The Search for Magnetic Monopoles

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1 Introduction

You could say that the idea of a magnetic monopole started in 1269. In that year, the scholar, soldier and monk, Pierre de Maricourt produced a remarkable document named the Epistola de Magnete \[1\] that identified for the first time that a magnet had a north and a south pole. This begs the age–old question: can there be a single pole, a magnetic monopole? By the 19th century Gauss’s law for magnetism, enshrined as one of Maxwell’s equations, stated mathematically that magnetic monopoles do not exist. Maxwell’s equations - that posit only electric charges occur in nature - can be made fully symmetric under the interchange of the electric and magnetic fields if magnetic charges also exist. A courageous Pierre Curie was the first to suggest that magnetic monopoles could conceivably be present in nature in a paper published in 1894 \[2\].

It was Dirac who took up Curie’s challenge. In 1931, he hypothesized that a magnetic monopole could exist within the framework of quantum mechanics \[3\]. He saw the monopole as the end of an infinitely thin infinitely long solenoid called a “Dirac string”. The annoying string does not pose a problem as long as it cannot be detected. The mathematics that ensured this gave rise to a quantum relation between the electric and magnetic charges: 
\[
e^{egg} = 1 \implies qg = 2\pi n (n = 1, 2, 3,...)
\]
where \(q\) represents the charge of the electron and \(g\) the Dirac (magnetic) charge. This relation is the Dirac Quantization Condition that expresses the quantization of electric charge, as long as at least one monopole exists. In 1969 Schwinger published a paper \[4\] describing an extension of the Dirac quantization condition to a dyon - a hypothetical particle that has both magnetic and electric charge.

In 1974 Gerard t Hooft \[5\] and Alexander Polyakov \[6\] discovered that model for Electroweak Unification proposed by Georgi and Glashow \[7\] contained a stable field configuration - like a knot that cannot unravel - corresponding to a magnetic monopole. The ’t Hooft-Polyakov monopole is totally different from the Dirac monopole, it is a topological defect or a topological soliton. The mass of such a monopole - roughly 100 GeV, determined by the energy scale associated with weak nuclear forces - is too low to be compatible with experimental results. But ’t Hooft and Polyakov noticed that the structure of the SU(5) Grand Unified Theory (GUT) was similar to that of the Georgi-Glashow model and hence also contained a monopole solution, but with the much higher mass of \(10^{16} \text{GeV}/c^2\). The ’t Hooft-Polyakov, or GUT, monopoles also have the exciting ability to catalyse nucleon decay \[8\]. The heart of the monopole retains the full SU(5) symmetry that held prior to the freezeout of the electroweak and strong forces, when leptons and quarks were part of the same extended family. This means that when a proton or a neutron gets in contact with a GUT monopole, it is very likely to decay.
The discovery of a Higgs-like boson in July 2012 by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) has lead unambiguously to the completion of the puzzle of the Standard Model spectrum. It has been asserted that the Weinberg-Salam model has no topological monopole of physical interest. But, Cho and Maison pointed out that the Weinberg-Salam model could be viewed as a gauged CP\textsuperscript{1} model, with the Higgs doublet field interpreted as the CP\textsuperscript{1} field. This would be an extension of our view of the Standard Model. Importantly, the second homotopy group of the gauged CP\textsuperscript{1} model is the same as that of the Georgi-Glashow model that contains the ’t Hooft-Polyakov monopole.

The Cho-Maison monopole is the electroweak (EW) generalization of Dirac’s monopole, that can be viewed as a hybrid of Dirac and t Hooft-Polyakov monopoles. But unlike Dirac’s monopole, it carries the magnetic charge 4\pi/e. This is because in the Standard Model the U(1)\textsubscript{EM} part has the period of 4\pi not 2\pi, as it comes from the U(1) subgroup of SU(2). Thus the magnetic charge of the EW monopole is twice that of the Dirac Monopole. Recent estimates of the EW monopole mass indicate that it’s possibly detectable at the LHC.

Since 1931 physicists have been assiduously searching for magnetic monopoles: in cosmic rays; trapped in bulk matter, in lunar dust, meteors and on Earth; also, at accelerators where they would be produced in high-energy particle interactions. Indeed, a monopole search has been performed at each advance of the high-energy frontier driven by the relentless increase of particle accelerator energy. MoEDAL - the Monopole and Exotics Detector at the Large Hadron Collider (LHC) - has been custom-made to continue the search, along with the general-purpose LHC detectors, to the multi-TeV realm.

2 Monopole Properties

Dirac showed the magnetic charge of a monopole is \( g = n(e/2\alpha) \), where \( \alpha \approx 1/137 \) is the fine structure constant. Thus, a unit of magnetic monopole is \( g \sim 68.5e \). The magnetic charge should be larger if \( n > 1 \) and also if the fundamental unit of electric charge is \( e/3 \), rather than \( e \). In analogy with the fine structure constant, \( \alpha = e^2/\hbar c \), the dimensionless magnetic coupling constant is \( \alpha_g = g^2/\hbar c = 34.25 \) which is much larger than one and thus perturbative calculations involving monopoles face serious difficulties.

As we can see from the Bethe formula for magnetic charge given below the energy loss of a singly charged (\( n=1 \)) very relativistic magnetic monopole (\( \beta \approx 1 \)) is amazingly about 4700 times that of a proton! The Bethe formula for ionization energy loss by a relativistic monopoles is given by replacing \( ze \) with \( ng\beta \):

\[
-\frac{dE}{dx} = (ng/e)^2 KZ A \left[ \frac{1}{2} \ln \left( \frac{2m_e \beta^2 \gamma^2}{I^2} \right) - \beta^2 \right]
\]

Also, the energy loss for magnetically charged particles falls with decreasing \( \beta \) unlike electrically charged particles where the energy loss rises quickly when \( \beta \gamma \lesssim 1.3 \).

A moving magnetic monopole traversing the superconducting wire coil of a SQUID (Superconducting Quantum Interference Device) drives an electrical current within the coil. One can use Faraday’s Law to calculate the magnitude of the current that would be generated: \( I = -\mu_0 g/L \), where \( L \) is the inductance of the coil and \( \mu_0 \) is the permeability of...
free space. Consequently, the induced current only depends on the magnetic charge and is independent of the speed or direction of the magnetic monopole.

Monopoles will accelerate along magnetic field lines acquiring energy. The energy $W$ acquired in a magnetic field $B$ is $W = n g_D B l = n 20.5 \text{ GeV/T m}$, where $l$ is the distance travelled in a coherent magnetic field. Thus, modern magnets can be easily be used to accelerate monopoles to multi-TeV energies. Another unique signature of a monopole is its usual trajectory in a magnetic field. For example in a solenoidal field electrically charged particles curve in a plane transverse to the field lines (the $r - \phi$ plane) but do not bend in the plane running parallel with the field lines (the $r - Z$ plane). Conversely, magnetic monopole move along parabolic paths in the $r - z$ plane but no not bend in the $r - \phi$ plane.

Figure 1: (Left) (a) Drell-Yan production of a lepton pair. (b) Drell-Yan production of a monopole pair. (c) Two photon production of a monopole pair. (d) Two photon production of a high energy photon pair production via a virtual monopole box.

3 Searching for Magnetic Monopoles at Colliders

Magnetic Monopole searches have been performed at colliders [12], in cosmic rays and in matter since the 1950s, and are still continuing today [13]. Table 1 gives a list of the accelerator searches at accelerators over the last 25 years. Most searches at accelerators rely on the highly ionizing nature of the magnetic monopole, utilizing the following detector technologies: scintillators, gaseous counters and Nuclear Track Detectors (NTDs).

Due to the large coupling constant of the magnetic monopole perturbative calculations of the magnetic monopole cross section cannot be made. Instead a Drell-Yan mechanism is assumed for the cross-section calculation. Figure 3 shows a Feynman diagram of the Drell-Yan mechanism for dimuons and monopole-antimonopole production. These two diagrams shows annihilation of the quark-antiquark via the intermediate virtual photon and later photon decay into the two leptons (a) and monopole-antimonopole pair (b). Monopoles pairs can also be produced in two photon interactions, as shown in Figure 3(c).

The search for Monopole production in nucleus-nucleus (AA) collisions has been pro-
posed [14] and performed [15]. This interest is motivated by the expected $\sim Z^4$ enhancement in production [16] of magnetic monopoles. But, this benefit of this enhancement is countered by the rapid fall in the intensity of interaction with the produced particle mass [17].

A virtual process involving a monopole box diagram [18] that gives rise to two high transverse momentum photons - as shown in Figure (d) - was sought by the D0 collaboration [19]. Such a process can be produced in $e^+e^-$ or $q\bar{q}$ collisions. The L3 experiment at LEP [20] searched for $Z$ decays into 3 photons that can take place via a monopole loop. However, calculations involving monopole loops are challenging due to the size of the monopole’s magnetic charge and coupling constant. Consequently, indirect limits based on this approach are questionable [21].

Table 1: A list of monopole searches at accelerators over the last 25 years.

| Reaction | $\sqrt{s}$ GeV | $M_{init}$ GeV/$c^2$ | $\sigma$ MM cm$^2$ | MM Chrg | Tech. | Year | Ref. |
|----------|----------------|----------------------|-----------------|--------|-------|------|------|
| pp       | 1800           | <850                 | 2.e-34          | $\geq0.5$ | Plstc | 1990 | [24] |
| e+e-     | 88-94          | <45                   | 3.e-37          | 1      | Plstc | 1992 | [25] |
| e+e-     | 88-94          |                       |                 | Plstc  | 1993 | [26] |
| pbA      | 17.9           | <8.1                 | 1.9e-33         | $\geq2$ | Plstc | 1997 | [27] |
| AuAu     | 4.87           | <3.3                 | 0.65e-33        | $\geq2$ | Plstc | 1997 | [27] |
| ppbar    | 1800           | 260-420              | 7.8e-36         | 2-6    | Indctn | 2000 | [28] |
| ppbar    | 1800           | 265-410              | 0.2e-36         | 1-6    | Indctn | 2004 | [29] |
| e+p      | 300            |                       | 0.5e-37         | 1-6    | Indctn | 2005 | [30] |
| ppbar    | 1800           | 369                  | 0.2e-36         | $\geq1$ | Cntr  | 2006 | [31] |
| e+e-     | 206.3          | 45 - 102             | 0.05e-36        | 1      | Cntr  | 2007 | [32] |
| pp       | 7000           | 200-1500             | 2e-39           | 1      | Cntr  | 2012 | [33] |

4 The Search for Monopoles for Cosmic Monopoles

Cosmic monopoles that are detectable on Earth can either be light, for example produced locally in cosmic ray interactions with the atmosphere with mass less significantly less that the GUT scale, or else so heavy that they can only have been produced soon after the birth of the Universe in the Big-Bang. Most of these searches have been based on the premise that the monopoles are produced in a symmetry-breaking phase transition in the early Universe as topological defects via the Kibble mechanism [22] - typically with the GUT mass $\sim 10^{16}$ GeV/$c^2$. Some GUT models and some supersymmetric models predict Intermediate Mass Monopoles (IMMs) with masses $10^5 < M_{mass} < 10^{12}$ GeV and with magnetic charges of multiples of $g_D$; these IMMs may have been produced in later phase transitions in the early Universe and could be present in the cosmic radiation [23].

A wide variety of techniques have been employed to search for cosmic monopoles, these include: induction techniques with SQUID magnetometers to detect magnetic charge trapped in matter or in flight; detector arrays based on ionisation energy loss; detection of Cherenkov radiation in water or ice to probe relativistic monopoles; and nucleon-decay detectors for probing the monopole catalysis reaction. A list of experiments designed to search for cosmic ray monopoles over the last 25 years is given in Table 2.
Table 2: A list of cosmic monopole searches performed over the last 25 years.

| Lab.      | \(\phi (\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1})\) | Comments       | Technique | Year  | Ref. |
|-----------|-------------------------------------------------|-----------------|-----------|-------|------|
|           | < 7.2e-13                                       | all \(\beta\)   | Induction | 1990  | [33] |
|           | < 6.1e-18                                       | \(3 \times 10^{-4} < \beta < 1.5 \times 10^{-3}\) | Mica      | 1990  | [34] |
|           | < 1.8e-14                                       | \(\beta > 1.1 \times 10^{-4}\) | He-PT     | 1990  | [35] |
| Baikal    | < 3.6e-16                                       | \(\beta < 10^{-3}\) | Catalysis | 1990  | [36] |
|           | < 3.8e-13                                       | all \(\beta\)   | Induction | 1991  | [37] |
|           | < 3.2e-16                                       | \(\beta > 0.05\) | Plastic   | 1991  | [38] |
|           | < 7.2e-13                                       | all \(\beta\)   | Induction | 1991  | [39] |
|           | < 4.4e-12                                       | all \(\beta\)   | Induction | 1991  | [40] |
| SOUDAN-2  | < 8.7e-15                                       | \(\beta > 2 \times 10^{-3}\) | Counters  | 1992  | [41] |
| IMB       | < 8.7e-15                                       | \(\beta \sim 10^{-4}\) | Catalysis | 1994  | [42] |
| MACRO     | < 5.6e-15                                       | \(\beta = (1.8 - 3.0) \times 10^{-3}\) | Plastic/cntrs | 1994 | [43] |
| MACRO     | < 1.6e-15                                       | \(\beta = 0.18 - 3.0 \times 10^{-4}\) | Plastic/cntrs | 1997 | [44] |
| MACRO     | < 1.5e-15                                       | \(5 \times 10^{-3} < \beta < 0.99\) | Plastic/cntrs | 2002 | [45] |
| MACRO     | < 1.4e-16                                       | \(1.1 \times 10^{-3} < \beta < 1\) | Plastic/cntrs | 2002 | [46] |
| MACRO     | < 3.6e-16                                       | \(1.1 \times 10^{-4} < \beta < 5 \times 10^{-4}\) | Catalysis | 2002  | [47] |
| RICE      | < 1.6e-18                                       | \(\gamma > 10^8\) | Ceramic   | 2008  | [48] |
| SLIM      | < 1.5e-15                                       | \(\beta > 0.05\) | Plastic   | 2008  | [49] |
| AMANDA2   | < 3.8e-17                                       | \(\beta > 0.76\) | Ceramic   | 2010  | [50] |
| ANITA2    | < 1.6e-18                                       | \(\gamma > 10^{10}\) | Ceramic   | 2011  | [51] |
| Super-K   | < 6.6e-28                                       | \(\beta = 10^{-5}\) | Catalysis | 2012  | [52] |
| ANTARES   | < 1.3e-17                                       | \(\beta > 0.625\) | Ceramic   | 2012  | [53] |
| IceCube   | < 3.6e-18                                       | \(\beta > 0.8\)  | Ceramic   | 2013  | [54] |
| IceCube   | < 1.6e-18                                       |                          | Catalysis | 2014  | [55] |

Cosmic monopoles will be accelerated by galactic and intergalactic magnetic fields, draining energy from these fields. Parker [56] obtained an upper bound on the flux of monopoles in the galaxy based on the containing existence of these fields. With reasonable choices for the astrophysical parameters [57], this Parker bound is: \(F < 10^{15} \text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}\), when the monopole mass is less than around \(10^{17}\) GeV.

4.1 Observations of Cosmic Monopole Candidate Events Using SQUIDs

In the early 1980s, Blas Cabrera was one of the first experimenters to deploy a SQUID device in order to detect magnetic monopoles from the cosmos. His initial detector employed a four-turn, 5-cm-diam loop, positioned with its axis vertical, connected to the superconducting input coil of a SQUID magnetometer. During the night of February 14, 1982, this detector recorded an event that was completely consistent with being due to a magnetic monopole [58]. A group at Imperial College London observed another perfect candidate magnetic monopole event on the 11th of August 1985 [59]. To this day it is still not clear what background process can explain these signals.
5 The MoEDAL Experiment at the LHC

MoEDAL, the 7th and newest experiment [50] is dedicated to the detection of the highly ionizing particle avatars of new physics such as the magnetic monopole and massive stable or metastable charged particles. Such particles originate from a number of Beyond the Standard Model (BSM) scenarios that, for example, incorporate: magnetic charge, new symmetries of nature (eg Supersymmetry); extra spatial dimensions; dark matter particles, etc. The MoEDAL detector is a largely passive detector that makes it totally unlike other collider detectors. Essentially MoEDAL is a largely passive detector, like a giant camera ready to reveal “photographic” evidence for new physics - where plastic Nuclear Ttrack Detectors are the film. MoEDAL also has trapping detector volumes capable of capturing long-lived electrically and magnetically charged particles from beyond the Standard Model for further monitoring and study at a remote SQUID magnetometer facility and a deep underground laboratory such as SNOLAB. The MoEDAL experiment will significantly expand the horizon for discovery of the LHC, in a complementary way. It will start to take data in the Spring of 2015 when the LHC restarts at the unprecedented energy of $\sim 14 \text{ TeV}$

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Figure 2: (Left) The MoEDAL experiment surrounding interaction sharing the relatively open interaction point 8 on the LHC ring with the LHCb experiment.

The main LHC experiments are optimized to detect conventionally charged relativistic particles produced with a velocity high enough for them to be fully registered in the detector in the time between bunch crossings. Exotic, highly ionizing detector-stable particles produced at the LHC might be sufficiently massive to travel through the detector within a single trigger window and so will have a low efficiency for detection. Also, the sampling time and reconstruction software of each sub-detector is optimized assuming that particles
are travelling at close to the velocity of light. Hence, the quality of the read-out signal, reconstructed track or cluster may be degraded for an SMP, especially for subsystems at some distance from the interaction point. Another problem is that the main LHC detectors cannot be directly calibrated for highly ionizing particles such as the magnetic monopoles.

An additional challenge is that very highly ionizing particles can be absorbed before they penetrate the detector fully. Additionally, the read-out electronics of conventional LHC detector systems are usually not designed to have a wide enough dynamic range to measure the very large dE/dx of highly ionizing particles properly. In the case of the magnetic monopole there is also the problem of understanding the response of conventional LHC detector systems to particles with magnetic charge. All the above drawbacks can only get worse for increasing magnetic charge.

The MoEDAL experiment bypasses these experimental challenges by using a passive plastic NTD technique that does not require a trigger. Also, track-etch detectors provide a tried-and-tested method to detect and measure accurately the track of a very highly ionizing particle and its effective $Z/\beta$. Importantly, heavy-ion beams provide a demonstrated calibration technique because they leave energy depositions very similar to those of the hypothetical particles sought. A magnetic monopole would leave a characteristic set of 20 collinear etch-pits. Uniquely, a trapping detector array incorporated into MoEDAL allows the possibility of the direct detection of magnetic charge and the possibility to directly study the monopole. In this case monopoles are ranged out, stopped and then captured in matter by their interaction with the magnetic moment of the detector nuclei, forming long-lived bound states [61]. There are no Standard Model particles that could produce the distinctive signatures described above thus, even one event would herald a discovery. A plot showing the estimated sensitivity of MoEDAL for magnetic monopoles compared to the other LHC detectors is shown in Figure 3.

MoEDAL’s groundbreaking and complementary physics program is presented in a recently published paper [62]. This program covers over thirty fundamentally important Beyond the Standard Model (BSM) scenarios that place MoEDAL firmly at the Terascale discovery frontier. A key physics aim of MoEDAL is the search for the magnetic Monopole/Dyon. In addition, several other magnetically charged messengers of new physics are described in the MoEDAL physics paper [62] and in references therein. Of major importance is MoEDALs sensitivity to a wide range of massive detector stable, single, fractionally (charge >1), or multiply electrically charged HIPs that arise from a number of well motivated beyond the Standard Model scenarios. More than 20 such topics are described in MoEDALs physics program [62]. These BSM arenas, include: new symmetries of nature such as supersymmetry and left-right symmetry; extra spatial dimensions; a fourth generation; technicolour; vector-like confinement; long lived heavy quarks, non-commutative geometry; and multi-particle excitations such as Q-balls, strangelets, and quirks, etc.

6 “Cosmic-MoEDAL” a Proposal

SLIM was the first experiment to extend the search for cosmic Monopoles with masses well below the GUT scale, with a high sensitivity. However, SLIM’s modest size (≈ 400
m²) precluded it searching for a flux of cosmic monopoles below the Parker Bound. In this conference and at other venues I proposed a very large array (≳ 10,000 m²) of CR-39 detectors -“Cosmic-MoEDAL” - to be deployed at very high altitude, for example at the Mt Chacaltaya lab. in Bolivia with an elevation of 5,400 m. Such, an array would be able to take the search for cosmic monopoles with velocities β ≳ 0.1, from the LHC’s TEV scale all the way to the GUT scale, for monopole fluxes well below the Parker Bound.

Figure 3: The expected reach of the search for direct monopole - anti-monopole Drell-Yan pair production process at the LHC (Ecm =14 TeV). Assuming the luminosity taken by LHCb/MoEDAL is 2 fb⁻¹, by ATLAS & CMS 20 fb⁻¹, and by ALICE 0.004 fb⁻¹.

Large scale underwater and under ice neutrino telescopes (Amanda, IceCube, ANTARES, NEMO) can also search for fast IMMs with β ≳ 0.5 to below the Parker bound [63]. However, searches for lighter IMMs by Earth based detectors are essentially limited to downgoing particles [64] where these detectors have to discriminate against the large background of cosmic ray muons. Detectors such as IceCube should be able to search for sub-relativistic velocities when the GUT monopole can catalyze nucleon decays along their trajectories (Rubakov-Callan effect). This effect depends on the gauge group of the respective GUT theory [65] and on other assumptions, for example on the fermion masses or the relative velocity between the quarks and the monopole utilized [66]. Importantly, this process is not possible for IMMs with masses below 10¹³ GeV [67]. Cosmic-MoEDAL does not suffer from these limitations.

7 Closing Remarks

Although, the experimental evidence for the monopole is still lacking the theoretical requirement for their existence has increased. Dirac’s monopole was nice but not required. But many modern theories including Grand Unified Theories, String Theory, M - theory all require magnetic monopoles. One of the world’s leading string theorists, Joseph Polchinski, has generalized Dirac’s connection between magnetic monopoles and charge quantization.
He has posited that in any theoretical framework that requires charge to be quantized, there will exist magnetic monopoles. He also maintains that in any fully unified theory, for every gauge field there will exist electric and magnetic sources. Speaking at the Dirac Centennial Symposium in 2002, he commented that "the existence of magnetic monopoles seems like one of the safest bets that one can make about physics not yet seen" [68].

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