Magnetic Monopole Searches in the Cosmic Radiation

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Talk Outline

- Theoretical framework
- Hints from astrophysics
- Detection techniques
- Experimental searches
- Results
- Conclusions
Theoretical framework

1931: Classical Dirac monopole.

Charge quantization:

\[ g = \left( \frac{e}{2\alpha} \right) \cdot n \]

1974: 't Hooft and Polyakov: GUT Monopoles

Each time a semisimple non abelian gauge group (e.g. SU(N)) is broken leaving a residual U(1) subgroup, magnetic monopoles are produced as topologically stable soliton solutions of the theory. Their mass is of the order of the energy scale at which the symmetry breaking takes place. The Dirac quantization condition also applies.

\[ m_M \sim \frac{m_X}{\alpha_{\text{GUT}}} \quad (\sim 10^{17} \text{ GeV in the MSSM}) \]
Theoretical framework

Cosmological production of monopoles as point-like topological defects via the Kibble mechanism at the GUT phase transition(s)

“Standard” cosmology

Inflationary cosmology

Inflationary cosmology + thermal production

The “monopole problem” \( \rho_m \gg \rho_c \)

\( \rho_m \rightarrow 0 \)

Measurable flux ?!
Theoretical framework

... Other models:
- Superstring models \( \rightarrow g = 3g_D \) monopoles at detectable flux
- Intermediate symmetry breaking \( \rightarrow \) “Light” monopoles (\( m = 10^{10} \) GeV)
- ..................

Rubakov – Callan effect:
GUT monopoles can catalyze nucleon decay along their path with a cross section of the order of magnitude of that of strong interactions:

\[ \sigma = \sigma_0 / \beta \]

Some authors foresee another \( 1/\beta \) enhancement factor (for protons only)
Hints from astrophysics

Velocity distribution

• If no gravitational or magnetic interactions were considered \( <\beta> \to 0 \)

• The gravitational fields of galaxies (clusters of galaxies) might accelerate GUT monopoles up to the escape velocity, i.e. \( \beta \sim 10^{-3} \ (\beta \sim 10^{-2} - 10^{-1}) \). However, this mechanism has very low efficiency.

• Galactic (intergalactic) magnetic fields can efficiently accelerate them up to velocities \( \beta \sim 10^{-3} \ (\beta \sim 10^{-4}) \).

• Relativistic velocities might be reached due to interactions with huge strength magnetic fields (e.g. neutron stars).

Supermassive GUT monopoles have to be searched for in a wide \( \beta \) range \( (10^{-5} – 1) \)
Hints from astrophysics

Flux upper limits

- The closure bound implies $\rho_m < \rho_c$
- By requiring that magnetic monopoles do not short-circuit the galactic B field faster than the dynamo mechanism can regenerate it, the Parker bound is obtained ($\sim 10^{-15}/\text{cm}^2\text{s sr}$ with dependencies on both mass and $\beta$). Similar flux upper limits can be obtained by “using” other existing fields but on a weaker basis due to poor B field knowledge.
- Indirect limits can be obtained by measuring the energy radiated from astrophysical objects (e.g. NS) in which the Rubakov-Callan effect might be at work. They are very stringent but strong assumptions on monopole properties (e.g. the catalysis cross section) and object characteristics (e.g. the B field strength and configuration) have to be made.

Detectors must have a very large acceptance to go beyond
Detection Techniques

**“Induction”**
Detect current variations induced by the passage of a magnetic charge in one or more superconducting loops

**“Energy Loss”**
Detection based on energy loss mechanisms due to magnetic monopole interactions with matter. Many different signatures: scintillation light production, primary ionization in gas detectors, damage in track-etch detectors, direct Černý light production, ....

**“Catalysis”**
Detect the monopole catalyzed nucleon decay products

**Background rejection:**
underground sites, time and/or space coincidences, time of flight, pulse height analysis, .......
Experimental Searches

**Experimental Searches**

**Indirect searches**

Look for damage *tracks in large ancient mica* crystals induced by the passage of a monopole-nucleus bound system.

Very stringent limits $\sim 10^{-18} \text{cm}^2 \text{s sr}$, due to the long time exposures

**Drawbacks**

- A stable monopole-nucleus bound system is needed
- The sensitivity is confined to a narrow region around $\beta \sim 10^{-3}$
Experimental Searches

Direct searches: “Induction”

Model independent technique, since sensitive just to the magnetic charge. However, very poor flux limits ($\sim 10^{-13} / \text{cm}^2 \text{s sr}$) essentially due to small acceptances.
Experimental Searches

Direct searches: “Energy loss”

- KGF (gas detectors)
- Baksan (scintillation counters)
- Soudan (gas detectors)
- CR-39 Ohya quarry (track-etch detectors)
- MACRO (scintillation counters, gas detectors, track-etch detectors)
- AMANDA (Čerenkov light)
- Baikal (Čerenkov light)

..............
A ~ 1300 m²sr  <h> ~ 2100 mwe

**Soudan**

- Proportional Drift Tubes (Ar-CO₂)
- Drift Velocity 0.6 cm/µs
- 200 ns sampling
- 1 cm resolution in all coordinates
Search for fast monopoles by looking for single, long and clean tracks with large specific ionization

Visual scanning also required for a subsample in order to reject showering muons or events with non uniform specific ionization along the track
Liquid scintillators (m~600t, $\sigma_t$~750ps)
Streamer tubes (S~19000m², $\sigma_\theta$~0.5°)
Nuclear track-etch (S~1260m²)

Very wide $\beta$ range (5·10^{-5} – 1)
Redundancy & Complementarity
The reduced etch rate $p = \frac{V_T}{V_B}$

is simply related to the Restricted Energy Loss (REL)

$$REL = \frac{dE}{dX}_{E<E_{\text{max}}}$$
MACRO: 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**: 200MHz WFD + ADC/TDC system + several independent triggers
MACRO: streamer tubes

Scintillators ⊕ Streamers ⊕ Track-etch
combined analysis also performed

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

Require single track in wire, strip and time view

Time of Flight measurement

Integrated live time from 1992 up to 1999: 6.6 \cdot 10^4 \text{ hours}
Sensitive to relativistic monopoles, by the detection of the huge amount of emitted Č light.

A \sim 32800 \text{ m}^2\text{sr} \quad \langle h \rangle \sim 1500 \text{ mwe}
Experimental Searches

Direct searches: “Catalysis”

- IMB (Čerenkov light)
- Kamiokande (Čerenkov light)
- Soudan (gas detectors)
- MACRO (scintillation counters, gas detectors, track-etch detectors)
- Baikal (Čerenkov light)
- .......
Sensitivity to very slow monopoles, by the detection of the Č light emitted by nucleon decay products.

Flux upper limits below the Parker bound for $\beta \sim 10^{-5}-10^{-4}$ monopoles but need assumptions on the catalysis cross section value.

Sensitive to relativistic monopoles by the detection of “direct” monopole Č light.
- Parker bound
- Extended Parker Bound
- Closure Bound (uniform)

Flux upper limits

- Direct searches
- \( g = g_D \)
- \( \sigma_{\text{cat}} < 1 \text{ mb} \)
- Isotropic flux

\( m \sim 10^{17} \text{ GeV} \)
Flux limits obtained by assuming the catalysis of nucleon decay with

$$\sigma_{\text{cat}} = \frac{\sigma_0}{\beta^2}$$

MACRO result coming soon
Results

- **Very strong limits** have been put by different experiments in a wide velocity range.

- No stringent conclusions on GUT/cosmology can be made on the basis of a negative result ....

  .. unless (may be) for some superstring models that foresee fluxes at the level of the Parker bound

- **New interest** in the field due to several models about the monopole-UHECR connection .....

  ... in this case expectations are near to the experimental sensitivities
The monopole-UHECR connection

UHECR events above the GZK cut-off explained as due to ....

Energy release in monopole-antimonopole annihilation

- The binding mechanism is very inefficient
- The UHECR flux can be explained only if monopoles are connected by strings.

Monopole induced showers in the atmosphere

- Large $\gamma$ needed to produce showers $\rightarrow$ ultra-relativistic monopoles only
- Low mass monopoles could be accelerated up to those velocities ($m<10^{15}$ GeV)
- The required monopole flux is at the level of the Parker bound (measurable !)
- Relativistic light monopoles could not cross the Earth if $m < 10^{11}$ GeV
- Sensitivity of under-water/ice experiments limited to $10^{11}$ GeV $< m < 10^{15}$ GeV if the search is performed for upward going particles only
Conclusions

Supermassive magnetic monopoles are foreseen by GUT theories as well as p-decay and massive neutrinos.

GUT “folding” with cosmology does not give strict prediction on their flux. Upper limits are given by astrophysics arguments.

Several searches produced stringent experimental limits, very difficult to improve with future experiments.

They also are a strong weir for future theoretical speculations.

Important progress might be done in the next few years by under-water/ice experiments, due to their large acceptances, but for relativistic monopoles only (unless the nucleon decay catalysis is assumed)

Searches for relativistic (light) monopoles look interesting because of the monopole-UHECR connection
“At the present time there is no experimental evidence for the existence of magnetic charges or monopoles, ... but the search is renewed whenever a new energy region is opened up”

J.D. Jackson, 1975
Beware of the **Sirens**!!

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