"The Search for Magnetic Monopoles"

Authors: Eleanor McNally, Judy Ayman, Sabina Guliyeva,

Susana Carmona, Yasmine Raouji

Research Mentor, Collaborator: Piyamini Tenahandi

Abstract

Magnets always share a common characteristic: they have two poles. Even though their division is considered, the result remains a smaller dipole. Nevertheless, physicists have been searching for a magnetic monopole. It is a hypothetical particle predicted by several theories. The magnetic monopole supposed a symmetry between electric and magnetic fields. The charge would be quantized in discrete units if this concept is proved. Experiments for their detection take place at CERN, specifically in the Large Hadron Collider (LHC).

01. Introduction

Magnetic monopoles were first introduced by Paul Dirac in 1931.The existence of a magnetically charged particle would add symmetry to Maxwell's equations and explain why electric charge is quantized in nature(Acharya et al., 2019,2) opening new directions to research in electromagnetism. Despite any theoretical approach, numerous experiments have been conducted to search for this particle; however, many have yet to succeed. Currently, LHC is focusing some of its experiments, such as ALICE, a heavy-ion collider, ATLAS, a general-purpose detector, and MoEDAL, designed to search for monopoles and other exotic particles, on detecting monopoles. The LHC is primarily using three methods to detect monopoles. The first method involves producing pairs of magnetic monopoles in particle interactions, either from a single photon—a technique known as the Drell-Yan mechanism—or from the fusion of two photons. The second method, known as the Schwinger mechanism, is based on producing pairs of magnetic monopoles from the vacuum in the intense magnetic fields created when heavy ions nearly collide. And the last one is the photon-fusion mechanism. ATLAS experiments results have benefited compared to previous searches, due to larger datasets.
This paper reviews the current state of research in monopole detection, focusing on its current detection, the fundamental theory of magnetic monopoles, and previous and ongoing research in the field.

02. Mathematical and physics implications.

This paragraph serves the purpose of explaining the mathematical and physics concepts behind the hypothesis of monopoles delving deeper also on the theoretical tradition that was present before this supposition.

It is possible to describe the magnetic force in a moving particle by using the vectorial product of the velocity vector, the magnetic field, the electric field, and the charge module.
This force is also called Lorentz force and it's written in the following way:

$$F = q(E + v \times B)$$

(Equation 1)

However consider the equation only in a magnetic field this time, which leads it to be,

$$F = qv \times B$$

(Equation 2)

Moreover, the magnetic force is a non-conservative force, with this information in hand we can state that since the force is always perpendicular to the velocity vector, which is also the direction of the motion; it means that the Work that the force does to move the charge is $L = F \cdot \Delta x$ and, since Δx is parallel to v and F is perpendicular to both of them, work is the scalar product of two vectors that are perpendicular to each other, in conclusion, the equation is null.
This means that if no work is put upon the charge, the module of the velocity is constant.
In case the charge has a circular trajectory, then it could be considered a circular motion, and the magnetic force is a centripetal force.

$$qvB = m(v^2/r)$$

(Equation 3)

$$1/qB = r/mv$$

(Equation 3.1)

$$r = mv/qB$$

(Equation 3.2)

This equation is necessary to experimental physicists as it helps in experiments and applications such as mass spectrometers (to separate various isotopes due to the difference in their mass), magnetic flowmeters (mainly used in medicine), and also in speed selectors.

An important but apparent aspect of magnets is that t*hey* always have two poles, a north and a south.
We can think about how when a magnet is divided, thanks to the concept of magnetization, due to the positions that the electrons take inside the magnets, there will always be two newly generated poles. To this concept, every single electron inside of a metal becomes a small magnet that reacts and aligns with the field.

But, only certain materials exhibit strong magnetic effects, these metals are called ferromagnetic.
In this category, it is possible to find chemical elements such as iron, cobalt, nickel, and gadolinium.
Instead, diamagnetism is the effect of the production, on behalf of a material, of a direct magnetic field but in the opposite direction of the external *B* field. Meanwhile, paramagnetism stands out since its elements do not have their own magnetic field; unless an Electromagnetic field is applied externally.

The mathematical concept that sets these three phenomena apart, is the *relative magnetic permeability.*

$$\mu r = \mu / \mu 0$$

(Equation 4)

- μ $is\ the\ permeability\ of\ a\ substance.$
- $\mu 0\ is\ the\ permeability\ in\ a\ vacuum.$

These pieces of information were considered a statement until Dirac formulated the concept of magnetic monopoles.
The magnetic monopole was hypothesized to explain a specific symmetry between *E* and *B* fields, therefore the monopole should be the equivalent of the electric point charge.

Moreover, if the concept of a monopole is proved this means that electric charge is necessarily quantized in discrete units.

The mathematical implication of said statement is the quantization equation:

$$e \cdot g = (n\hbar)/2$$
(Equation 5)

Where: *e* is the electric charge, *g* is the magnetic charge, $\hbar$ is the reduced Planck's constant ($\hbar$= *h* /(2π)) (Equation 6), n is an integer number (a number that belongs to the mathematical set N.
This condition implies that the product of the eclectic and magnetic charge must be quantized in units of $\hbar/2$.

The mathematical implications of these equations are mainly three.
The theory of charge quantization, which is explained formerly, the gauge symmetry, highlights the deep connection between these symmetries and the topological properties of space and the concept of duality and how it furthers the hypothesis of the GUTs (grand unified theories).
In the next paragraph, it will be explained how such a physical concept is produced in world-leading experiments such as MoEDAL in LHC.

03. How magnetic monopoles are generated at LHC

Although magnetic monopoles have never been detected at the MoEDAL experiment at CERN, the experiment aims to detect monopoles generated by three different mechanisms: the Drell-Yan process, the photon fusion mechanism, and the Schwinger mechanism. These are all processes that occur during high-energy Pb-Pb collisions.

In all three processes of generating magnetic monopoles, the monopoles would appear due to a vibration in the magnetic monopole quantum field where energy is converted to matter. As mass is directly proportional to energy via Einstein's $E = mc^2$ equation, and also considering the fact that a magnetic monopole is predicted to be around 4700x the mass of a proton, in order to generate a particle of such high mass it would require a huge amount of energy. Thus, high-energy heavy ion collisions are studied.

Role of LHC in the acceleration of Pb ions

In order for the Pb-Pb collision to have sufficient energy to trigger the mechanisms mentioned above they must be accelerated to 99.9999991% of the speed of light. LHC is the final and most integral part of this process. Before being injected into LHC the Pb ions are accelerated by a series of different accelerators. To a final energy of 177 Gev per nucleon which also strips the ions of all their electrons. In LHC, the particles are accelerated by radiofrequency (RF) cavities. LHC consists of 16 RF cavities. The RF cavities are driven by electron beams that oscillate 400 million times per second. A conductive pipe called a waveguide directs energy to the cavity which is designed to allow intensity electromagnetic waves to build reaching a maximum of 16MV per beam. The RF cavities are housed in cryomodules which keep them at a sufficiently cool temperature to maintain superconductivity.

The lead ions colliding in LHC are initially Pb 208 atoms. They begin as a 2cm 500mg strip of pure lead which is heated to 500 degrees Celsius to vaporize a small number of atoms, the first few electrons of which are ionized using an electric current. The electromagnetic waves produced by the RF cavities increase the energy of the incoming particles by more than 14 times. The particles pass through the RF cavities more than 100 million times over the course of about 20 minutes before reaching maximum speed.

During LHC heavy ion collisions, it is theorised that magnetic monopoles can be generated via three different mechanisms: The Drell-Yan process, the photon fusion mechanism and the Schwinger mechanism.

The Drell-Yan process occurs during these high-energy collisions in high-energy hadron-hadron scattering which comes from the interactions between the wavefunctions of the particles. The collisions also trigger the annihilation of a quark from one hadron and an antiquark from another hadron. This creates a virtual photon.

A virtual photon is a fluctuation in the quantum photon field. The vibration required to produce a real photon is similar to that of a virtual photon however it is more regular and more permanent.

In the Drell-Yan process, a magnetic monopole particle-antiparticle pair can be created by a virtual photon decaying into these particles. This has not been observed.

The photon fusion mechanism happens under the same conditions as stated above in reference to the Drell-Yan process. However in this case the virtual photons interact, involving interactions between vibrations in the quantum field) and this produces a magnetic monopole particle and antiparticle pair.

The Schwinger mechanism occurs during near-miss heavy ion collisions. When heavy ions such as lead engage in near-miss collisions the protons and neutrons (with positive and neutral charges respectively) that do not collide would be set aswirl generating the strongest known magnetic fields in the current universe as they're traveling at speeds very close to the speed of light. Pairs of magnetic monopoles could be produced from the vacuum in the magnetic field.

04. Detection of Magnetic monopoles

Despite the theoretical appeal of magnetic monopoles, scientists have developed several methods to try to detect them. The quest to detect magnetic monopoles through electromagnetic induction has been a fascinating journey in experimental physics. Current research in monopole detection encompasses a variety of techniques, each with its own strengths and limitations. These methods span different energy scales and leverage diverse physical phenomena, reflecting the multifaceted nature of the monopole search. Some of the prominent detection techniques under investigation include:

4.1 SQUIDs

Scientists first discovered the idea of directly observing magnetic charges using electromagnetic induction. The principle was elegantly simple: a magnetic monopole passing through a closed conducting ring would induce a persistent change in current, as the system attempted to maintain its original magnetic flux. This simply would not happen in the case of a magnetic dipole or higher order magnetic pole, for which the net induced current is zero, and hence the effect can be used as an evident test for the presence of magnetic monopoles. Initial experiments utilized room-temperature conducting coils, laying the groundwork for future developments.

The introduction of superconducting technology revolutionized magnetic monopole detection. Superconducting rings provided a key benefit: the capacity to maintain induced current changes indefinitely without the Joule heating inherent in conventional conductors. This innovation enabled more sensitive, longer-duration experiments. However, early superconducting detectors were limited by the inadequate sensitivity of available current-measuring electronics. This constraint required multiple passes of potential monopole-containing samples to produce detectable signals, restricting initial investigations mainly to bulk matter searches. Despite these challenges, superconducting technology laid the foundation for more advanced monopole detection methods.

The true revolution in monopole detection came with the development of the Superconducting Quantum Interferometer Device (SQUID) and ultra-low magnetic field shields. These technologies dramatically enhanced the sensitivity and precision of monopole detection methods. SQUIDs, capable of detecting incredibly minute magnetic fields, opened the door to dynamic monopole detection. This advancement allowed researchers to move beyond static bulk matter searches to more versatile and sensitive detection methods.

In 1982, physicist Blas Cabrera made a potentially groundbreaking discovery where Cabrera's custom-built detector registered a signal consistent with the existence of a magnetic monopole, which was described as a hypothetical particle that had never been observed before. Cabrera had spent three years developing and fine-tuning his experimental apparatus to detect these elusive particles. The detector was designed to be extremely sensitive, capable of registering the minute magnetic field that a monopole would produce as it passed through the device. Despite the initial enthusiasm this event has caused, the Cabrera event remains an isolated incident, where since that discovery, neither Cabrera nor any other researcher has been able to replicate the result or detect another magnetic monopole. This lack of corroboration has led to ongoing debate about the nature of the original signal.

4.2 Material-Specific Searches

The search for magnetic monopoles in matter and within our Solar System represents a fascinating chapter in modern physics, blending theoretical predictions with innovative experimental approaches. This quest has led scientists to explore a variety of potential sources and trapping mechanisms for monopoles.

At the core of this search is the possibility that monopoles could be present in ordinary matter. This presence could arise from two primary mechanisms: accretion during the formation of matter or the stopping of monopoles after they lose kinetic energy. The behavior of these particles in matter is theorized to be complex, with potential binding to ferromagnetic or paramagnetic materials through image charges, and even possible interactions with atomic nuclei.

Spin ice is a class of magnetic materials that has gained significant attention in the field of condensed matter physics, particularly in relation to the study of magnetic monopoles. These materials, typically rare-earth titanates such as Dy2Ti2O7 or Ho2Ti2O7, exhibit fascinating magnetic properties at low temperatures due to their unique crystal structure and magnetic interactions. The crystal structure of spin ice materials consists of corner-sharing tetrahedra, where magnetic rare-earth ions (such as Dy3+ or Ho3+) occupy the vertices. The magnetic moments of these ions are constrained by crystal field effects to point either directly toward or away from the center of each tetrahedron, resembling the arrangement of hydrogen atoms in water ice (hence the name "spin ice"). This geometric arrangement leads to magnetic frustration, a phenomenon where the system cannot simultaneously satisfy all pairwise magnetic interactions. This frustration results in a highly degenerate ground state with residual entropy, analogous to the residual entropy in water ice discovered by Linus Pauling.

The connection between spin ice and magnetic monopoles arises from the concept of emergent excitations. Castelnovo, Moessner, and Sondhi proposed that the elementary excitations in spin ice could be described as emergent magnetic monopoles. When a single spin in the spin ice structure is flipped, it creates a pair of defects that can be interpreted as a north and south magnetic monopole pair. These monopoles are not fundamental particles like those sought in high-energy physics experiments (such as Cabrera's), but rather quasiparticles – collective excitations that behave effectively as monopoles within the material.

In planetary bodies, the distribution of monopoles is expected to follow gravitational forces, leading to a concentration near the core. This expectation has prompted searches in various terrestrial contexts. One intriguing approach involves examining iron from the Earth's surface, though the uniform distribution of monopoles throughout the planet's interior complicates this method. A more novel strategy targets iron refinery operations, where vast quantities of ore are heated above the Curie point annually, potentially allowing trapped monopoles to fall out under gravity.

The detection of the presence of monopoles extends beyond Earth to other celestial bodies in our Solar System. Meteors, with their smaller gravitational fields, have been proposed as potential harbors for monopoles. However, the high momentum of monopoles presents a challenge, as any meteor-trapped monopole striking Earth would likely pass through unimpeded.

Perhaps the most audacious proposal in this field is the concept of solar monopoles. This hypothesis, partly motivated by unexpectedly high flux events like the Cabrera observation, suggests that the Sun could contain a vast number of monopoles and regularly emit them. According to this model, solar flares might expel monopoles at velocities comparable to Earth's orbital speed, creating a cloud of these particles in Earth's orbit. Intriguingly, this solar monopole model uniquely accommodates the 11-year sunspot cycle in its flux predictions, adding an extra layer of intrigue to the hypothesis.

However, the solar monopole theory faces significant challenges. Calculations indicate that the concentrating effect for Grand Unified Theory (GUT) monopoles in the Sun is likely insufficient to achieve the proposed solar population. This discrepancy highlights the ongoing tension between theoretical predictions and observational constraints in the field. The diverse approaches to monopole detection in matter and our Solar System underscore the creativity and persistence of the scientific community.

05. Previous Experiments and Techniques at CERN

These particles are extremely difficult to detect and extensive experimentation along with state-of-the-art techniques are used at the European Organization for Nuclear Research or CERN. Among these, the experiments include ATLAS and MoEDAL detectors and heavy ion collisions. I will make these notes in this discussion regarding the earlier experiments and techniques at CERN: the contribution of ATLAS and MoEDAL, heavy ion collisions, and the possibilities of monopole detection at HL-LHC.

5.1) ATLAS Detector:

- Picking on the LHC big infrastructural apparatus, ATLAS (A Toroidal LHC Apparatus) is one of the largest and most flexible detectors. Its main objective is to scan a spectrum of physics subjects, from the detection of magnetic monopoles.
- In ATLAS numerous specific searches for monopoles have been performed with the utilization of vast samples of data obtained with high-energy proton-proton interactions. This was accompanied by tracking systems and have greatly improved the sensitivity to rare and exotic particles.
- However, the searches for monopoles have not been successful and have not provided the aspects of monopoles up to date but the searches have set certain cross-sections and masses of monopoles which is beneficial for the field of science.

5.2) MoEDAL Detector:

- MoEDAL – Monopole and Exotics Detector at the LHC are going to search for magnetic monopoles and other highly ionizing particles.
- Several methods to identify monopoles are used in MoEDAL; they include the use of plastic nuclear track detectors and trapping volumes.
- In the absence of any monopole discoveries so far, MoEDAL has expanded the scope of the detected capacities and given fairly tight constraints on various theories.

5.3) Heavy Ion Collisions:

- The heavy ion program of the LHC especially by the ALICE experiments explores the appearance of monopoles in gargantuan magnetic fields created during heavy ion collisions.
- As these experiments did not find any monopoles, the work is perfecting the detection methods and giving important data for subsequent studies.

06. Future Plans and Prospects at CERN

However, as CERN moves forward in their quest for magnetic monopoles the future looks even more promising. The new High-Luminosity LHC (HL-LHC) is slated to boost collision frequencies, improving the possibility of seeing strange phenomena such as monopole creation. The subsequent improvement of key detectors like MoEDAL and designing new techniques will improve the search to provide extraordinarily high sensitivity and a precise outcome.

6.1) High-Luminosity LHC (HL-LHC):

Expected to start operation in the mid-2020s, the HL-LHC will provide a much higher interaction rate at the LHC thereby providing better chances for the observation of the otherwise rare phenomena like the monopole production.

The HL-LHC should produce ten times more data than LHC, and thus improve the monopole search sensitivity by one order of magnitude.

Better tracking and resolution of new upgraded versions of the ATLAS and MoEDAL detectors will be the key to these endeavors.

6.2) Upgraded MoEDAL Detector:

Several improvements to MoEDAL will be made to improve the detector sensitivity; New nuclear track detectors, New Timepix pixel detectors, and New data acquisition systems.

These improvements can be useful for experiments and for enhancing identification and characterization of the monopole events in the MoEDAL detector.

Advanced Detection Techniques:

Methods for the enhanced identification of monopoles are being devised to facilitate detection at CERN at the present moment. Some of them are high-precision timing detectors, and track structure sensors which are used to filter and sort monopole signals from other interfering sources.

Moreover, with the advancements in the algorithm and machine learning, there will be advancements in the identification methods of the event of monopole.

Conclusions

This paper explored the theoretical foundations and experimental approaches for magnetic monopoles, tracing the journey from early theoretical proposals to modern particle accelerator technology. The quest to detect magnetic monopoles began in the 1960s when scientists suggested observing them experimentally. The ATLAS, MoEDAL, and ALICE experiments, each employing different methods to transform energy into matter, represent significant efforts in this pursuit. While these experiments have not yet detected magnetic monopoles, they have advanced both experimental and theoretical boundaries in electromagnetism.

These pioneering experiments have paved the way for future studies at the Large Hadron Collider (LHC), with prospects of higher collision rates, increased data collection, and improved detection techniques. Such advancements will enhance the chances of discovering monopole particles. Future investigations could extend to exploring alternative experimental setups, integrating cutting-edge technology, and collaborating across different research fields to broaden the search for magnetic monopoles.

Overall, the experiments have been successful in contributing substantial knowledge and methodological innovations to the field of electromagnetism, despite yet to achieve direct detection of magnetic monopoles.

Author Contributions:

- Abstract, introduction - Susana C.
- Mathematical and physics implications - Yasmine R.
- Generation - Eleanor M.
- Detection - Judy A.
- Previous Experiments and Techniques - Sabina G.
- Future Plans and Prospects - Sabina G.
- Conclusions - Susana C.

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