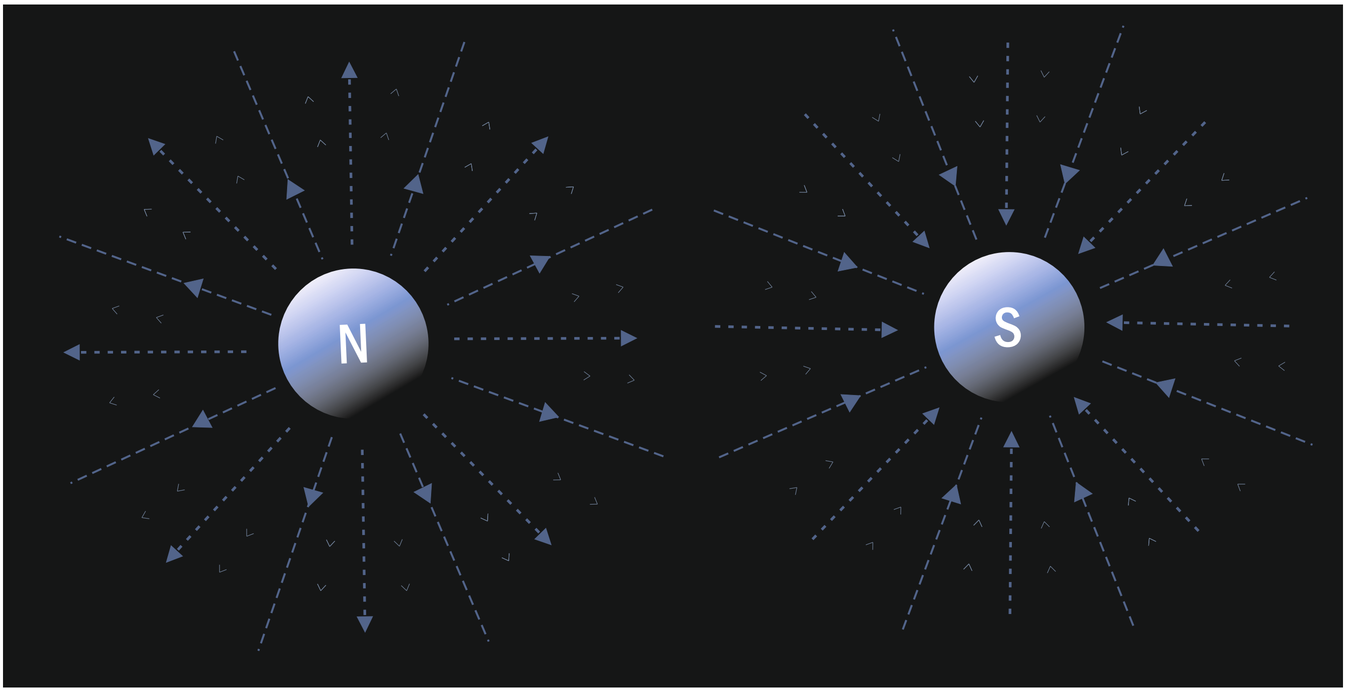

Hunting the Magnetic Monopoles

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A new pathway in basic and fundamental research has opened up due to the development of many state-of-the-art instruments for carrying out multi-messenger astronomy in the present era. These current generation astronomical instruments are capable of exploring the corners of Universe under extreme physical conditions and with kinetic ranges not accessible at man-made terrestrial accelerators and other laboratory environments. Thus, astrophysical observations provide unique and complementary opportunities for searching new particles as well as physics beyond the standard model and science in general. This contribution highlights the searches for an elusive particle known as Magnetic Monopole which was speculated in quantum mechanics in 1931 by Dirac in his study on quantized singularities in the electromagnetic fields.

More than a century ago, Max Planck introduced the natural units of measurement in 1900 and wrote: *"All systems of physical units including the so-called absolute C.G.S.- system, appeared up to now due to accidental circumstances, as the choice of basic units in each of these systems occurred not from a general point of view valid for any place and time, but from the needs of our earthly culture"* [1]. And, units for length, mass and time were derived in terms of three constants of nature: the speed of light in vacuum (c), the Planck constant or Dirac constant (h or $\hbar=h/2\pi$) and Newton's gravitational constant (G) and referred to as the Planck unit or scale [1,2,3]. These units have their natural meaning as long as the laws of gravitation and of light propagation remain valid. As the fundamental principles of physics mainly emphasise the role of c, $\hbar$ and G, a broad structure of different theories in physics can be described by a *Cube of Theories* through a suitable choice of units and setting the numerical values of these constants to unity. The cube of theories is located along three orthogonal axes marked by c^{-1}, $\hbar$ and G in a three dimensional space. Moving along the c^{-1}-axis (with $G = \hbar = 0$) leads to the special theory of relativity wherein space and time are parts of a continuum instead of being separate entities. Non-relativistic quantum mechanics is invoked along the $\hbar$-axis (with $G = c^{-1} = 0$). The path along the G-axis (with $\hbar = c^{-1} = 0$) takes to non-relativistic, classical, Newtonian theory of gravitation. The origin of cube (with $G = \hbar = c^{-1} = 0$) represents an ideal non-relativistic mechanics and its vertices provide better and more accurate description of nature than the regions close to the origin. The vertex at $G = \hbar = c^{-1} = 1$ represents the study of quantum field theory in curved space-time, leading to the quantum gravity and the futuristic theory of everything.

Use of electromagnetic fields has now opened a new window in the fundamental physics research. Focused laser pulses are used to create extreme environments to study the high density and simultaneous interaction of particles and their dynamics. Formation of high density electron-positron plasma in the laboratory-mimicking the astrophysical environments in the Universe, can be exploited to produce particles and radiation sources with extraordinary physics properties. The particle dynamics is significantly modified in the presence of strong electric and magnetic fields, giving rise to new physics phenomena which are generally not encountered in the classical or quantum theories of electromagnetic interactions. In order to illustrate such phenomena, a new cube of theories (analogous to the above described cube) has been proposed [4]. In this cube, the *G*-axis is substituted by a critical field of quantum electrodynamics (E_{cr}). In the theory of quantum electrodynamics, the critical electric field, E_{cr}, is defined as

$$E_{cr} = m^2c^3/e\hbar \;=\; 1.323 \times 10^{18}\,\mathrm{Vm}^{-1} \qquad (1)$$

where mc^2 is the characteristic rest mass energy of electron and *e* is the unit electric charge. The equivalent critical magnetic field, B_{cr}, is given by

$$B_{cr} = E_{cr}/c = 4.41 \times 10^9\,\mathrm{T} \qquad (2)$$

These strong electric (E_{cr}) and magnetic (B_{cr}) fields also represent critical fields corresponding to the so called *Schwinger limit* of pair production [5] and are ubiquitous in understanding the quantum effects in strong electromagnetic fields. E_{cr} can be interpreted as an electric field which does work equal to the electron rest mass energy over a single reduced Compton length (λ_c = $\hbar/mc$ ~ 3.86 × 10^{-13}m) and gyroradius of an electron in a magnetic field equivalent to B_{cr} would be equal to λ_c. When an electromagnetic field is characterized as strong or weak, its magnitude is implicitly compared to the scale of E_{cr} and B_{cr}. The vertex of cube of theories located at (c, $\hbar$, E_{cr}) encompasses quantum electrodynamics in ultrastrong fields. The strong-field aspect of quantum electrodynamics significantly alters the physics giving birth to new physics concepts which can be encountered only in the astrophysical environments in the space.

Magnetic Monopole

Magnetic Monopoles (MMs) are hypothetical particles explicitly predicted by several extensions of the standard model of particle physics, the widely accepted model for describing the subatomic Universe, as well as in theories describing the fundamental laws of physics. French physicist Pierre Curie was first to mention the idea of isolated magnetic charges in 1894. In 1931, English physicist Paul Dirac speculated about the point-like particle possessing an isolated magnetic charge in quantum mechanics by formulating the first field theory of a point-like MM interacting with quantum charged matter and proved that the existence of MM is necessary for quantization of electric charge [6]. He also proved that this hypothesis offers an explanation for the observation that electric charge is quantized. From the *Dirac Quantization Condition*, the allowed magnetic charges are given by

$$q_m = Ne/2\alpha \qquad (3)$$

where *N* is an integer and α is the fine structure constant. *N* = 1 corresponds to the smallest allowed magnetic charge (e/2α) known as the Dirac charge (q_D). Thus, the unit magnetic charge q_D of 1.09 × 10^{-17} Coulomb is much higher than the unit electric charge (*e*). In the Dirac's theory, MMs are treated as elementary particles with their mass as a free parameter which can be constrained experimentally. Moreover, in solutions of the grand unified theories (GUTs) of the known forces in nature, MMs appear as composites of the fundamental non-Abelian gauge and Higgs fields [7]. The masses of MMs are expected to be close to the GUT scale of 10^{16} GeV/c^2 and therefore cannot be produced in a realistic terrestrial collider experiment. The stability of MMs is attributed to the Higgs field configuration that cannot be smoothly transformed to a vacuum configuration having spatial uniformity. MMs have also been predicted by string theories and their masses are much lower than the GUT scale depending on the string scale [8]. The composite monopoles of GUTs may have an internal structure unlike Dirac's point monopoles. Finite energy MMs with masses of a few TeV have also been proposed using the spontaneous symmetry breaking and Higgs mechanism in various theories beyond the standard model [9]. This gives prospects for plausible existence of magnetic monopoles in terrestrial collider laboratories.

The famous Maxwell equations of classical electrodynamics, introduced by the Scottish mathematician James Clerk Maxwell in 1870 by incorporating the electric and magnetic forces, offered the first hint of a possible unification of fundamental forces of nature. These set of beautiful equations appear asymmetric due to the absence of magnetic charges or monopoles. However, a magnetic current and a magnetic charge density can be introduced in Maxwell equations without loss of internal consistency or contradiction with experimental results. Thus, Maxwell equations also allow the existence of MMs to maintain their symmetry. They could have been formed in the early Universe as the temperature of the primordial plasma dropped below the energy scale of the GUT symmetry breaking. The expected production rate depends on the unknown nature of this phase transition, but it leads to a production comparable to the amount of baryons. This predicts a relic density of MMs at present epoch above the current observational limits. This is referred to as the m*onopole problem* [10]. The primordial density of MMs can be brought to a level consistent with observations through inflation. Remaining MMs will be accelerated along the Galactic and extragalactic magnetic field lines.

Search for the Magnetic Monopoles

MMs are characterized as the isolated magnetic charge similar to a single north or south pole. Despite being allowed in theory, evidence of creating an isolated MM by separating a north pole from its south has not been found. Most searches for MMs, based on particle accelerator experiments, look for products of collisions between elementary particles such as electrons or quarks. But the strong coupling of MMs to each other and other standard model particles, as predicted by the Dirac's theory of point-like monopoles, makes it difficult to estimate the expected monopole yield. Although MMs have not been detected experimentally so far, searches for their existence are being continuously attempted with more powerful tools, opening a new pathway for exotic physics in fundamental research. In this direction, the current scenario from different physics and astrophysics experiments are described below:

■ ***Schwinger mechanism in strong magnetic field*:** In 1951, the US physicist Julian Schwinger demonstrated that electrically charged particles can be produced by the decay of a strong electric field [5]. This is referred to as *Schwinger mechanism*. Therefore, the principle of electromagnetic duality (electric and magnetic fields are linked) suggests that MMs can also be produced in a sufficiently strong magnetic field by the Schwinger mechanism [11]. Recently, an attempt has been made at the Large Hadron Collider (LHC) to search for MM production by the Schwinger mechanism in the enormous magnetic field induced by Pb-Pb heavy ion collisions [12]. The trapping detectors were exposed to ~ 10^9 Pb-Pb collisions with about 5TeV center of mass energy per collision. The magnetic field strength of ~ 10^{16} T (approximately 10^4 times stronger than the surface magnetic field of neutron stars) was the strongest magnetic field measured on Earth so far. A superconducting quantum interference device (SQUID) magnetometer scanned the trapping detectors for the presence of magnetic charge which would induce a persistent


MACE Telescope facility under night sky.

current in the SQUID. No statistically significant signal of a magnetic charge trapped in the detector was found and therefore existence of Schwinger monopoles with magnetic charges of q_D , $2q_D$ and $3q_D$ and masses up to $75GeV/c^2$ was excluded at the 95% confidence level. This sets limits on the expected yield of MMs produced by strong magnetic fields and provides a lower mass limit for finite-size MM from a collider search.

■ ***Atomic physics techniques in synthetic magnetic field environment*:** Motivated by the analogues of MMs found in the exotic spin ices and other systems, a small group of researchers in the USA have demonstrated the creation of Dirac monopoles in the synthetic magnetic field produced by a spinor Bose–Einstein (BE) condensate [13]. The synthetic magnetic field arises in the context of a ferromagnetic spin-1 Rb-atom BE condensate in a tailored excited state. The BE condensate is described by a quantum mechanical order parameter, and the synthetic gauge potentials describing a north magnetic pole are generated by the spin texture. The phase variations of synthetic magnetic field accompany spatial variations in the intrinsic angular momentum or spin of the Rb-atom. The preferred spin varies in space in an engineered environment. Direct imaging is used to identify zero-density Dirac string that terminates within the BE condensate at the Dirac monopole. These results provide an unprecedented opportunity to observe and manipulate quantum mechanical entities in a controlled environment and lead to further exploration of the dynamics and excitations of a Dirac monopole.

■ ***Astrophysical neutrino observatory*:** The initial velocity of MMs must have slowed down to the non-relativistic speed. However, dynamo effects in magnetic fields of cosmic ray accelerators (galaxy clusters, active galactic nuclei, pulsars, magnetars) could have re-accelerated a fraction of MMs. A magnetic monopole traversing a magnetic field B with coherence length L gains $E = q_m BL$ in kinetic energy. For typical galaxy cluster with $B = 3\mu G$ and $L = 1kpc$, the energy gain corresponds to $E = 1.8 \times 10^{11}$GeV. This mechanism allows that MMs could be associated with ultra high energy cosmic rays [14].

In the passage through matter or a dielectric medium, MMs moving at a speed faster than 0.75c would behave like an electric charge with strong exciting and ionizing power. Therefore, MMs can induce Cherenkov light like any other relativistic charge particle in a medium if their kinetic energy (E) is greater than a threshold energy given by

$$E_{th} = \frac{m_0 c^2}{\sqrt{1 - 1/n^2}} \tag{4}$$

where $m_0 c^2$ is the rest mass energy of charge particle and n is refractive index of medium. Therefore, Cherenkov detectors can be utilized to search for cosmic monopoles. IceCube neutrino observatory is equipped with a cubic-kilometer array of digital optical modules deployed at ~ 2.5km depth below the surface of the glacial ice at the South Pole. It uses the ice both as target and detection medium to detect the Cherenkov light from secondary particles produced in neutrino interactions. It is also sensitive to searches for any new particles that can produce light that is detectable by the optical modules. It can be easily shown that a relativistic monopole produces $(q_m n/e)^2$ times as much Cherenkov light as an electron in a medium. In ice (n=1.33), a single charge monopole above the Cherenkov threshold emits about 8300 times more photons per unit length than a minimum ionizing muon. In a recent study, the IceCube collaboration has reported an all-sky 90% confidence level upper limit on the cosmic flux ($2\times10^{-19}\ cm^{-2}s^{-1}sr^{-1}$) of the relativistic Dirac monopoles with speeds between 0.75c and 0.995c without any explicit restriction on the monopole mass [15].

■ ***Very high energy gamma-ray telescopes:*** An MM can start producing Cherenkov light in the Earth atmosphere at a height of ~ 80km from the ground. This emission may last throughout the full length of monopole track and will be confined within a narrow Cherenkov cone with angle starting from 0.1^{o} increasing to 1.2^{o} at the ground. The Cherenkov light produced by MMs can be recorded by the state-of-the-art *Imaging Atmospheric Cherenkov Telescopes* (IACTs) operating around the globe for very high energy gamma-ray astronomy. The magnetic monopole would be observed as a double-spot system in the camera of an IACT like MACE (Major Atmospheric Cherenkov Experiment): a first due to the very high altitude emission, and a second due to the low-altitude emission. The emission from the central part of the track would not be geometrically focused. The images of MMs in the camera of an IACT will mostly consist of small clusters of very bright pixels, for the high-altitude signal, or very bright fraction or rings, for low-altitude emission. Thus, illuminated pixels in the imaging camera will show extremely high signal due to large Cherenkov yield of MMs, at least 1000-times larger than that of muons. This will lead frequent saturation of photomultiplier tubes in the camera. The H.E.S.S. (High Energy Stereoscopic System) telescope at Namibia, an array of five IACTs, has performed a long-term search of MMs. For a total of 2400 Hours of data collected in 5 years, no MM candidate is detected. This null result has provided an upper limit of $4.5\times10^{-14}\ cm^{-2}s^{-1}sr^{-1}$ on the cosmic flux of MMs [16]. This is an extremely poor constraint, orders of magnitude less constraining than IceCube limits. These limits are taken as conservative limits in a very simplified scenario, and further exploration is required. This gives a strong motivation to fully exploit the potential of the MACE telescope for fundamental research. MACE (depicted in figure) is a state-of-the-art current generation telescope for very high energy gamma-ray astronomy at Hanle (altitude ~ 4.3km above mean sea level) in the UT of Ladakh, India. It has capability of detecting cosmic gamma-ray photons of energy above 20GeV through imaging atmospheric Cherenkov technique with high point source flux sensitivity. Thus, MACE stands a potential instrument for searching the cosmic magnetic monopoles in the coming future.

Outlook

The existence of magnetic monopoles is a mystery as they are hypothetical fundamental particles predicted by the theories beyond the standard model of particle physics. They are predicted to have a wide range of masses and need not be point-like. Low mass monopoles have a substructure and can be produced in particle accelerators. The implications of the existence of magnetic monopoles are far reaching. The unification theories, advocating for the existence of magnetic monopoles, motivate the development of a popular cosmological model to explain the inflation phase during which the volume of space expanded exponentially. Many investigations are ongoing for evidence of magnetic monopoles - by searching in the Universe, and by attempting to produce and detect them in high-energy particle collider experiments on Earth.

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