Searches for magnetic monopoles: 
A review

Vasiliki A. Mitsou

Mini-workshop on Highly Ionising Avatars of New Physics

ICNFP 2018
7th International Conference on New Frontiers in Physics
4 – 12 July 2018, Kolymbari, Crete, Greece
Magnetic monopoles

- Motivation
- (Some) theoretical proposals

Talk by Sarben Sarkar in "avatars" workshop
In 1873, Maxwell makes the connection between electricity and magnetism - the first Grand Unified Theory!
Magnetic monopoles: symmetrising Maxwell

- As no magnetic monopole had ever been seen, Maxwell kept isolated magnetic charges out from his equations – making them asymmetric.
- A magnetic monopole restores the symmetry to Maxwell’s equations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Without Magnetic Monopoles</th>
<th>With Magnetic Monopoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss's law:</td>
<td>$\nabla \cdot \vec{E} = 4\pi \rho_e$</td>
<td>$\nabla \cdot \vec{E} = 4\pi \rho_e$</td>
</tr>
<tr>
<td>Gauss' law for magnetism:</td>
<td>$\nabla \cdot \vec{B} = 0$</td>
<td>$\nabla \cdot \vec{B} = 4\pi \rho_m$</td>
</tr>
<tr>
<td>Faraday's law of induction:</td>
<td>$-\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$</td>
<td>$-\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi \vec{J}_m$</td>
</tr>
<tr>
<td>Ampère's law (with Maxwell's extension):</td>
<td>$\nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$</td>
<td>$\nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$</td>
</tr>
</tbody>
</table>

- Symmetrised Maxwell’s equations invariant under rotations in $(\mathbf{E}, \mathbf{B})$ plane of the electric and magnetic field.
- Duality ➤ distinction between electric and magnetic charge is only a matter of definition.
Dirac’s monopole

- Paul Dirac in 1931 hypothesised that the magnetic monopole exists
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid
- Dirac’s quantisation condition:

\[
ge = \left[\frac{\hbar c}{2}\right] n \quad \text{OR} \quad g = \frac{n}{2\alpha} e \quad \text{(from)} \quad \frac{4\pi e g}{hc} = 2\pi n \quad n = 1, 2, 3, ..
\]

- where \(g\) is the magnetic charge and \(\alpha\) is the fine structure constant 1/137
- This means that \(g = 68.5e\) (when \(n=1\))!
- If magnetic monopole exists then charge is quantised:

\[
e = \left[\frac{\hbar c}{2g}\right] n
\]
GUT monopoles

- ‘t Hooft and Polyakov (1974) showed that monopoles are fundamental solutions to non-Abelian gauge grand unification theories (GUTs)
- **Topological solitons**: stable, non-dissipative, finite-energy solutions
- **Mass**:
  - $10^{13}$ GeV < $M$ < $10^{19}$ GeV
  - in intermediate stages of symmetry breaking:
    - $10^7$ GeV < $M$ < $10^{13}$ GeV
    - cannot be produced in accelerators
- **Size**: extended object
  - radius > few femtometers
Electroweak monopole


• Non-trivial hybrid between the Dirac and the ‘t Hooft & Polyakov monopole

• Properties
  ▫ charge $2g_D$
  ▫ mass predicted to be $\sim 4 \div 10$ TeV
    $\Rightarrow$ accessible to LHC!

Monopolium

Dirac or other monopoles may not be free states but bound states
→ monopolium (MM)

Production cross section @ LHC, √s = 14 TeV vs. monopole mass

Binding energy fixed = 2m/15 , e.g. for m=750 GeV, binding energy = 100 GeV
→ monopolium mass M = 1400 GeV

**Monopolium detection**

- Via its decay to **two photons** [Epele, Fanchiotti, Garcia-Canal, VAM, Vento, arXiv:1607.05592]
- Monopolium is neutral in its ground state thus, if produced in such a state, it is difficult to detect it directly
- However... it may be produced in an excited state, which could be a magnetic multiple ➔ highly ionising

Monopolium might break up into highly-ionising **Dyons**

Its decay via photon emission would produce a **peculiar trajectory** in the medium, if the decaying states are also magnetic multipoles

In presence of magnetic fields ➔ huge polarisability

\[ d \sim r_M^3 B \sim (\alpha E_{binding})^{-3} B \]

Single magnetic charge (Dirac charge): $g_D = 68.5e$
- higher charges are integer multiples of Dirac charge: $g = ng_D$, $n = 1, 2, ...$
- if carries electric charge as well, is called Dyon

Large coupling constant: $g/\hbar c \sim 34$

Monopoles would *accelerate* along field lines – and *not curve* as electrical charges in a magnetic field – according to the Lorentz equation:

$$\vec{F} = g \left( \vec{B} - \vec{v} \times \vec{E} \right)$$

Dirac monopole is a point-like particle; GUT monopoles are extended objects

Monopole spin is not determined by theory $\rightarrow$ free parameter

Monopole mass not predicted within Dirac’s theory; other theories predict masses from $\mathcal{O}(\text{TeV})$ (electroweak) to $\gtrsim 10^{17} \text{ GeV}$ (GUT) $\rightarrow$ free parameter

Monopole interaction with matter: high ionisation, Cherenkov radiation, transition radiation and multiple scattering
Searches for magnetic monopoles

- Detection techniques
- Past results
- Currently operating experiments

Talk by Laura Patrizii on July 7th

Illustration by Sandbox Studio, Chicago with Corinne Mucha
Monopole origin

- Cosmic monopoles
  - only way to probe GUT-scale monopoles
- Monopoles produced in high-energy collisions
  - only \( \lesssim \) TeV masses accessible
  - plus: indirect detection of virtual monopoles yielding multi-photon events
- Various detection techniques can be (have been) deployed to detect both cosmic and collider monopoles
  - certain limitations apply
Detection techniques

• High ionisation in gaseous detectors – transition radiation
  ▫ MACRO, ATLAS, ...
• Induction technique in superconductive coils (SQUID)
  ▫ initially for cosmic monopoles; not competitive with other techniques nowadays
  ▫ for monopoles trapped in material: rocks, beam pipes, ...
• Cherenkov light in scintillators
  ▫ cosmic monopoles
  ▫ balloon-borne experiments
  ▫ deep-sea/ice experiments: ANTARES, IceCube
• Energy loss in nuclear track detectors
  ▫ cosmic (SLIM, ...)
  ▫ colliders: PETRA, Tevatron (D0), LEP (MODAL, OPAL), LHC (MoEDAL)
• Catalysis of nucleon decay
  ▫ GUT monopoles may catalyse B-number violating decays via the Callan-Rubakov mechanism
  ▫ Soudan, MACRO, IMB
  ▫ v-telescopes: IceCube, Super-Kamiokande
Energy loss

\[ \frac{-dE}{dx} = K \frac{Z^2}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right] \]

charge \quad velocity: \beta = v/c \quad = \frac{z}{\beta}

High ionisation (HI) possible when:

- multiple electric charge (H\textsuperscript{++}, Q-balls, etc.) = n \times e
- very low velocity & electric charge
- magnetic charge (monopoles, dyons) = ng\textsubscript{D} = n \times 68.5 \times e  
  - a singly charged relativistic monopole has ionisation \sim 4700 times MIP!!
- any combination of the above

Magnetic charge
Ahlen formula

Electric charge
Bethe-Bloch formula

talks by Igor Ostrovskiy & by Stanislav Pospisil in “Avatars” workshop
Nuclear Track Detectors (NTDs)

- Passage of a highly ionising particle through the plastic NTD marked by an invisible damage zone ("latent track") along the trajectory
- The damage zone is revealed as a **cone-shaped etch-pit** when the plastic sheet is chemically etched
- Plastic sheets are later **scanned** to detect etch-pits

Looking for aligned etch pits in multiple sheets
**NTD analysis procedure**

- **Track diameter:**
  \[ D = 2v_B [(v_T - v_B) / (v_T + v_B)]^{-1/2} \]

- **Track depth:**
  \[ L = (v_T - v_B) t \]

- **Reduced etch rate:**
  \[ p = v_T / v_B \]

- **Electrically-charged particle:** \( dE/dx \sim \beta^{-2} \) → slows down appreciably within NTD → opening angle of etch-pit cone becomes **smaller**

- **Magnetic monopole:** \( dE/dx \sim \ln \beta \)
  - slow MM: slows down within an NTD stack → its ionisation falls → opening angle of the etch pits would become **larger**
  - relativistic MM: \( dE/dx \) essentially constant → trail of equal diameter etch-pit pairs

- The reduced etch rate is simply related to the **restricted energy loss**
  \[ REL = (dE/dx)_{10\text{nm}} \text{ from track} \]

---

**see, e.g.** Cecchini, Patrizii, Sahnoun, Sirri, Togo, arXiv:1606.01220
Induction technique

- Binding energy of monopoles in nuclei with finite magnetic dipole moments $\mathcal{O}(100 \text{ keV})$
- Monopole trapping volumes analysed with superconducting quantum interference device (SQUID)
- **Persistent current**: difference between resulting current after and before
  - first subtract current measurement for empty holder
  - if other than zero → monopole signature

Typical sample & pseudo-monopole curves
Induction – evidence?

- Data from Cabrera’s apparatus taken on St. Valentine’s day in 1982
  - the trace shows a jump consistent with a monopole traversing the coil
- In August 1985 a group at Imperial College London reported the “observation of an unexpected event” also compatible with a monopole traversing the detector
  - however their analysis conclude that “it is increasingly likely that Cabrera’s original candidate event was spurious”

Nature 317 (1985) 234
Monopoles of cosmic origin

- Searches in bulk matter
  - terrestrial magnetic materials
  - meteorites
  - moon rocks: One of the first scientific experiments with moon rocks was to search for a concentration of magnetic monopoles

- Searches in cosmic rays
  - passive detectors, e.g. NTDs
  - Cherenkov detectors
  - scintillators
  - streamer tubes
  - nucleon-decay catalysis

- Galactic magnetic field implies that monopole flux has to respect an upper limit ➔ Parker bound
Cosmic monopole searches

![Graph showing monopole search results](image-url)
Focus on “fast” (β>0.1) monopoles

Catalysis of proton decay

Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

σ_{cat/β} ≈ 1.8 \times 10^{-28} \text{ cm}^2
Monopole production at colliders

Various high ionisation techniques (including NTDs) and induction (D0, CDF, HERA) have been used to search for monopoles at colliders.

Dirac monopole production with $\sigma > 0.05$ pb at LEP was excluded by OPAL for $45 < \text{mass} < 102$ GeV [Phys.Lett. B663 (2008) 37]

CDF @ Tevatron excluded MM pair production at the 95% CL for cross-section $< 0.2$ pb and monopole masses $200 < m_M < 700$ GeV [Phys.Rev.Lett. 96 (2006) 201801]
**ATLAS @ LHC**

- Distinct signals in Transition Radiation Tracker (high-threshold hit) and EM calorimeter (large localised energy deposit)
- Upper cross-section limits set for Dirac monopoles of mass of $200 - 2500$ GeV
- Magnetic charges probed: $0.5 < |g| < 2.0 \, g_D$

**Talk by Judita Mamuzic in “Avatars” workshop**
Monopole & Exotics Detector At LHC

MoEDAL is unlike any other LHC experiment:
- mostly passive detectors; no trigger; no readout
- the largest deployment of passive Nuclear Track Detectors (NTDs) at an accelerator
- the 1st time trapping detectors are deployed as a detector

DETECTOR SYSTEMS

1. Low-threshold NTD (LT-NTD) array
   - $z/\beta > \sim 5 - 10$

2. Very High Charge Catcher NTD (HCC-NTD) array
   - $z/\beta > \sim 50$

3. Monopole Trapping detector (MMT)

4. TimePix radiation background monitor

MoEDAL physics program
[arXiv:1405.7662]

talk by Jim Pinfold in “Avatars” workshop
Latest MoEDAL results

- More exposure (× 5.7) including 2016
- New interpretations w.r.t. previous analyses
  - spin-1 monopoles
  - β-dependent γM̅M coupling

<table>
<thead>
<tr>
<th>DY lower mass limits [GeV]</th>
<th>Magnetic charge</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g_d</td>
<td>2g_d</td>
</tr>
<tr>
<td>MoEDAL 13 TeV 2015+2016 exp.</td>
<td>spin 0</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>spin ½</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>spin 1</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>spin 0, β-dep.</td>
<td>490</td>
</tr>
<tr>
<td></td>
<td>spin ½, β-dep.</td>
<td>850</td>
</tr>
<tr>
<td></td>
<td>spin 1, β-dep.</td>
<td>930</td>
</tr>
<tr>
<td>MoEDAL 13 TeV 2015 exp.</td>
<td>spin 0</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>spin ½</td>
<td>890</td>
</tr>
<tr>
<td>MoEDAL 8 TeV</td>
<td>spin 0</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>spin ½</td>
<td>700</td>
</tr>
<tr>
<td>ATLAS 8 TeV</td>
<td>spin 0</td>
<td>1050</td>
</tr>
<tr>
<td></td>
<td>spin ½</td>
<td>1340</td>
</tr>
</tbody>
</table>

Detector: 222 kg of Al bars
Exposure: 2.11 fb⁻¹ of pp collisions

- Mass limits are highly model-dependent
  - Drell-Yan production does not take into account non-perturbative nature of the large monopole-photon coupling
- World-best collider limits for |g| ≥ 2 g_d


More exposure (× 5.7) including 2016
New interpretations w.r.t. previous analyses
- spin-1 monopoles
- β-dependent γM̅M coupling

for γ-fusion ☞ talks by
Stephanie Baines & Arka Santra in “Avatars” workshop
Collider searches summary (as of August 2017)

\[ g = g_D \]

Monopoles continue to excite interest and have been the subject of numerous experimental searches.

There are several strong arguments to expect that magnetic monopoles exist.

The MoEDAL experiment at the LHC is one of the key players in this quest.

Stay tuned for upcoming results!
Thank you for your attention!

*Project supported by a 2017 Leonardo Grant for Researchers and Cultural Creators, BBVA Foundation*
Spares
Magnetic monopole mass

- No real prediction for classical Dirac monopole mass
  - if monopole radius $\sim$ electron radius $\Rightarrow m_{\text{monopole}} \approx n \times (2.4 \text{ GeV})$
- There are other models where monopoles could appear in a mass range accessible to the LHC. e.g.:
  - the electroweak Cho-Maison monopole [PLB 391 (1997) 360]
  - the Troost-Vinciarelli monopole had a matter field: 50-100 GeV [PLB 63 (1976) 453]
- GUT monopoles
  - 't Hooft and Polyakov (1974) showed that monopoles are fundamental solutions to non-Abelian gauge “GUT” theories – in any theory with an unbroken U(1) factor embedded
  - $m(M_{\text{GUT}}) \geq m_x / G > 10^{16} \text{ GeV} \quad 10^{17} \text{ GeV} \sim 0.02 \text{ g} - \text{not producible by particle accelerators}$
- We consider the magnetic monopole mass a free parameter
MMT 2015-2016 results

Detector: prototype of 222 kg of Al bars
Exposure: 2.11 fb\(^{-1}\) of 13 TeV pp collisions 2015&2016

\[ \beta \text{-independent} \]

\[ \beta \text{-dependent} \]

\[ \text{DY spin-0} \]

\[ \text{DY spin-1/2} \]

\[ \text{DY spin-1} \]

Cosmic monopoles

\[ g = g_0 \]

\[ \beta_{\text{min}} \]

\[ \text{Monopole Mass (GeV)} \]

\[ \text{MM from above at MACRO depth} \]

\[ \text{MM at 5230 m altitude} \]

\[ \text{MM at 20 km altitude} \]
