"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Magnetic Monopole Searches

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Magnetic Monopole Searches

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7th School, ICTP, Trieste, 26/7-6/8, 04
1. Introduction
An idea of long time ago...

Symmetry of Maxwell Equations

\[ \nabla \cdot \vec{E} = 4\pi \rho_e \]
\[ \nabla \cdot \vec{B} = 4\pi \rho_m \]

\[ \nabla \times \vec{B} = \frac{4\pi}{c} \vec{J}_e + \frac{1}{c} \frac{\partial \vec{E}}{\partial t} \]
\[ (\text{cgs units}) \]

\[ \nabla \times \vec{E} = -\frac{4\pi}{c} \vec{J}_e - \frac{1}{c} \frac{\partial \vec{B}}{\partial t} \]

1931 Dirac: Quantization of electric charge
Proc. R. Soc. London, 133 (1931) 60

\[ eg = n \frac{\hbar c}{2} , \quad n = 1,2,3,... \quad \text{Dirac relation} \]
\[ g_D = \frac{\hbar c}{2e} = \frac{137}{2} e \quad , \quad g = n \ g_D \]

1974 GUT of Strong and Electroweak interactions
2. Classical ("Dirac") MMs

- **Mass**: No prediction. Estimate:
  \[ m_M \approx g_D^2 m_e/e^2 \approx 4700 \, m_e \approx 2.4 \, \text{GeV} \]

- **Magnetic Charge**
  If \( n = 1 \) and \( e = \text{electron charge} \)
  \[ g_D = \frac{c}{2e} = e/2\alpha = 68.5 \, e = 3.3 \times 10^{-8} \, \text{esu} \]
  If \(|e|=1/3 \rightarrow 3 \, g_D\)

- **Electric charge**
  \( = 0 \) MM, \( \neq 0 \) Dyon
  Systems \( M-p, \, M-Al^{27} \) (Monopole-Dipole Interaction)

- **Coupling constant**
  \[ \alpha_M = g_D^2/c = 34.25 \]

- **Energy gain in a magnetic field**
  \[ W = n \, g_D \, B \, L = n \, 20.5 \, \text{keV/G cm} \]
  If \( L = 1 \, \text{kpc} \) and \( B = 3 \, \mu G \)
  \[ W \approx 1.8 \times 10^{11} \, \text{GeV} \]
**MM Energy Losses**

- **β > 10^{-2}**  
  Ionization \((\text{à la Bethe-Bloch})\) \((Z_{\text{eq}})^2 = (g\beta)^2\)  
  \[ \text{for } \beta = 1 : \frac{dE}{dx}_{\text{MM}} = 4700 \left(\frac{dE}{dx}\right)_{\text{m.i.p.}} \]  

- **10^{-4} < β < 10^{-2}**  
  Excitation  
  Medium as Fermi gas

- **10^{-4} < β < 10^{-3}**  
  Drell effect  
  \(M + \text{He} \rightarrow M + \text{He}^*\) 
  + Penning effect  
  \(\text{He}^* + \text{CH}_4 \rightarrow \text{He} + \text{CH}_4 + e^-\)

- **β < 10^{-4}**  
  Elastic collisions  
  (coupling of the atom magnetic moment with the MM magnetic charge)
3. Searches for classical MMs at accelerators

\[ e^+e^- \rightarrow MM, \quad \bar{p}p \rightarrow M\bar{M}, \quad pp \rightarrow ppM\bar{M} \]

• Direct experiments:
  poles produced - detected immediately (large dE/dx)

Searches with
  scintillation counters
  nuclear track detectors

Limits (95 % CL)
  \[ \sigma(e^+e^-) < 5 \times 10^{-37} \text{ cm}^2 \]
  \[ \sigma(p\bar{p}) < 2 \times 10^{-34} \text{ cm}^2 \]

m_M < 102 GeV
m_M < 850 GeV

• Indirect expts:
  Produced
  Stopped
  Trapped

Later
  Extracted
  Accelerated
  Detected

\[ M \]
\[ \bar{M} \]
Limits for classical MMs at accelerators

Upper limits vs mass

Upper limits vs charge
Searches for classical MMs at accelerators /2

• Multi-$\gamma$ events
  - At ISR \( pp \rightarrow \text{multi-$\gamma$} \) at \( \sqrt{s} = 53 \text{ GeV} \) \( \sigma < 2 \times 10^{-37} \text{ cm}^2 \)
  - At Fermilab (D0 Coll.) search for $\gamma$-pairs of high transverse energies in pp collisions \( M > 870 \text{ GeV} \) for spin 1/2 Dirac MMs (95 % CL)
  - At LEP (L3 Coll.) search for \( Z \rightarrow \gamma \gamma \gamma \) events \( M > 510 \text{ GeV} \) (95 % CL)

• Searches in bulk matter
  - Moon rocks
  - Meteorites
  - Terrestrial magnetic materials

  \begin{align*}
  &\text{Superconducting loop} \\
  &\text{+SQUID}
  \end{align*}

• Searches in the cosmic radiation
  - with counters
  - with emulsions + Lexan
  - fossil tracks in mica

  the "Price event" (1975)
4. GUT Monopoles (Gauge, Cosmic,..)

Gauge theories of unified interactions predict MMs

\[ \text{SU}(5) \xrightarrow{10^{15}\text{ GeV}} \text{SU}(3)_c \times [\text{SU}(2)_L \times \text{U}(1)_y] \xrightarrow{10^2\text{ GeV}} \text{SU}(3)_c \times \text{U}(1)_{\text{EM}} \]

* Mass \( m_M \geq \frac{m_X}{G} > 10^{16}\text{ GeV} \sim 0.02\ \mu\text{g} \rightarrow 10^{17}\text{ GeV} \)

( Kaluza-Klein poles \( \rightarrow \) > 10^{19}\text{ GeV} , SUSY \( \rightarrow \) > 10^{17}\text{ GeV} )

* Size: extended object

\[ r > \text{few fm} \quad B \sim g/r^2 \]

\[ 10^{-15} \quad 10^{-16} \quad 10^{-13} \text{ Radius (cm)} \]
The large scale structure of particle physics:

- $SU(3) \otimes SU(2) \otimes U(1)$ unify at $M_{\text{GUT}}$
- at $M_{\text{Pl}}$: quantum gravity

Superstring theory: a 10-dimensional non-local, unified theory of all interact’s

$G_{\text{Newton}} = \frac{\hbar c}{M_{\text{Pl}}^2}$

$r \sim 10^{-33} \text{ cm}$

G. Altarelli

The really fundamental level
**GUT MMs**

- **Magnetic charge** \( g = n g_D \) several models predict \( n > 1 \) (2,3)

- **Production:** In the Early Universe at G.U.T. phase transition
  - as topological defects \( G \rightarrow U(1) \times \ldots \) (\( t \sim 10^{-35} \) s )

- in high energy collisions (\( t \sim 10^{-34} \) s )

MMs follow "history" of the Universe ⇒ slowed down ⇒ formation of galaxies
⇒ magnetic fields ⇒ poles accelerated
GUT MMs

May be present today in the Cosmic Radiation as "relic" particles

In  N_M

Escape velocity

3 \cdot 10^{-5}

10^{-3}

10^{-1}

\beta

Earth
Sun
Galaxy

Cosmological limits on MM flux

\rho_M \leq \rho_c

\begin{align*}
\text{Uniform} & \quad \Rightarrow \\
\text{Clumped} & \quad \Rightarrow \\
F & \leq 5 \times 10^{-12} \beta \left( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right) \\
& \times 10^5
\end{align*}
Astrophysical limits on the GUT MM flux

Survival of galactic magnetic fields ⇒ the Parker bound

\[ F < 10^{-15} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \quad \text{for} \quad \beta < 3 \times 10^{-3} \]

\[ F < 10^{-15} \left( \frac{\beta}{3 \times 10^{-3}} \right) \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \quad \text{for} \quad \beta > 3 \times 10^{-3} \]

Survival of early seed magnetic field ⇒ Extended Parker Bound

\[ F < 1.2 \times 10^{-16} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \]
5. Searches for GUT Magnetic Monopoles

*Induction devices*

Method depends only on long range E.M. interaction

\[ \Delta i = \frac{4\pi N}{L} g_D = 2\Delta i_0 \]

Superconducting solenoid

Early experiments:
1 loop, 10 cm\(^2\), no coincidence arrangements
Stanford, 1982: the “Cabrera” event

Later detectors:
coincidence arrangements+accelerometers, cosmic ray and R.F. monitors

Present combined limit:

\[ F < 2 \times 10^{-13} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \ (90\% \ CL) \]
Different analysis techniques were used for various β regions, by using the three subdetectors.

Redundancy & Complementarity
MACRO: Scintillation counters

Liquid scintillator:
mineral oil+pseudocumene +wls

Total mass: 600 t

Time resolution: ~500 ps

Calibration tools: cosmic muons, LED’s, UV laser
MACRO: MM Searches with scintillators

- Study of the PMT pulse
- Measurement of the light yield
- Consistency check between the box crossing time and the ToF across MACRO

For slow monopoles: the PMT pulse might reduce to a train of single photoelectrons

For fast monopoles: look for large energy deposits

Dedicated hardware: 200 MHz WFD + ADC/TDC system + independent triggers
MACRO: Streamer Tubes

3 cm x 3 cm x 12 m cell with 100 mm Cu-Be wire

Gas mixture: He (73%) + n-pentane (27%)

Total surface: ~ 19000 m²

Pick-up strips for stereo track reconstruction

Angular resolution: ~ 0.5°

Look for time alignments in a ~ 500 ms window with 150 ns resolution

Require single track in wire, strip and time view
Total surface: \( \sim 1263 \, \text{m}^2 \) (\( S\Omega \sim 7100 \, \text{m}^2 \, \text{sr} \))

modules 24.5 x 24.5 cm\(^2\)

MACRO: The Nuclear Track Subdetector

The track-etch technique

Relativistic S\(^{16}\) ion tracks in CR39
Restricted Energy Loss vs $\beta$ for MMs in CR39

![Graph showing Restricted Energy Loss vs $\beta$ for MMs in CR39. The graph includes curves for different $g$ values: $g=g_n$, $g=2g_n$, and $g=3g_n$. The CR39 threshold is indicated by a horizontal dashed line. The coincidence in position, angle, and REL is highlighted.]
MACRO final results

\[ g = g_D \]

\[ \sigma_{\text{cat}} < 1 \text{ mb} \]
Flux upper limits for GUT MMs

Direct searches, \( g = g_D \), isotropic flux, \( \sigma_{\text{cat}} < 1 \text{ mb} \)
6. Catalysis of proton decay

GUT MM – p interaction may violate baryon and lepton number conservation

\[ M + p \rightarrow M + e^+ + \pi^0 \]

If \( \sigma_{\Delta B=0} \sim \sigma_{\text{core}} \sim 10^{-56} \text{ cm}^2 \sim \text{negligible} \)

Rubakov-Callan mechanism

If \( \sigma_{\Delta B=0} \sim \sigma_{\text{strong}} \) could see a string of p decays along MM trajectory

\[ \sigma_{\Delta B=0} \sim \sigma_0/\beta \quad (\text{or} \quad \sigma_0/\beta^2) \]

p-decay detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>( \Phi &lt; 1 \pm 3 \times 10^{-15} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} )</th>
<th>( 10^{-5} &lt; \beta &lt; 10^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kamiokande</td>
<td></td>
<td>( 5 \times 10^{-5} &lt; \beta &lt; 10^{-3} )</td>
</tr>
</tbody>
</table>

\( \nu\)-telescopes

<table>
<thead>
<tr>
<th>Detector</th>
<th>( \Phi &lt; 6 \times 10^{-17} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} )</th>
<th>( \beta \sim 10^{-5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Baikal</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**MACRO: dedicated search for MM induced p decay**

using the streamer tube system

\[ S\Omega = 4250 \text{ m}^2\text{sr} , \ t = 70,000 \text{ hours} \]

\[
\begin{align*}
\star \sigma &= 5 \times 10^{-25} \text{ cm}^2 \\
\square \sigma &= 10^{-24} \text{ cm}^2
\end{align*}
\]

Look for

\[
\begin{align*}
\text{Slow MM track} \\
\text{Fast e\textsuperscript{+} track}
\end{align*}
\]

EPJ C26 (2002) 163
7. Intermediate mass MMs

\((10^5 - 10^{12} \text{ GeV})\)

1994 De Rujula CERN-TH 7273/94
E. Huguet & P. Peter hep-ph/901370
Shafi - Talk at the Neutrino Workshop, Venice, 2001

Produced in the Early Universe in later phase transitions

\[
\begin{align*}
SO(10) & \xrightarrow{10^{15} \text{ GeV}} SU(4) \times SU(2) \times SU(2) & SU(3) \times SU(2) \times U(1) & \xrightarrow{10^9 \text{ GeV}} \\
\text{10}^{-35} \text{ s} & \text{10}^{-23} \text{ s}
\end{align*}
\]

ex. (Shafi) \(M \sim 10^{10} \text{ GeV} \quad , \quad g = 2 \ gD \quad , \quad \text{no p-decay catalysis}\)

IMMs can be accelerated in the galactic B field to relativistic velocities

\[
W = gD \ B \ L \sim 6 \times 10^{19} \text{ eV} \ (B/3 \times 10^{-6} \ G) (L/300 \text{pc})
\]

Galaxy \(W \sim 6 \times 10^{19} \text{ eV}\)
Neutron stars \(W \sim 10^{20} - 10^{24} \text{ eV}\)
AGN \(W \sim 10^{23} - 10^{24} \text{ eV}\)

Could they produce highest energy cosmic ray showers \(E > 10^{20} \text{ eV}\)?
IMM searches in the cosmic radiation: the present situation

\[ M = 10^{10} \text{ GeV} \]
IMM searches at high altitudes

SLIM

Chacaltaya, Bolivia  5290 m asl
440 m² of nuclear track detectors
Koksil, Himalaya, 4275 m asl
100 m² of nuclear track detectors

Accessible regions in the plane (mass, $\beta$) for MMs coming from above for an experiment at high altitudes and underground.
The SLIM detector layout @ Chacaltaya

Modules 24 x 24 cm²

90 % C.L. flux upper limits vs MM mass for SLIM (expected, in absence of candidates) and MACRO
AMANDA, Lake Baikal, ANTARES

Direct light $\beta_{\text{MM}} > 1/n \sim 0.75$

$\delta$-rays light $\beta_{\text{MM}} > 0.6$

$M > 10^{10-11} \text{ GeV}$ from below

$(M > 10^{6-9} \text{ GeV}$ from above)
8. NUCLEARITES

- Aggregates of $u, d, s$ quarks + electrons, $n_e = 2/3 \, n_u - 1/3 \, n_d - 1/3 \, n_s$
- Ground state of nuclear matter; stable for any barion number $A$: $\sim 300 < A < 10^{57}$
- $Z \sim A^{1/3}, \sim A^{2/3}$; $Z/A \ll 1$, $\rho_N \sim 3.5 \times 10^{14} \text{ g cm}^{-3}$ ($\rho_{\text{nuclei}} \sim 10^{14} \text{ g cm}^{-3}$)

Produced in Early Universe: candidates for cold Dark Matter
Searched for in CR reaching the Earth [black points are electrons]

$R_N = 10^2 \text{ fm} \quad 10^3 \text{ fm} \quad 10^4 \text{ fm} \quad 10^5 \text{ fm} \quad 10^6 \text{ fm}$

$M_N = 10^6 \text{ GeV} \quad 10^9 \text{ GeV} \quad 10^{12} \text{ GeV} \quad 10^{15} \text{ GeV}$
Nuclearites: Interaction with matter

Main energy loss mechanism for nuclearites with $\beta \sim 10^{-3}$ is by atomic collisions

$$\frac{dE}{dx} = -\sigma \rho_{\text{medium}} v^2_N$$

$$\sigma \sim \pi \times 10^{-16} \text{ cm}^2 \quad R_N < 1\text{Å}$$

$$\sigma \sim \pi \times R^2_N \quad R_N > 1\text{Å}$$

In scintillators and track-etch detectors: signal similar to that of a MM

In water: part of the lost energy is radiated as visible light

Accessible regions in the plane (mass, $\beta$) for nuclearites coming from above for an experiment at high altitudes and underground.
High Mass Nuclearites: present situation:

White Mountain 4800 m a.s.l.
Mt. Norikura 2000 m a.s.l.
Ohya: 100 hg/cm² undergr.
MACRO: 3700 hg/cm² undergr.
Low mass nuclearites

Flux of light nuclearites may increase strongly with decreasing mass
Flux may become almost equal to flux of ordinary nuclei
Light nuclearites may be accelerated to relativistic velocities

G. Wilk et al. hep-ph/0009164;
I. Madsen et al PRL 90(2003)121102

Predicted Flux @ Chacaltaya: \(7 \times 10^{-6} \text{ m}^{-2} \text{ h}^{-1} \text{ sr}^{-1}\) for \(m_N > 3 \times 10^3\)

SLIM: ~ 100 events in 4 y
8. Supersymmetric Q-balls


**Q-balls** : coherent states of *squarks, sleptons and Higgs fields*

\[ Q \leq 10^{30} \quad 10^8 < M_Q < 10^{25} \text{ GeV} \]

- Produced in the Early Universe
- Candidates for Cold Dark Matter, concentrated in the galactic halos, \( \beta \sim 10^{-3} \)

**SECS** : Supersym. Electrically Charged Solitons

**SENS** : Supersym. Electrically Neutral Solitons

\[ R_Q : \text{dimension of the Q-ball core; } \]
\[ \text{the black points indicate electrons, open circles indicate s-electrons.} \]

\[ \text{R}_Q = 10 \text{ fm} \quad \text{R}_Q = 10^2 \text{ fm} \quad \text{R}_Q = 10^3 \text{ fm} \quad \text{R}_Q = 10^4 \text{ fm} \quad \text{R}_Q = 10^5 \text{ fm} \]
Supersymmetric electrically charged solitons (SECS) should essentially behave in detectors like nuclearites.
Charged Q-balls: current / near future situation

AKENO, KEK: ground level
MACRO: 3700 hg/cm$^2$ undg.
AMS: Space Station
SLIM: 500 g/cm$^2$ atm depth

$Z_Q = 1$
9. Conclusions - Outlook

• Dirac MMs at accelerators \( m_M > 0.9 \) TeV
  In the future: at LHC probe \( 0.9 < m_M < 7 \) TeV

• Flux of GUT MMs in the cosmic radiation:
  MACRO: \( \Phi < 1.4 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) for \( 4 \times 10^{-5} < \beta < 1 \)
  For the future: one would need new detectors with much larger surfaces

• IMMs:
  Experiments at mountain altitudes \( \Phi < 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \)
  For the future: need much larger detectors
  Experiments with neutrino telescopes for \( \beta > 0.6 \) from below
  For the future: need measurements from above

• Nuclearites: None found, limits \( \sim \) as for GUT MMs

• Q-balls
  

99 - ICTP 2004 - MMs