverse energies; virtual heavy pointlike Dirac MMs could rescatter pairs of nearly real photons into the final state via a box monopole diagram as shown in Fig. 4. They set a 95% C.L. lower limit of 870 GeV for spin 1/2 Dirac monopoles [6]. At LEP the L3 collaboration searched for anomalous $Z \to \gamma\gamma\gamma$ events; they observed no significant deviation from QED predictions, setting a 95% C.L. lower mass limit of 510 GeV [7]. Many authors studied the effects from virtual monopole loops [2, 23]. The authors of Ref. [9] criticized the underlying theory and believe that no significant limit can be obtained from present experiments based on virtual monopole processes.

- *Searches in bulk matter.* Classical MMs could be produced by cosmic rays and could stop at the surface of the Earth, where they could be trapped in ferromagnetic materials. A search for MMs in bulk matter used a total of 331 kg of material, including meteorites, schists, ferromanganese nodules, iron ore and other materials. The detector was a superconducting induction coil with a SQUID. The material was passed at constant velocity through the magnet bore. The passage of a MM trapped in a sample would cause a jump in the current in the superconducting coil. From the absence of candidates the authors conclude that the monopole/nucleon ratio in the samples was $< 1.2 \times 10^{-29}$ at 90% C.L. [3].

The searches for classical MMs performed at accelerators are not relevant to the question of the existence of very massive poles. Ruzicka and Zrelov summarized all searches for classical monopoles performed before 1980 [24]. A more recent bibliography, until the end of 1999, is given in Ref. [25]. Possible effects arising from low mass MMs have been reported [26].

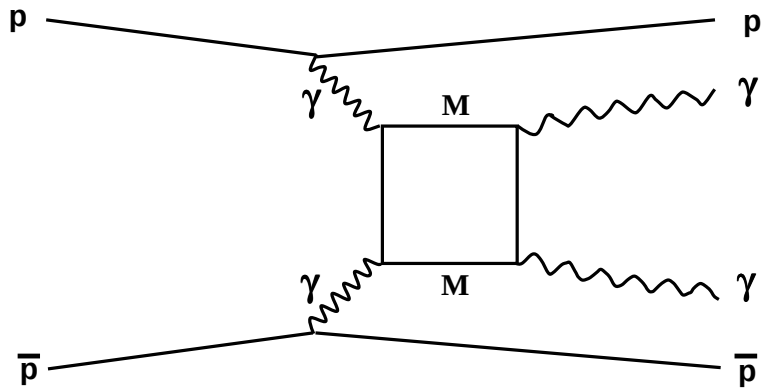

Figure 4: Feynman diagram for $\gamma\gamma$ producion via a virtual monopole loop in $p\overline{p}$ collisions at the Tevatron. The $\gamma\gamma \to \gamma\gamma$ process cross sections at energies below the magnetic monopole production threshold could be enhanced due to the strong coupling of the virtual MMs to photons [6].

5 Supermassive GUT monopoles

As already stated, GUT theories of the electroweak and strong interations predict the existence of superheavy magnetic monopoles produced in the Early Universe (EU) as topological point defects when a GUT gauge group breaks into separate groups, one of which is U(1). Assuming that the GUT group is SU(5) (in reality it is excluded by proton decay experiments) one should have the following transitions in the EU:

$$SU(5) \quad \underset{10^{-35}s}{\overset{10^{15}\ GeV}{\longrightarrow}} \quad SU(3)_C \times [SU(2)_L \times U(1)_Y] \quad \underset{10^{-9}s}{\overset{10^{2}\ GeV}{\longrightarrow}} \quad SU(3)_C \times U(1)_{EM} \tag{2}$$

MMs would be generated as topological point defects in the GUT phase transition, about one monopole for each causal domain. In the standard cosmology this leads to too many monopoles: the present monopole density would be $\rho_M \sim 5 \times 10^{-18}$ g/cm^3, while the critical density is $\rho_c \sim 8 \times 10^{-29}$ g/cm^3 (the monopole problem!). Inflation would defer the GUT phase transition, after extreme supercooling; in its simplest version the number of generated MMs would be very small. However the flux depends critically on several parameters, like m_M, the reheating temperature, etc. If the reheating temperature is large enough one would have MMs produced in high energy collisions, like $e^+e^- \to M\overline{M}$.

Fig. 5 shows the possible structure of a GUT magnetic monopole, with a very small core, an electroweak region, a confinement region, a fermion–antifermion condensate region (which may contain 4–fermion baryon–number–violating terms); for $r \geq 3$ fm a MM behaves as a point particle which generates a field $B = g/r^2$ [27].

A flux of cosmic GUT supermassive magnetic monopoles may reach the Earth and may have done so for the whole life of the Earth. The velocity spectrum of these MMs could be in the range $4 \times 10^{-5} < \beta < 0.1$, with possible peaks corresponding to the escape velocities

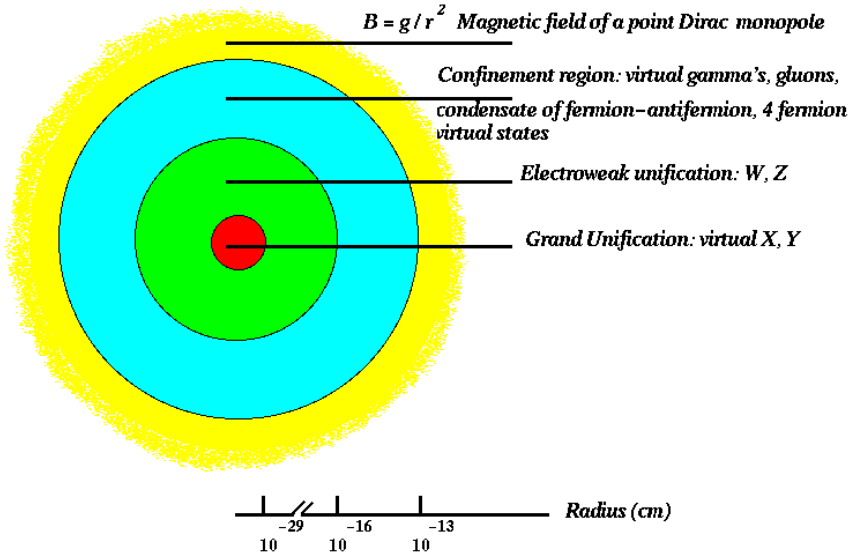

Figure 5: Figure 5: Structure of a GUT monopole. The various regions correspond to: (i) Grand Unification ($r \sim 10^{-29}$ cm; inside this core one finds virtual X and Y particles); (ii) electroweak unification ($r \sim 10^{-16}$ cm; inside one finds virtual $W^{\pm}$ and Z^0); (iii) confinement region ($r \sim 10^{-13}$ cm; inside one finds virtual γ, gluons and a condensate of fermion-antifermion pairs and possibly 4-fermion virtual states); (iv) for $r >$ few fm one has the field of a point magnetic charge.

from the Earth, the Sun and the Galaxy. Searches for such MMs in the cosmic radiation have been performed with superconducting induction devices, whose combined limit is at the level of 2×10^{-14} cm^{-2} s^{-1} sr^{-1}, independent of β [18]. Several direct searches were performed above ground and underground [18, 28-31]. The most complete search was performed by the MACRO detector, using three different types of subdetectors (liquid scintillators, limited streamer tubes and nuclear track detectors) and with an acceptance of about 10,000 m^{2}sr for an isotropic flux. No monopoles have been detected; the 90% C.L. flux limits are shown in Fig. 6 vs β for $g = g_D$ MMs [29]: the limits are at the level of 1.4×10^{-16} cm^{-2} s^{-1} sr^{-1} for $\beta > 4 \times 10^{-5}$. The figure shows also the limits from the Ohya [28], Baksan, Baikal, and AMANDA experiments [30]. Previous limits are at levels larger than 10^{-15} cm^{-2} s^{-1} sr^{-1} [29].

Fig. 7 shows the 90% C.L. flux upper limits obtained with the MACRO CR39 nuclear track detector for MMs with different magnetic charges, $g = g_D$, $2g_D$, $3g_D$ and for M + p composites [31].

The interaction of the GUT monopole core with a nucleon can lead to a reaction in which the nucleon decays (monopole catalysis of nucleon decay), f. e. $M + p \rightarrow M + e^+ + \pi^0$. The cross section for this process is of the order of magnitude of the core size, $\sigma \sim 10^{-56}$ cm^2, practically negligible. But the catalysis process could proceed via the Rubakov-Callan mechanism with a cross section of the order of the strong interaction cross section [32]. MACRO developed a dedicated analysis procedure aiming to detect nucleon decays induced by the passage of a GUT monopole in their streamer tube system. The flux upper limit

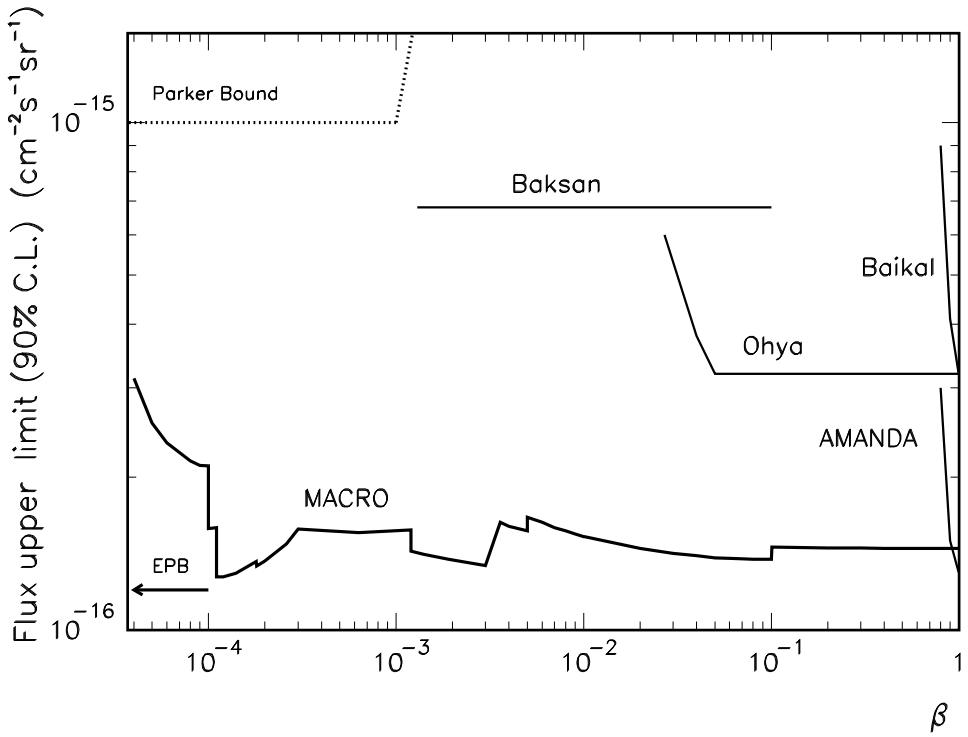

Figure 6: The 90% C.L. global MACRO direct upper limits vs β for GUT $g = g_D$ monopoles in the penetrating CR, compared with limits from other experiments [28-31].

results of this search as a function of the MM velocity and of the catalysis cross section are shown in Fig. 8 [33]. Previous limits are at levels larger than 10^{-15} cm^{-2} s^{-1} sr^{-1} [33], with the exception of the Baikal limit which is 6×10^{-17} cm^{-2} s^{-1} sr^{-1} for $\beta \simeq 10^{-5}$ [30].

Some indirect searches used ancient mica, which has a high z threshold. The mica experiment scenario assumes that a bare monopole passing through the Earth captures an aluminium nucleus and drags it through subterranean mica causing a trail of lattice defects. As long as the mica is not reheated, the damage trail will survive. The mica pieces analyzed are small (13.5 and 18 cm^2), but should have been recording tracks since they cooled, about $4 \div 9 \times 10^8$ years ago. The flux upper–limits are at the level of 10^{-17} cm^{-2} s^{-1}sr^{-1} for $10^{-4} < \beta < 10^{-3}$ [34]. There are many reasons why these indirect experiments might not be sensitive. For example, if MMs have a positive electric charge or have protons attached, then Coulomb repulsion could prevent capture of heavy nuclei.

6 Cosmological and astrophysical bounds

Rough, order of magnitude upper limits for a GUT monopole flux in the cosmic radiation were obtained on the basis of cosmological and astrophysical considerations. Here we shall quote only some of these limits.

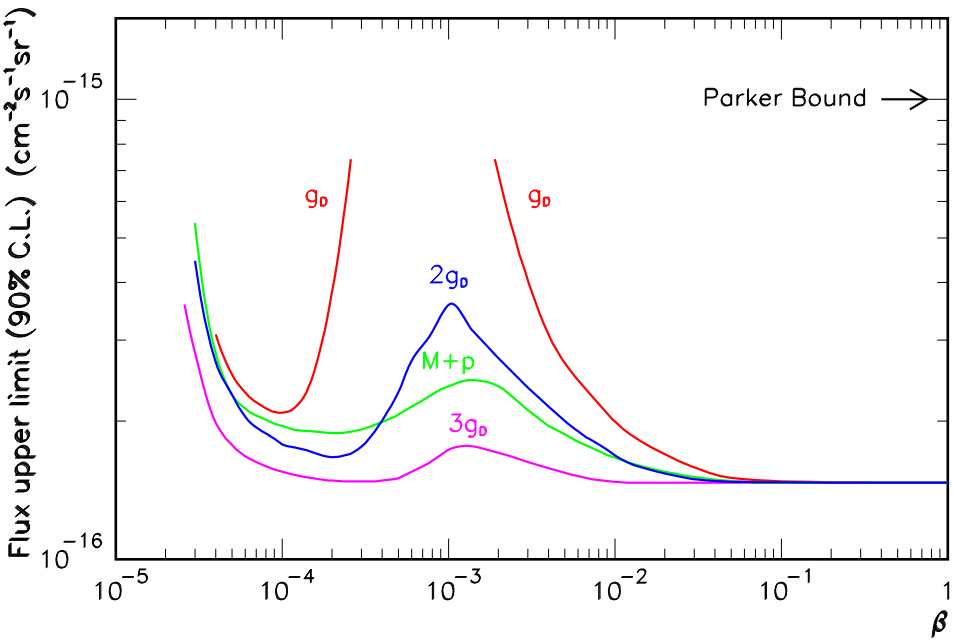

Figure 7: Upper limits (90% C.L.) for an isotropic flux of MMs in the cosmic radiation, obtained with the CR39 subdetector of MACRO, for poles with magnetic charges $g = g_D$, $2g_D$, $3g_D$ and for M+p composites.

- *Limit from the mass density of the universe.* This bound is obtained requiring that the present MM mass density be smaller than the critical density ρ_c of the universe. For $m_M \simeq 10^{17}$ GeV one has the limit: $F = \frac{n_M c}{4\pi}\beta < 3 \times 10^{-12} h_0^2 \beta$ (cm^{-2}s^{-1}sr^{-1}). It is valid for poles uniformly distributed in the universe. If poles are clustered in galaxies the limit could be much larger.
- *Limit from the galactic magnetic field. The Parker limit.* The ~ 3 μG magnetic field in our Galaxy is stretched in the direction of the spiral arms; it is probably due to the non–uniform rotation of the Galaxy. This mechanism generates a field with a time–scale approximately equal to the rotation period of the Galaxy ($\tau \sim 10^8$ yr). Since MMs are accelerated in magnetic fields, they gain energy, which is taken away from the stored magnetic energy. An upper bound for the MM flux is obtained by requiring that the kinetic energy gained per unit time by MMs be less than or equal to the magnetic energy generated by the dynamo effect. This yields the so–called Parker limit: $F < 10^{-15}$ cm^{-2} s^{-1} sr^{-1} [35]. The original limit was re–examined to take into account the almost chaotic nature of the galactic magnetic field, with domain lengths of about $\ell \sim 1$ kpc; the limit becomes mass dependent [35]. More recently an extended Parker bound was obtained by considering the survival of an early seed field [36]. The result was $F \leq 1.2 \times 10^{-16}(m_M/10^{17} GeV)$ cm^{-2} s^{-1} sr^{-1}.
- *Limit from the intergalactic magnetic field.* Assuming the existence in the local group of

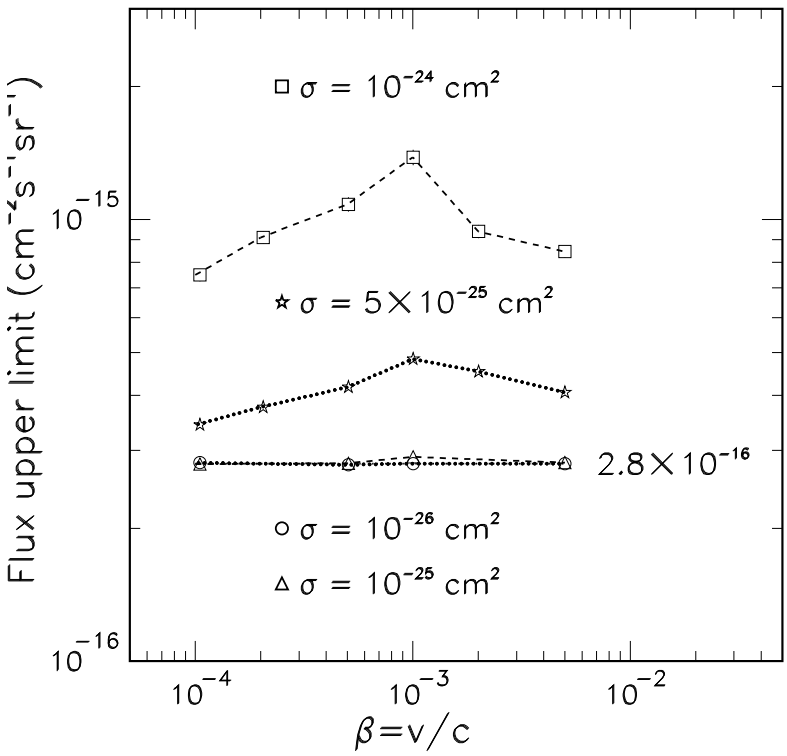

Figure 8: The MACRO 90% C.L. upper limits for a MM flux as a function of the MM velocity for various catalysis cross sections [31]. The limit from the Baikal underwater detector is $\Phi \leq 6 \times 10^{-17}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for $\beta \simeq 10^{-5}$ [30, 33].

galaxies of an intergalactic field $B_{IG} \sim 3 \times 10^{-8}$ G with a regeneration time $\tau_{IG} \sim 10^9$ y and applying the same reasoning discussed above, a more stringent bound is obtained; the limit is less reliable because the intergalactic field is less known.
- *Limits from peculiar A4 stars and from pulsars.* Peculiar A4 stars have their magnetic fields ($B \sim 10^3$ G) in the direction opposite to that expected from their rotation. A MM with $\beta \leq 10^{-3}$ would stop in A4 stars; thus the number of MMs in the star would increase with time (neglecting $M\overline{M}$ annihilations inside the star). The poles could be accelerated in the magnetic field, which would therefore decrease with increasing time. Repeating the Parker argument, one may obtain strong limits, but it is not clear how good are all the assumptions made. With similar considerations applied to the superconducting core of neutron stars, the field survival of a pulsar gives an upper limit of the monopole flux in the neighbourhood of the pulsar. The limit would be particulary stringent for pulsar PSR 1937+214 [3, 4].

7 Intermediate mass magnetic monopoles

IMMs would appear as topological point defects at a later time in the Early Universe; in this case the GUT group would not yield a U(1) group at the end of the GUT phase transition,

it would appear a later new phase transition, as for instance in the following sequence

$$SO(10) \underset{10^{-35}s}{\overset{10^{15}\ GeV}{\longrightarrow}} SU(4) \times SU(2) \times SU(2) \underset{10^{-23}s}{\overset{10^{9}\ GeV}{\longrightarrow}} SU(3) \times SU(2) \times U(1) \qquad (3)$$

which would lead to MMs with masses of the order of 10^{10} GeV; these monopoles survive inflation, are stable, "doubly charged" (n=2 in Eq.1) and do not catalyze nucleon decay [11]. The structure of an IMM would be similar to that of a GUT monopole, but the core would be much larger (since R $\sim 1/m_M$) and the outer cloud would not contain 4–fermion baryon–number–violating terms.

Relativistic magnetic monopoles with intermediate masses, $10^5 < m_M < 10^{12}$ GeV, could be present in the cosmic radiation. IMMs could be accelerated to large values of γ in one coherent domain of the galactic magnetic field. Thus one would have to look for $\beta \geq 0.1$ fast, heavily ionizing MMs.

Detectors underground, underwater and under ice would mainly have a sensitivity for poles coming from above. Detectors at the Earth surface could detect MMs coming from above if they have masses larger than $10^5 - 10^6$ GeV [13]; lower mass MMs may be searched for with detectors located at high mountain altitudes, or in balloons and in satellites.

Few experimental results are available [37]. Fig. 9 shows the present situation on flux upper limits for intermediate mass MMs. The Cherenkov neutrino telescopes under ice and underwater are sensitive to fast and very fast ($\gamma >> 1$) MMs mainly coming from above.

The SLIM experiment is searching for fast IMMs with nuclear track detectors at the Chacaltaya high altitude lab (5230 m above sea level) [38]. It is sensitive to MMs with $4 \times 10^{-5} < \beta < 3 \times 10^{-4}$ and $\beta > 2 \times 10^{-3}$ if $g = g_D$, the whole range $4 \times 10^{-5} < \beta < 1$ if $g = 2g_D$. Nuclear track detectors are sensitive to these poles and are also sensitive to slow moving nuclearites (strangelets, strange quark matter).

8 Conclusions. Outlook

Direct and indirect accelerator searches for classical Dirac monopoles have placed 95 % C.L. mass limits at the level of $m_M > 850$ GeV with cross section upper values as shown in Fig. 2. Future improvements could come from experiments at the LHC [39].

Many searches have been performed for superheavy GUT monopoles in the penetrating cosmic radiation. The 90 % C.L. flux limits are at the level of $\Phi \leq 1.4 \times 10^{-16}$ cm^{-2} s^{-1} sr^{-1} for $\beta \geq 4 \times 10^{-5}$. It would be difficult to do much better since one would require refined detectors of considerably larger areas. Or one has to devise completely new techniques.

Present limits on Intermediate Mass Monopoles with high β are relatively poor. Experiments at high altitudes and at neutrino telescopes should improve the situation. In particular stringent limits may be obtained by large neutrino telescopes for IMMs with $\beta > 0.5$ coming from above.

As a byproduct of GUT MM searches MACRO obtained stringent limits on nuclearites in the CR [31]. Future experiments at neutrino telescopes and at high altitude should perform searches for smaller mass nuclearites.

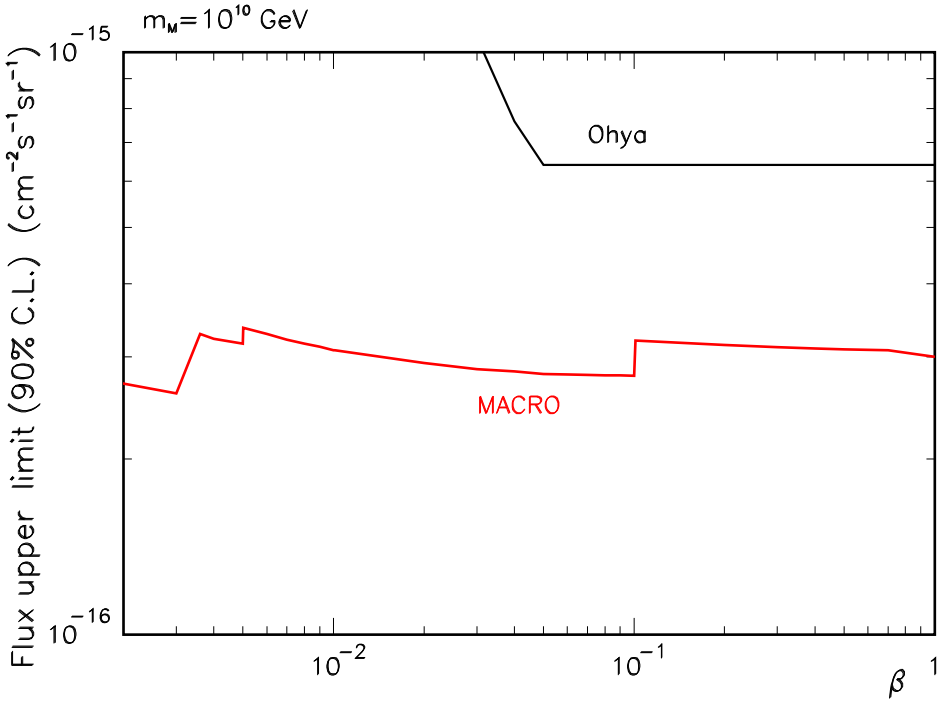

Figure 9: Experimental 90% C.L. upper limits for a flux of IMMs with mass $m_M = 10^{10}$ GeV plotted versus β.

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References

[1] P. A . M. Dirac, Proc. R. Soc. London 133 (1931) 60; Phys. Rev. 74 (1948) 817.

[2] A. De Rujula, Nucl. Phys. B435 (1995) 257.

[3] G. Giacomelli, Riv. Nuovo Cimento 7 (1984) N.12, 1.

[4] G. Giacomelli and L. Patrizii, hep-ex/011209;
G. Giacomelli and M. Sioli (Astroparticle Physics), Lectures at the 2002 Int. School of Physics, Constantine, Algeria, hep-ex/0211035.

[5] G.R. Kalbfleisch, Phys. Rev. Lett. 85 (2000) 5292; hep-ex/0005005;
K. A. Milton et al. (New limits on the production of magnetic monopoles at Fermilab), hep-ex/0009003.

[6] B. Abbott et al., hep-ex/9803023, Phys. Rev. Lett. 81 (1998) 524.

[7] M. Acciarri et al., Phys. Lett. B345 (1995) 609.

[8] Private communication by M. Cozzi.

[9] L. Gamberg et al. (Direct and indirect searches for low-mass MMs), hep-ph/9906526.

[10] G. 't Hooft, Nucl. Phys. B29 (1974) 276;
A.M. Polyakov, JETP Lett. 20 (1974) 194;
N. S. Craigie, G. Giacomelli, W. Nahm and Q. Shafi, Theory and Detection of Magnetic Monopoles in Gauge Theories, World Scientific, Singapore (1986).

[11] G. Lazarides et al., Phys. Rev. Lett. 58 (1987) 1707;
Q. Shafi (Proton decay, magnetic monopoles and extra dimensions), invited paper at the Neutrino Telescope Workshop, Venice, March 2001;
T. W. Kephart and Q. Shafi, hep-ph/0105237.

[12] P. Bhattacharjee et al., Phys. Rept. 327 (2000) 109 and refs. therein.

[13] J. Derkaoui et al., Astrop. Phys. 9 (1998) 173.

[14] J. Derkaoui et al., Astrop. Phys. 10 (1999) 339.

[15] M. Ambrosio et al., Nucl. Instr. Meth. A486 (2002) 663;
S. Ahlen et al., Phys. Rev. Lett. 72 (1994) 608;
M. Ambrosio et al., Astrop. Phys. 6 (1997) 113.

[16] M. Calicchio et al., Nucl. Tracks Radiat. Meas. 15 (1988) 331;
M. Ambrosio et al., Astrop. Phys. 4 (1995) 33;
M. Ambrosio et al., Astrop. Phys. 18 (2002) 27.

[17] G. F. Drell et al., Nucl. Phys. B209 (1982) 45.

[18] G. Giacomelli (MM searches), Lectures at the Lake Louise Workshop (1994).

[19] M. Cozzi and L. Patrizii (Nuclear track detectors. Searches for MMs and nuclearites), Proc. NATO ARW on Cosmic Radiations, Oujda (Morocco) (2001).

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

[21] M. Bertani et al., Europhys. Lett. 12 (1990) 613.

[22] M. Schein et al., Phys. Rev. 99 (1955) 643.

[23] I. F. Ginzburg and A. Schiller, Phys. Rev. D60 (1999) 075016; hep-ph/9903314.

[24] J. Ruzicka and V. P. Zrelov JINR-1-2-80-850 (1980).

[25] G. Giacomelli et al. (Magnetic Monopole Bibliography), hep-ex/0005041.

[26] V. A. Skvortsov et al. (The magnetic monopoles generation in laser–induced discharges), Proc. of the 29th EPS Conf. on Plasma Phys., ECA 26B, D–5.013 (2002).

[27] D. Bakari et al. (MMs, Nuclearites, Q-balls: a qualitative picture), hep-ex/0004019.

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

[29] M. Ambrosio et al., MACRO Coll., hep-ex/0207020, Eur. Phys. J. C25 (2002) 511; Phys. Lett. B406 (1997) 249; Phys. Rev. Lett. 72 (1994) 608.

[30] E.N. Alexeyev et al. ("Baksan"), 21st ICRC, 10(1990)83;
V.A. Balkanov et al. ("Baikal", "Amanda"), Proc. of ICRC 2001 (The lake Baikal Neutrino Experiment) (2001); Prog. Part. Nucl. Phys. 40 (1998) 391.

[31] G. Giacomelli (Search for GUT MMs with the MACRO experiment at the Gran Sasso Lab.), ICHEP 2002 Conf., Amsterdam, hep-ex/0210021.

[32] V.A. Rubakov, JETP Lett. B219 (1981) 644;
G.G.Callan, Phys. Rev. D26 (1982) 2058.

[33] M. Ambrosio et al. (Search for Nucleon Decays induced by GUT MMs with the MACRO experiment), hep-ex/0207024, Eur. Phys. J. C26 (2002) 163.

[34] P. B. Price, Phys. Rev. D38 (1988) 3813;
D. Ghosh and S. Chatterjea, Europhys. Lett. 12 (1990) 25.

[35] E. N. Parker, Ap. J. 160 (1970) 383;
M. S. Turner et al., Phys. Rev. D26 (1982) 1296.

[36] F. C. Adams et al., Phys. Rev. Lett. 70 (1993) 2511.

[37] S. Nakamura et al., Phys. Lett. B263 (1991) 529.

[38] D. Bakari et al. (Search for "light" MMs) SLIM Coll., hep-ex/0003028.

[39] Proposal MOEDAL (Monopole and Exotic Particle Detector) at the LHC.