Searches for Magnetic Monopoles, Nuclearites and Q-balls

G. GIACOMELLI, S. MANZOOR, E. MEDINACELI and L.PATRIZII
Dept. of Physics, Univ. of Bologna and INFN, v.le C. Berti Pichat 6/2, Bologna, I-40127, Italy
E-mail: giacomelli@bo.infn.it, manzoor@bo.infn.it, medinaceli@bo.infn.it, patrizii@bo.infn.it

Abstract. The searches for classical Dirac Magnetic Monopoles (MMs) at accelerators, for GUT superheavy MMs in the penetrating cosmic radiation and for Intermediate Mass MMs at high altitudes are discussed. Also the searches for nuclearites and Q-balls are considered.

1. Introduction
Though the concept of magnetic monopoles (MMs) goes back even to the origin of magnetism, it is only since 1931 that systematic searches have been performed. In 1931 Dirac introduced the MM in order to explain the quantization of the electric charge [1]. He established the relation between the elementary electric charge $e$ and a basic magnetic charge $g$: $eg = n\hbar c / 2 = ng_D$, where $n$ is an integer, $n = 1, 2, \ldots$; $g_D = \hbar c / 2e = 68.5e$ is the unit Dirac charge. The existence of magnetic charges and of magnetic currents would symmetrize in form Maxwell’s equations, but there would be a numerical asymmetry since $e \neq g$ (but the couplings could be energy dependent and could merge in a common value at high energies) [2]. There was no prediction for the MM mass; a rough estimate, obtained assuming that the classical monopole radius is equal to the classical electron radius yields $m_M \simeq g^2 m_e / e^2 \simeq n \times 4700 \ m_e \simeq n \times 2.4 \ GeV/c^2$. From 1931 searches for “classical Dirac monopoles” were carried out at every new accelerator using simple setups, and recently also parts of large collider detectors [3-7,20].

Electric charge is naturally quantized in Grand Unified Theories (GUT) of the basic interactions; they imply the existence of GUT monopoles with calculable properties. The MMs would appear in the Early Universe at the phase transition corresponding to the breaking of the GUT group into subgroups, one of which is U(1) [8]. The MM mass is related to the mass of the X, Y carriers of the unified interaction, $m_M \geq m_X / G$, where G is the dimensionless unified coupling constant at energies $E \simeq m_X$. If $m_X \simeq 10^{14} - 10^{15} \ GeV$ 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 may have been produced only in the first instants of our Universe and may be looked for as fossil particles in the cosmic radiation.

Larger MM masses are expected if gravity is brought into the unification picture, and in some SuperSymmetric models [3].

Intermediate Mass Monopoles (IMMs) may have been produced in later phase transitions in the Early Universe, when a semisimple gauge group yields a U(1) group [9]. IMMs with $m_M$
\( \sim 10^7 \div 10^{13} \) GeV may be accelerated to relativistic velocities in one galactic magnetic field domain. Very energetic IMMs could yield the highest energy cosmic rays [10].

The lowest mass MM is stable, since magnetic charge is conserved like electric charge. Thus the poles produced in the Early Universe should still exist as cosmic relics; their kinetic energy was affected by the Universe expansion and by travel through galactic and intergalactic magnetic fields.

GUT poles are best searched for underground in the penetrating cosmic radiation (CR). IMMs may be searched for at high altitude laboratories.

*Nuclearites* and *Q-balls* are defined and discussed in Section 8 [11, 12].

In this lecture notes the searches for MM, nuclearites and Q-balls, are reviewed and discussed.

2. Properties of magnetic monopoles

The main properties of MMs are obtained from the Dirac relation.

- If \( n=1 \) and the basic electric charge is that of the electron, then the basic magnetic charge is \( g_D = \frac{hc}{2e} = 137e/2 \). The magnetic charge is larger if \( n > 1 \) and if the basic electric charge is \( e/3 \).

- In analogy with the fine structure constant, \( \alpha = e^2/hc \simeq 1/137 \), the dimensionless magnetic coupling constant is \( \alpha_g = g_D^2/hc \simeq 34.25 \); since it is \( > 1 \) perturbative calculations cannot be used.

- Energy \( W \) acquired in a magnetic field: \( W = n g_D B \ell = n \ 20.5 \text{ keV/G cm} \). In a coherent galactic–length (\( \ell \simeq 1 \text{ kpc}, B \simeq 3 \mu\text{G} \)), the energy gained by a \( g = g_D \) MM is \( W \simeq 1.8 \times 10^{11} \) GeV. Dirac poles and IMMs in the CR may be accelerated to relativistic velocities, GUT poles may have \( 10^{-4} < \beta < 10^{-1} \).

- MMs may be trapped in ferromagnetic and paramagnetic materials.

- Electrically charged monopoles (dyons) may arise as quantum–mechanical excitations or as M–p, M-nucleus composites.

- The interaction of a MM magnetic charge with a nuclear magnetic dipole could lead to the formation of M–nucleus bound systems. Such states may exist for nuclei with large gyromagnetic ratios.

- Energy losses of fast poles. A fast MM with magnetic charge \( g_D \) and velocity \( v = \beta c \) behaves like an electric charge \( (ze)_\text{eq} = g_D \beta \), Fig.1.

- Energy losses of slow poles \( (10^{-4} < \beta < 10^{-2}) \) may be due to ionization or excitation of atoms and molecules of the medium (“electronic” energy loss) or to recoiling atoms or nuclei (“atomic” or “nuclear” energy loss). Electronic energy loss predominates for \( \beta > 10^{-5} \).

- Energy losses at very low velocities. MMs with \( v < 10^{-4}c \) may lose energy in elastic collisions with atoms or with nuclei [13]. Fig. 1 shows the energy losses in liquid hydrogen of a \( g = g_D \) MM plotted vs \( \beta \).[4]

- Energy losses of MMs in celestial bodies, for \( \beta < 10^{-4} \), are due to pole–atom and pole–nucleus elastic scattering and to eddy currents. MMs may be stopped by celestial bodies if they have: Moon: \( \beta \leq 5 \times 10^{-5} \), Earth: \( \beta \leq 10^{-4} \), Sun: \( \beta \leq 10^{-3} \).

3. Monopole detectors

Monopole detectors are based on the MM properties obtained from the Dirac relation.

- Superconducting induction devices are sensitive to MMs of any velocity [3]. A moving MM induces in a ring an electromotive force and a current change \((\Delta i)\). For a coil with \( N \) turns and inductance \( L: \Delta i = 4\pi Ng_D/L = 2\Delta i_o \), where \( \Delta i_o \) is the current change corresponding to a change of one unit of the flux quantum of superconductivity. This method of detection is based on the long–range electromagnetic interaction between the magnetic charge and the macroscopic quantum state of a superconducting ring.
Figure 1. The energy losses (in MeV/cm) of $g = g_D$ MMs in liquid hydrogen vs $\beta$: a) ionization energy loss; b) interactions with level crossings; c) elastic monopole–hydrogen atom scattering.

- Scintillation counters for MMs have a threshold $\beta \sim 10^{-4}$, above which the light signal is larger than that of a minimum ionizing particle [13, 14].

- Gaseous detectors of various types have been used. MACRO used a gas mixture of 73% helium and 27% n–pentane [14], which allows exploitation of the Drell [15] and Penning effects [3]: a MM leaves a helium atom in a metastable state (He*); the excited energy of the He* is converted into ionization of the n–pentane molecule (Penning effect).

- Nuclear track detectors (NTDs). The formation of an etchable track in a NTD is related to the Restricted Energy Loss (REL), the fraction of the energy loss localized in a cylindrical region of few tens of nm diameter around the particle trajectory. It was shown that both the electronic and the nuclear energy losses are effective in producing etchable tracks in the CR39 NTD which has a threshold at $z/\beta \geq 5$ [16]; CR39 is the most sensitive NTD and it allows to search for MMs with $g = g_D$ for $\beta$ around $10^{-4}$ and $> 10^{-3}$, the whole $\beta$-range of $4 \times 10^{-5} < \beta < 1$ for MMs with $g \geq 2g_D$ [13]. The Lexan and Makrofol polycarbonates are sensitive for $z/\beta \geq 50$ [17]. Fig. 2 shows the calibration of CR39 and Makrofol NTDs with $In^{49}$ and $Pb^{82}$ relativistic lead ions and their fragments [18].

Figure 2. Calibration of CR39 (left) and Makrofol (right) detectors with 158 AGeV ions ($In^{49}$ and $Pb^{82}$ respectively) and their fragments.
4. Searches for “classical Dirac monopoles”

- **Accelerator searches.** If MMs are produced at high–energy accelerators, they would in general be relativistic and ionize heavily. Examples of direct searches are the experiments performed with scintillators or NTDs. Early experiments at the Fermilab \( \bar{p}p \) collider established cross section upper limits of \( \sim 2 \times 10^{-34} \text{ cm}^2 \) for MMs with \( m_M < 850 \text{ GeV} \) [19]. Early direct searches at \( e^+e^- \) colliders excluded masses up to 45 GeV [7]. The OPAL experiment searched for Dirac MMs in \( e^+e^- \) collisions in the \( 45 < \sqrt{s} < 104 \text{ GeV} \) range (\( \sigma < 5 \times 10^{-37} \text{ cm}^2 \)), Fig. 3 left [20]. The CDF experiment established a direct limit using some of its sub-detectors at the \( \bar{p}p \) Fermilab collider, see Fig. 3 right [21]. In \( e^+p \) collisions, indirect experiments placed a limit for MMs using the process sketched in Fig. 4 left [3].

Most searches are sensitive to poles with magnetic charges \( g = n g_D/q \) with \( 0.5 < n < 5 \).

Examples of indirect searches are those performed at the CERN SPS and at Fermilab: the protons interacted in ferromagnetic or paramagnetic targets; later the targets were placed in front of a superconducting solenoid with a field \( B > 100 \text{ kG} \), large enough to extract and accelerate the MMs, to be detected in scintillators and in NTD sheets [3]. An indirect experiment performed at the \( \bar{p}p \) Tevatron collider, assumed that produced MMs could stop, be trapped and bound in the matter surrounding a collision region [5]. Small Be and Al samples were passed through the 10 cm diameter bore of two superconducting coils, and the induced charge measured by SQUIDs. Limits for \( m_M < 285 \text{ GeV} \) for \( g = g_D \) poles were published. The authors consider these experiments as direct experiments. In our terminology they are indirect: for their interpretations some extra hypotheses are needed, and it is not easy to establish their validity.

- **Multi–\( \gamma \) events.** Five peculiar photon showers found in emulsion plates exposed to Cosmic Rays at high–altitude, are characterized by an energetic narrow cone of tens of photons, without any incident charged particle [23]. The total energy of the photons is \( \sim 10^{11} \text{ GeV} \). The small radial spread of photons suggested a c.m. \( \gamma = (1 – \beta^2)^{-1/2} > 10^3 \). The energies of the photons are too small to have \( \pi^0 \) decays as their source. One possible explanation is the following, a high–energy \( \gamma \)–ray, with energy \( > 10^{12} \text{ eV} \), produced a pole–antipole pair, which suffered bremsstrahlung and annihilation producing the final multi–\( \gamma \) events. Searches for multi–\( \gamma \) events were performed in \( pp \) collisions at the ISR at \( \sqrt{s} = 53 \text{ GeV} \), at the \( \bar{p}p \) 1.8 TeV collider and in \( e^+e^- \) collisions at LEP. The D0 experiment at FNAL searched for \( \gamma \) pairs with high transverse energies; virtual pointlike MMs may rescatter pairs of nearly real photons into the final state via a box monopole diagram (see Fig. 4 right); a 95% CL limit of 870 GeV was set [5]. At LEP the L3 coll. searched for \( Z \rightarrow \gamma\gamma \gamma \) events; no deviation from QED predictions was observed, setting a 95% CL limit of \( m_M > 510 \text{ GeV} \) [5]. Many authors studied the effects from virtual monopole loops [2, 24]. Ref. [6] criticizes the underlying theory and doubts that significant limits can be obtained from these experiments.

In the search made by the H1 experiment at HERA, the beam pipe surrounding the interaction region was analyzed using a SQUID magnetometer to look for stopped monopoles; the limit is given in the context of the so called model A based on the diagram in figure 4 left [22].

- **Searches in bulk matter.** Classical MMs could be produced by CRs and could stop at the Earth surface, where they may be trapped in ferromagnetic materials. Bulk matter searches used hundreds of kg of material, including meteorites, schists, ferromanganese nodules, iron ore and others. A superconducting coil through which the material was passed, yielded a monopole/nucleon ratio in the samples \( < 1.2 \times 10^{-20} \) at 90% CL [3].

Ruzicka and Zrelov summarized all searches for classical poles performed before 1980 [25]. A more recent bibliography is given in Ref. [27]. Possible effects arising from low mass MMs were reported in Ref. [28].
5. Searches for GUT monopoles

GUT theories of the electroweak and strong interactions predict the existence of superheavy MMs produced in the Early Universe (EU) when the GUT gauge group breaks into separate groups, one of which is U(1). For example one could have the following transitions:

\[
\begin{align*}
10^{15} \text{GeV} & \quad \text{SU}(5) \quad 10^{-35} \text{s} \\
10^2 \text{GeV} & \quad \text{SU}(3)_C \times [\text{SU}(2)_L \times \text{U}(1)_Y] \quad 10^{-9} \text{s} \\
& \quad \text{SU}(3)_C \times \text{U}(1)_{EM}
\end{align*}
\] (1)

MMs would be generated as topological point defects in the GUT phase transition \(\text{SU}(5) \rightarrow U(1)_Y\), about one pole for each causal domain. In the standard cosmology this leads to too many poles (the monopole problem). A rapid expansion of the early Universe (inflation) would defer the GUT phase transition; in the simplest version of inflation the number of generated MMs would be very small. However if there was a reheating phase up to large enough temperatures one would have MMs produced in high energy collisions, like \(e^+ e^- \rightarrow MM\).

The structure of a GUT MM consists in a very small core, an electroweak region, a confinement region, a fermion–antifermion condensate (which may contain 4–fermion baryon–number–violating terms); for \(r \geq \text{few fm}\) a GUT pole behaves as a point particle generating a...
Figure 5. Compilation of 90% CL direct upper limits vs $\beta$ for GUT $g = g_D$ poles in the penetrating CR.

field $B = g/r^2$ [29].

A flux of cosmic GUT MMs may reach the Earth with a velocity spectrum in the range $4 \times 10^{-5} < \beta < 0.1$, with possible peaks corresponding to the escape velocities from the Earth, the Sun and the Galaxy. Searches for such MMs in the CR performed with superconducting induction devices yielded a combined 90% CL limit of $2 \times 10^{-14}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, independent of $\beta$ [4].

Direct searches were performed above ground and underground using many types of detectors [25, 27, 29]. MACRO performed a search with liquid scintillators, limited streamer tubes and NTDs with an acceptance of $\sim 10,000$ m$^2$sr for an isotropic flux. No MM was detected. The 90% CL flux limits, shown in Fig.5 vs $\beta$ for $g = g_D$, are at the level of $1.4 \times 10^{-16}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for $\beta > 4 \times 10^{-5}$ [30]. The figure shows also the limits from the Ohya [31], Baksan [32], Baikal [33], and AMANDA [34] experiments. Adding to the MACRO limit the limit from the SLIM experiment (described below in section 7), Fig. 7 right, over $4\pi$, improves the MACRO limit by about 11%.

Figure 6. Left: Illustration of monopole catalysis of proton decay. Right: MACRO flux upper limits for MM induced proton decay.

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), i.e. \( M + p \rightarrow M + e^+ + \pi^0 \), see Fig. 6 left. The catalysis process could proceed via the Rubakov-Callan mechanism with a \( \sigma \) of the order of the strong interaction cross section [35]. MACRO performed a dedicated search for nucleon decays induced by the passage of a GUT pole in the streamer tube system. The flux limits obtained, \( 3 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) (Fig. 6 right), depend on the MM velocity and on the catalysis cross section [36]. Previous limits were at levels of \( 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) [36], except the Baikal limit which is \( 6 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) for a limited \( \beta \) range around \( \beta \sim 10^{-5} \) [33].

Indirect GUT MM searches used ancient mica samples; mica is a NTD with a very high threshold. It is assumed that a pole passing through the Earth captures an Al nucleus and drags it through subterranean mica causing a trail of lattice defects, which survive as long as the mica is not reheated. Only small sheets were analyzed (13.5 and 18 cm²), but they should have been recording tracks for \( 4 \times 9 \times 10^8 \) years. The flux limits may be at the level of \( \sim 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) for \( 10^{-4} < \beta < 10^{-5} \) [37]. There are several reasons why these indirect experiments might not be sensitive.

6. Cosmological and astrophysical bounds

Rough, orders of magnitude, upper limits for a GUT monopole flux in the CR were obtained on the basis of cosmological and astrophysical considerations.

- **Limit from the mass density of the universe:** For \( m_M \sim 10^{17} \text{ GeV} \) one has the limit:
  \[
  F = \frac{n_{\text{DM}}}{4\pi} \beta < 3 \times 10^{-12} \frac{\beta}{m_M^2} \text{ (cm}^{-2}\text{s}^{-1}\text{sr}^{-1})
  \]
  It is valid for poles uniformly distributed in the universe. If poles are clustered in galaxies the bound is weaker [3].

- **Limit from the galactic magnetic field (Parker bound).** The \( \sim 3 \mu\text{G} \) magnetic field in our Galaxy is probably due to the non-uniform rotation of the Galaxy, which generates a field with a time-scale of the order of the rotation period of the Galaxy (\( \tau \sim 10^8 \text{ yr} \)). An upper bound for the MM flux is obtained by requiring that the kinetic energy gained per unit time by MMs be less than the magnetic energy generated by the dynamo effect:
  \[
  F < 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
  \]
  Taking into account the almost chaotic nature of the field, with domains of \( \ell \sim 1 \text{ kpc} \), the limit becomes mass dependent [38]. An “extended Parker bound”, obtained by considering the survival of an early seed field [39], yields \( F \leq 1.2 \times 10^{-16} (m_M/10^{17}\text{GeV}) \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \).

- **Limit from the intergalactic (IG) magnetic field.** If \( B_{\text{IG}} \sim 3 \times 10^{-8} \text{ G} \), a more stringent bound is obtained; the limit is less reliable because the IG field is even less known.

- **Limits from peculiar A4 stars and from pulsars** may be stringent, but the assumptions made are not clear (see the pulsar PSR 1937+214) [3, 4].

7. Searches for Intermediate Mass Magnetic Monopoles (IMMs)

IMMs may appear as topological point defects at a later time in the Early Universe, e. i. f. the GUT group yields the U(1) group of the Standard Model in the following two steps:

\[
\begin{align*}
SO(10) & \rightarrow \frac{10^5 \text{ GeV}}{10^{-35}s} \quad SU(4) \times SU(2) \times SU(2) & \rightarrow \frac{10^9 \text{ GeV}}{10^{-23}s} \\
& \rightarrow SU(3) \times SU(2) \times U(1)
\end{align*}
\]

This would lead to MMs with masses of \( \sim 10^{10} \text{ GeV} \); they would survive inflation, be stable, “doubly charged” (\( g = 2g_D \)) and do not catalyze nucleon decay [9]. The structure of an IMM would be similar to that of a GUT MM, but the core would be larger (since \( R \sim 1/m_M \)) and the outer cloud would not contain 4-fermion baryon-number-violating terms.

Relativistic IMMs with masses, \( 10^7 < m_M < 10^{13} \text{ GeV} \), could be present in the cosmic radiation, and may be accelerated to high \( \gamma \) in one domain of the galactic magnetic field. Thus one may look for \( \beta \geq 0.1 \) IMMs.

Detectors at the Earth surface could detect IMMs coming from above if they have \( m_M > 10^5 - 10^6 \text{ GeV} \) [13]; lower mass MMs may be searched for with detectors located at high mountain.
altitudes, in balloons and in satellites. Fig. 7 left shows the flux upper limits for downgoing IMMs with $m_M \sim 10^{10}$ GeV obtained by the MACRO and Ohya experiments[4].

The SLIM experiment at the Chacaltaya High Altitude Lab. (5260 m a.s.l.) (Bolivia) [40] is based on 440 m$^2$ of CR39 and Makrofol detectors exposed for 4 years to the CR. The detector is organized in modules of $24 \times 24$ cm$^2$ each consisting of 3 layers of CR39 (called L1, L3, and L6, respectively) interleaved with 3 layers of Makrofol (called L2, L4 and L5, respectively) and 1 mm Al absorber. Each module is tightly packed in an aluminized polyethylene envelope at 1 atm of dry air to prevent the CR39 loss in sensitivity at a reduced oxygen content in the air at the Chacaltaya site (0.5 atmospheric pressure). SLIM is sensitive to $g = 2 g_D$ IMMs in the whole range $4 \times 10^{-5} < \beta < 1$ [40]. All CR39 was produced by the Intercast Co, Italy. An area of 351 m$^2$ of SLIM CR39 sheets exposed for 4 y has been etched and analysed. No candidate was observed; the 90% CL upper flux limits for downgoing IMMs with $g = g_D$, $2g_D$, $3g_D$ and M+p are plotted in Figure 7 right, versus $\beta$.

8. Nuclearites and Q-balls

Strange Quark Matter (SQM) should consist of aggregates of $u$, $d$ and $s$ quarks in almost equal proportions; but the number of $s$ quarks should be lower than the number of $u$ or $d$ quarks and the SQM should have a relatively small positive integer charge. The overall neutrality of SQM is ensured by an electron cloud which surrounds it, forming a sort of atom (see Fig.8) [29]. SQM should have a constant density $\rho_N = M_N/V_N \simeq 3.5 \times 10^{14}$ g cm$^{-3}$, slightly larger than that of atomic nuclei, and it should be stable for all baryon numbers in the range between ordinary heavy nuclei and neutron stars ($A \sim 10^{57}$). Lumps of SQM with baryon number $A < 10^6 - 10^7$ are often called “strangelets”; the word “nuclearite” was introduced to indicate large lumps of SQM which could be present in the CR [11]. SQM could have been produced shortly after the Big Bang and may have survived as remnants; they could also appear in violent astrophysical processes, such as neutron star collisions. SQM could contribute to the cold dark matter in the Universe.

The main energy loss mechanism for low velocity nuclearites is elastic or quasi-elastic collisions with the ambient atoms. The energy loss is large; therefore nuclearites should be easily
Figure 8. Sketch of nuclearite structure: the quark bag (radius $R_N$) and of the core+electron system; the black points are electrons (the border of the core+electron cloud for small nuclearite masses is indicated by dashed lines). For nuclearite masses $< 10^9$ GeV, the electrons are outside and the core+electron system has size of $\sim 10^5$ fm; for $10^9 < M_N < 10^{15}$ GeV the $e^-$ are partially inside the core; for $M_N > 10^{15}$ GeV all electrons are inside the core.

detected in scintillators and CR39 NTDs [41]. Nuclearites should have typical galactic velocities, $\beta \sim 10^{-3}$, and for masses larger than 0.1 g could traverse the Earth.

Most nuclearite searches were obtained as byproducts of CR MM searches; the flux limits are similar to those for MMs. The most relevant direct flux limits for nuclearites come from three large area experiments: the first two use CR39 NTDs; one experiment was performed at mountain altitude (Mt. Norikura at 2770 m a.s.l.) [42], the 2nd at the depth of $10^4$ g cm$^{-2}$ in the Ohya mine [31]; the third experiment, MACRO, at an average depth of $3700$ hg cm$^{-2}$, used liquid scintillators besides NTDs [43].

Experimental limits for heavy nuclearites are at the level of those presented in Fig.5 for GUT MMs: $\sim 1.4 \times 10^{-16} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. For Intermediate Mass Nuclearites the limits are at the level indicated in Fig. 7 left, that is $\sim 3 \times 10^{-16} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$; for slightly smaller masses the limits of Fig.7 right, apply: $\sim 1.7 \times 10^{-15} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (SLIM experiment) [40]. For very small nuclearites, $A < 8000$ the predicted flux in the cosmic radiation is expected to increase with decreasing mass [44]. The present status of the search for galactic nuclearites is given in ref. [40]; the combination of the best limits come from the AMS, SLIM and MACRO experiments.

Indirect searches could yield lower limits, but they are affected by several systematic uncertainties. Some exotic cosmic ray events were interpreted as due to incident nuclearites, f. e. the “Centauro” events and the anomalous massive particles, but the interpretation is not unique [44]. Supermassive nuclearites (M>1 ton) passing through Earth could possibly induce epilineral earthquakes [11, 45].

$Q$-balls should be aggregates of squarks $\tilde{q}$, sleptons $\tilde{l}$ and Higgs fields [12]. The scalar condensate inside a $Q$-ball core has a global baryon number $Q$ (and may be also a lepton number). Protons, neutrons and may be electrons could be absorbed in the condensate. There could exist neutral and charged $Q$-balls. Supersymmetric Electrically Neutral Solitons (SENS) are generally more massive and may catalyse proton decay. SENS may obtain a positive electric charge when absorbing a proton in their interactions with matter yielding SECS (Supersymmetric Electrically Charged Solitons), which have a core electric charge, have generally lower masses and the Coulomb barrier could prevent the capture of nuclei. SECS have only integer charges because they are color singlets. Fig.9 [29] shows sketches of SECS and SENS. A SENS which enters the Earth atmosphere could absorb a nitrogen nucleus and would thus become a SECS with charge $z = 7$. Other nuclear absorptions may be prevented by Coulomb repulsion. If the Q-ball can absorb electrons at the same rate as protons, the positive charge of the absorbed nucleus may be neutralized by the charge of absorbed electrons. If, instead, the absorption of electrons is slow or impossible, the Q-ball carries a positive electric charge after the capture of
the first nucleus in the atmosphere.

Q-balls could be cold DM candidates. SECS with $\beta \sim 10^{-3}$ and $M_Q < 10^{13}$ GeV could reach an underground detector from above. SENS may be detected by their continuous emission of charged pions (estimated energy loss $\sim 100$ GeV g$^{-1}$cm$^2$); SECS may be detected by scintillators, NTDs and ionization detectors, like those used in nuclearite and MM searches. Fig. 10 shows the present status of the searches for galactic charged Q-balls with a net charge of 1 ($Z_Q = 1$) as flux limit vs. $m_Q$. The lowest limits come from the AMS, SLIM and MACRO experiments.

We did not consider here the possibility of strongly interacting, colored, MMs [46], nuclearites and Q-balls.

Figure 9. Sketch of the Q-ball structure: upper row, SECS; lower row, SENS. The black points represent electrons, the empty dots are s-electrons.

Figure 10. Flux upper limits for charged Q-balls with a net electric charge $Z_Q = 1$.

9. Non reproducible candidates
In the past, a number of magnetic monopole candidates and of other exotic events [48] were thought to have been observed and some results were also published in the press. But these results were not confirmed and most of them are now neglected.

In 2006 the SLIM experiment faced a problem of this type when analysing the top face of the top CR39 layer of stack 7408. We found a sequence of many “tracks” (etch-pits) along a 20 cm line; each one of them looked complicated and very different from usual ion tracks, see Fig. 11 a, b. For comparison Fig. 11 c shows “normal” tracks from 158 AGeV Pb$^{+82}$ ions and their fragments from a CERN-SPS exposure and Fig. 11 d shows tracks from a 400 A MeV Fe$^{+26}$ exposure at the HIMAC accelerator in Japan.
Figure 11. (a) Global view of the “event” tracks in the L1 layer of wagon 7408 exposed at Chacaltaya from 20-2-01 to 28-11-05XS, (b) Microphotographs of the 22 etched-pids at the top of Fig.11 a. (c) Normal tracks of 158 A GeV Pb\(^{82}\) ions and their fragments from a CERN-SPS exposure (soft etching), and (d) of 400 A MeV Fe\(^{26}\) ions and their fragments from the HIMAC accelerator, Japan (strong etching).

Figure 12. Example of “tracks” in the L6 layer of wagon 7410: (a) after 30 h of soft etching, observed magnification of 25x, (b) after 5 more hours of strong etching, (c) after 4h of more strong etching and (d) after 10h of more strong etching.
Since the “event” in the L1 sheet of module 7408 is rather peculiar, we decided to make a thorough study of all the sheets of module 7408, and a thorough search for similar events and in general for background tracks in all NTD sheets in the wagons around module 7408 (within a ∼1m distance from module 7408). We etched “softly” all the sheets so as to be able to follow the evolution of the etch-pits. A second event was found in the CR39 bottom layer (top face) of module 7410, see Fig.12. Some background tracks in other modules were found after 30 h of soft etching (6N NaOH 70°C). We decided to further etch “strongly” the 7410-L6 layer in short time steps (5 hr.) and to follow the evolution of the “tracks” by systematically making photographs at each etching step. After additional strong etching the “tracks” began looking more and more like those in the 7408-L1 layer, see Fig.12b, c, d. The presence of this second event/background and its evolution with increasing etching casts stronger doubts on the event interpretation and supports a “background” interpretation also of the “tracks” in module 7408. The background may have originated in the fabrication of the CR39: we made different hypotheses and we checked them with the Intercast Co. Since 1980’s we have analyzed more than 1000 m² of CR39 using different etching conditions and we have not seen before any of the above mentioned cases. It appears that we may have been hit by an extremely rare manufacturing defect involving 1 m² of CR39.

10. Conclusions. Outlook

Direct and indirect accelerator searches for classical Dirac MMs placed limits for $m_M \leq 800$ GeV with specific cross section upper values. Future improvements may come from experiments at the LHC [47].

Many searches were performed for GUT poles in the penetrating cosmic radiation. The 90% CL flux limits from the MACRO experiment are at the level of $\sim 1.4 \times 10^{-16} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ for $\beta \geq 4 \times 10^{-5}$. It may be difficult to do much better since one would require refined detectors of considerably larger areas.

Present limits on Intermediate Mass Monopoles with high $\beta$, in the downgoing cosmic radiation are at the level of $1.7 \times 10^{-15} \text{cm}^{-2} \text{s}^{-1} \text{m}^{-1}$. Experiments at high altitudes and may be with neutrino telescopes should improve the situation.

As a byproduct of GUT MM searches some experiments obtained stringent limits on nuclearites and on Q-balls. Future experiments at neutrino telescopes and at high altitudes should perform searches for nuclearites and Q-balls of smaller masses.

Acknowledgments

We thank the organizers of the Summer School in Puebla, Mexico, and the discusions with several participants, in particular A. De Rujula and O. Saavedra. The cooperation of many colleagues, in particular S. Cecchini, M. Cozzi, M. Giorgini, G. Mandrioli, A. Margiotta, G. Sirri, V. Popa, M. Spurio, is gratefully acknowledged.

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 et al. (Preprint hep-ex/011209; hep-ex/0302011; hep-ex/0211035; hep-ex/0506014).
[5] G.R. Kalbfleisch, Phys. Rev. Lett. 85(2000)5292. K.A.Milton et al. Preprint hep-ex/0009003.
   B. Abbott et al., Phys. Rev. Lett. 81(1998)524.
   M. Acciarri et al., Phys. Lett. B345(1995)609.
[6] L. Gambarg et al., Preprint hep-ph/9906536.
[7] K. Kinoshita et al., Phys. Rev. D46(1992)R881.
[8] G.’t Hooft, Nucl. Phys. B29(1974)276. A.M. Polyakov, JETP Lett. 20(1974)194.
N.S. Craigie et al., Theory and Detection of MMs in Gauge Theories, (World Scientific), Singapore (1986).

[9] G. Lazarides et al., Phys. Rev. Lett. 58(1987)1707.

[10] T. W. Kephart and Q. Shafi, Phys. Lett. B520(2001)313.

[11] P. Bhattacharjee and G. Sigl, Phys. Rept. 327(2000)109 and refs. therein.

[12] E. Witten, Phys. Rev. D30(1984)272.

[13] A. De Rujula and S. Glashow, Nature 31(1984)272.

[14] S. Coleman, Nucl. Phys. B262(1985)293.

[15] A. Kusenko and A. Shaposhnikov, Phys. Lett. B418(1998)46.

[16] J. Derkaoui et al., Astrop. Phys. 9(1998)173; Astrop. Phys. 9(1999)339.

[17] S. Ahlen et al., Phys. Rev. Lett. 72(1994)608.

[18] M. Ambrosio et al., Astrop. Phys. 6(1997)113; Nucl. Instr. Meth. A486(2002)663; Astrop. Phys. 4(1995)33; Astrop. Phys. 18(2002)27.

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

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

[21] S. Cecchini et al., 22nd ICNTS, Barcelona, Spain, 2004, Preprint hep-ex/0503003; hep-ex/0502034.

[22] V. Togli et al., Preprint physics/0611105 v1.

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

[24] M. Cozzi, private communication. K. Ahmet et al., Nucl. Instrum. Meth. B209(2003)67.

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

[26] B. Abbott et al., (MACRO collab.) M. Ambrosio et al., Eur. Phys. J. C109(1998)524.

[27] G. Giacomelli et al., Preprint hep-ex/0005041.

[28] V.A. Skvortsov et al., 29th EPS Plasma Conf., ECA 26B, D5.013 (2002).

[29] D. Bakari et al., Preprint hep-ex/0004019.

[30] (MACRO collab.) M. Ambrosio et al., Eur. Phys. J. C25(2002)511; Phys. Lett. B406(1997)249; Phys. Rev. Lett. 72(1994)608; Astropart. Phys. 18(2002)27.

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

[32] (Baksan collab.) E.N. Alexeyev et al., 21st ICRC (1990)83.

[33] Yu. F. Novoselov et al., Nucl. Phys. B151(2006)337.

[34] (Baksan collab.) V. Aynutdinov et al., Preprint astro-ph/0507713.

[35] (AMANDA collab.) M. Kowalski, Phys. in Collision (2003) pag. 369.

[36] (MACRO collab.) P. Niessen et al., 27th ICRC 3(2001)1496.

[37] V.A. Rubakov, JETP Lett. B219(1981)644.

[38] G.G. Callan, Phys. Rev. D26(1982)2058.

[39] (MACRO collab.) M. Ambrosio et al., Eur. Phys. J. C26(2002)163.

[40] P. B. Price, Phys. Rev. D38(1988)3813.

[41] D. Ghosh and S. Chatterjee, Europhys. Lett. 12(1990)25.

[42] E.N. Parker, Ap. J. 160(1970)383.

[43] M.S. Turner et al., Phys. Rev. D26(1982)1296.

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

[45] (SLIM collab.) S. Balestra et al., Preprint hep-ex/060236; hep-ex/0506075.

[46] S. Cecchini et al., TAUP2003 Conf., Nucl. Phys. B(Proc. Suppl.) 138(2005)529.

[47] (MACRO collab.) M. Ambrosio et al., Eur. Phys. J. C13(2000)453.

[48] A. Ahlen et al., Phys. Rev. Lett. 69(1992)1860.

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

[50] G. Giacomelli, Preprint hep-ex/0210021.

[51] M. Rybczynski et al., Preprint hep-ex/0410064.

[52] D. P. Anderson et al., Preprint astro-ph/0205089.

[53] S.D. Wick et al., Preprint astro-ph/0012339.

[54] Proposal MOEDAL at the LHC, LHCC 98-5.

[55] P.B. Price et al., Phys. Rev. Lett 35(1975)487; Phys. Rev. D18(1978)1382.

[56] B. Cabrera, Phys. Rev. Lett. 48(1982)1378.

[57] V.V. Kopenkin et al., 28th ICRC, Tsukuba, Japan (2003)1583.