Magnetic Monopoles from a Hidden Magnetic Symmetry

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Abstract

It is proposed that Magnetic Monopoles (MMs) could originate from a new U(1)M symmetry. Such an abelian symmetry is then assumed to be related to the conservation of a magnetic number M. This magnetic number is associated with massive MMs from an expected high scale breaking of this magnetic symmetry. The involved scales are approached and the properties of such MMs are investigated along with the prospects for their detection.

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1. Introduction

Recently, with the significant improvement of cosmological, astrophysical and neutrino observation quality [1, 2, 3, 4], the search for Magnetic Monopoles (MMs) becomes increasingly important to probe a modern physics going beyond the Standard Model of particle physics (SM) [4, 5, 6, 7]. The existence of MMs is theoretically motivated from the fact that they are predicted by most non trivial high energy theories including Grand Unified Theories (GUT) and String Theory [8, 9, 10, 11]. It has been suggested that they could be exploited to discuss many long-standing problems in relations with the Dark Matter (DM) origin remaining a mystery in both particle physics and cosmology [8, 11, 12]. Although the origin of MMs in the Universe is theoretically supported, their experimental evidence is a great challenge in the particle physics community [5, 6]. Concretely, the study of the properties of MMs is then among the most thrilling problem in modern physics since they are considered as a fascinating possibility opening a new road towards a new physics above the SM [10, 11, 12]. In the SM, gauge singlets could, in principle, play a primordial role in the elaboration of the physics dealing with MMs. In particular, this is practically possible because they do not involve physical properties associated with the color and the electroweak gauge anomalies of fundamental interactions. Assuming that they are neutral under some new gauge forces, their magnetic number is not constrained. In fact, the most suggested patterns of MMs turn out to be difficult to prove or refute by using direct observations. The simplest method, but well incited pattern, could be based on a possible extension of the SM by introducing additional magnetic charged particles. They have specific couplings to the physics of the SM visible sector. In this way, definite and proper predictions of the MMs sector should be provided in terms of certain scalars, the involved symmetry, and the consequences of its spontaneous breaking.

In this work, we build a simple physical model in which MMs are considered as particles whose existence belongs to a high scale magnetic symmetry. Using a simple abelian symmetry U(1)X extension of the SM, we show how MMs m can easily be accommodated. Precisely, we examine in some details the breaking of such a magnetic symmetry along with the associated magnetic number X = M predicting a natural origin of a potential MM candidate. Then, we deal with massive MMs m and we reveal how this can emerge from the breaking scale of the proposed magnetic symmetry by supporting the case of heavy MMs. We also speculate on the searches for MMs.

This paper is organized as follows. In section 2, we list some theoretical arguments in favor to MMs. In section 3, we provide a simple model in which a new magnetic symmetry U(1)M extending the SM and its breaking generate MMs. The searches for MMs are discussed in section 4. The last section is devoted to a summary and outlook.

2. Theoretical arguments for MMs

We start by recalling that the large part of the observable Universe is made of electrically charged elementary particles being quarks qf=udc, s, t, b, some leptons ℓf=e,µ,τ, and certain gauge bosons W±. Up to now, though no magnetic charged elementary particle has been observed, there are various theoretical reasons for believing that the MMs must exist in nature. Let us, therefore, cite some arguments being emerged in the discussion on the existence of MMs supported by many pioneering investigation works [1].

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1. The first argument is based, essentially, on the asymmetry between the magnetic and the electric fields in Maxwell equations. This problem remains an open issue in the related physics [3].

2. The observed quantization of the electric charge can be seen as a possible evidence for the existence of MMs [10, 14, 15, 11, 16].

3. It has been suggested that the magnetic charge of a monopole could be considered as a topological charge associated with various topologies of physical field configurations [17]. In this way, the correspondence magnetic charge/topology can be investigated from gauge group theory.

4. MMs can be arisen at spontaneous symmetry breaking of certain non abelian symmetries associated with particular topological properties of some manifolds [18, 19].

5. It has been proposed that most high-scale theories including GUT of extended SM models involving large gauge symmetries should contain MMs [8, 9, 10, 11].

6. String theory also predicts that MMs must exist as solitons which could be discussed in terms of D-brane physics [20].

7. The problem of MMs is one of the three cosmological motivations, flatness and horizon, in favor to cosmic inflation [2].

8. A confirmed fact is that SM is just a low-energy limit of a more extended theory [21, 22, 23, 24]. There must be an undiscovered physics surpassing the SM scale which can be explored to unveil certain properties of MMs.

It is important to recall that the magnetic charge \( M \) of MMs relies on the elementary electric charge \( e \) according to the Dirac basic relation [10] as

\[
M = \frac{n}{2e} n M_D, \tag{1}
\]

where \( n \) is an integer and \( M_D \) is the Dirac unit of the magnetic charge being

\[
M_D = \frac{1}{2e} = \frac{e}{2\alpha_e}, \tag{2}
\]

where \( \alpha_e = e^2 \approx 1/137 \) is the fine structure constant. In an analogous manner, a dimensionless magnetic coupling constant is defined as

\[
\alpha_M = M_D^2 \gg 1. \tag{3}
\]

Assuming that it is larger than 1, this magnetic coupling constant prevents reliable perturbative calculations of MM production processes. Thus, according to Dirac theory in which the fundamental charge is \( e \), the minimum value of the magnetic charge is \( M_D \). However, it would become multiples of \( M_D \) in particular \( 2M_D \) or \( 3M_D \), as shown in various works [14, 15, 11, 16].

Based on these theoretical arguments, one should support the idea that there is no particular reason to evince the investigation of the existence and the origin of MMs. From a particle physics view, one should encourage the search for such particles and shed lights on their hidiness in nature. In what follows, we discuss this physical problem in the context of a SM extension involving an abelian symmetry associated with MMs relying on the \( U(1)_M \) group and extra physical fields.

3. Magnetic extension model

In this section, we build the model from a simple extension of the SM by introducing an extra abelian continuous symmetry \( U(1)_X \) and a single complex field \( S \). It has been shown that there are many roads to handle such physical pieces. Properly, it is noted that models beyond the SM can be engineered using theories involving extra dimensions and supersymmetry including superstring and M-theories. In this regards, the geometry and the topology of extra dimensions engender abelian gauge symmetries \( U(1) \)'s and scalar fields \( S \) using different approaches either in the context of M-theory on G2 manifolds or in intersecting type II D-branes wrapping non trivial cycles embedded in Calabi-Yau manifolds [25, 26, 27, 28]. It has been revealed that the scalar fields can play an important role in the elaboration of new physical models extending the SM. Assuming that the present model could be obtained from such stringly inspired theories, we consider this extended gauge symmetry of the SM

\[
G_{SM+MM} = G_{SM} \otimes U(1)_X. \tag{4}
\]

The first group refers to the SM symmetry \( G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \) describing three generations of quarks and leptons governed by the strong, weak and electromagnetic interactions [21, 22, 23, 24]. It has been confirmed that the corresponding theory is an interesting quantum field theory model of elementary particles and fundamental interactions in nature. The additional group \( U(1)_X \) is associated with the conservation of a quantum number \( X \) to be specified later on. It is noted in passing that this symmetry could find a place in string theory, M-theory, and related models based on D-brane objects.

In the present model [4], all the SM fields are assumed to be neutral under this new symmetry. This can be ensured by the constraint

\[
X(q_i) = X(\ell_i) = X(H) = 0, \tag{5}
\]

where the fields \( q_i \) and \( \ell_i \) are the SM quarks and leptons, respectively and \( H \) represents the SM Higgs field. The subscript \( i = 1, 2, 3 \) refers to the three generations of SM fermions. The simplest way allowing for the breaking of this symmetry is to impose the new symmetry \( U(1)_X \) on the complex scalar field \( S \). This means that this scalar becomes charged under such a symmetry as required by

\[
X(S) \neq 0. \tag{6}
\]

However, this scalar field \( S \) is neutral under the SM symmetry \( G_{SM} \) such that

\[
C(S) = I(S) = Y(S) = 0. \tag{7}
\]

A careful examination shows that, for this field-extended SM, the most general renormalizable scalar potential takes the following form

\[
V(H,S)_{SM+MM} = V(H)_{SM} + \mu_H^2 |H|^2 + \lambda_H |H|^4 + \lambda_S |S|^4 + \lambda_{SH} |S|^2 |H|^2 + |S|^2 + |H|^2. \tag{8}
\]

Here, the first term \( V(H)_{SM} = \mu_H^2 |H|^2 + \lambda_H |H|^4 \) denotes the usual Higgs potential of the SM where the field \( H^T = (h^+, h^-) \)...
is the standard Higgs doublet of the SU(2)\textsubscript{L} symmetry. The parameters \( \mu_\text{H}^2, \lambda_\text{H}, \mu_\text{S}^2, \lambda_\text{S} \) and \( \lambda_{\text{SH}} \) are real constants. For the SM sector, the electroweak symmetry of the SM \( G_{\text{EW}} = \text{SU}(2)_L \otimes \text{U}(1)_Y \subset G_{\text{SM}} \) is indeed broken by a non-vanishing vacuum expectation value (VEV) of the Higgs field \( \langle h \rangle \sim 10^2 \text{GeV} \). For the \( U(1)_X \) symmetry of the conserved number \( X \), a close computation reveals that the breaking is realized if \( -\frac{\mu_\text{H}^2 + \mu_\text{S}^2 + (2\lambda_\text{H} + \lambda_{\text{SH}})\langle H \rangle^2}{2\lambda_\text{S} + \lambda_{\text{SH}}} > 0 \). In such a case, the scalar field \( S \) develops a real VEV given by

\[
\langle S \rangle = \sqrt{-\frac{\mu_\text{H}^2 + \mu_\text{S}^2 + (2\lambda_\text{H} + \lambda_{\text{SH}})\langle H \rangle^2}{2\lambda_\text{S} + \lambda_{\text{SH}}}}. (9)
\]

The corresponding mass reads as

\[
m_S = \sqrt{-\frac{\mu_\text{H}^2 + \mu_\text{S}^2 + (2\lambda_\text{H} + \lambda_{\text{SH}})\langle H \rangle^2}{2\lambda_\text{S} + \lambda_{\text{SH}}}}. (10)
\]

In this view, the interaction of the scalar \( S \) with the SM sector results indirectly through its coupling with the Higgs sector described by the term \( \lambda_{\text{SH}}S^2\langle H \rangle^2 \). It turns out that this term has to be very small \( \lambda_{\text{SH}} \ll 1 \). Otherwise, this would impact seriously the Higgs decay channels with the rate expected in the SM. In the present model, this can be interpreted as a small mixing between the two scalars \( H \) and \( S \) ensuring a negligible communication between the SM sector and the new \( U(1)_X \) symmetry. In this way, no relevant effects on the SM gauge sector will take place.

At this stage, we can think about the physical meaning of the presumed broken symmetry \( U(1)_X \). Because there is no place for a new broken global symmetry in the SM, it is natural to look of a symmetry associated particles beyond the SM, but whose existence is theoretically supported. A likely case is that of spin-\( \frac{1}{2} \) massive MMs. Thus, we assume now that the conserved quantum number \( X \) corresponding to the symmetry \( U(1)_X \) is the magnetic number \( M \), that is

\[
X \equiv M = nM_D, \tag{11}
\]

being the number of MMs \( m \) minus the number of the their antiparticles \( \overline{m} \) like

\[
M = N_m - N_{\overline{m}}. \tag{12}
\]

At this level, one should add one comment on this magnetic symmetry \( U(1)_M \). If we consider the charged magnetic particles \( m \), together with the complex scalar field \( S \), the magnetic quantum number \( M \) of the charged SM fields being neutral under the \( U(1)_M \) should be zero. According to \( 5 \) and \( 6 \), we list, thus, a set of magnetic charges of SM and the added fields

\[
M(q_i) = N_m(q_i) - N_{\overline{m}}(q_i) = 0, \tag{13}
\]

\[
M(\ell_i) = N_m(\ell_i) - N_{\overline{m}}(\ell_i) = 0, \tag{14}
\]

\[
M(H) = 0, \tag{15}
\]

\[
M(m) = N_m(m) - N_{\overline{m}}(m) = 1, \tag{16}
\]

\[
M(S) \neq 0, \tag{17}
\]

where the magnetic charge \( M(S) \) of the scalar field \( S \) could be specified in order to elaborate consistently the present physical model. Given the scalar field \( S \) an arbitrary magnetic quantum number \( M(S) = nM_D \), the most general renormalizable terms involving the added fields, that can be supplemented to the SM lagrangian, are

\[
\xi_{MM} = \frac{m^\mu_\text{H}^2 + \mu_\text{S}^2 + (2\lambda_\text{H} + \lambda_{\text{SH}})\langle H \rangle^2}{2\lambda_\text{S} + \lambda_{\text{SH}}} + h.c. \tag{18}
\]

where \( M \) denotes an underlying high physical scale. \( \lambda_{\text{SM}} \) is real coupling constant. These relevant terms describe the MMs propagation and the communication with the scalar field \( S \) with a coupling constant \( \lambda_{\text{SM}} \). Using the non-zero VEV of the scalar field \( S \) given in \( 9 \), the mass of MM particles is

\[
m_m = \frac{\lambda_{\text{SM}}\langle H \rangle}{M'_s} \left[ \mu_\text{H}^2 + \mu_\text{S}^2 + (2\lambda_\text{H} + \lambda_{\text{SH}})\langle H \rangle^2 \right]. \tag{19}
\]

In this route, it is noted MMs mass is indeed determined by the breaking scale \( 9 \) of the magnetic symmetry \( U(1)_M \) and the \( M'_s \) mass scale. It is recalled that their masses could be largely heavy \( m_m \gg M_{SM} \). This could lead to the idea that there is no hope of producing them in any foreseen accelerator. However, a best hope is observing them in cosmic rays of the Universe.

4. Searches for MMs

It has been suggested that the detection of MMs might be either indirectly via their annihilation product searches or directly by studying their communication with ordinary particles within the detector. It should be noted that one important difference between MMs and the most other SM particles resides on the fact that the lighter MMs, if they exist, would be absolutely stable. Whereas, they could disappear only if they meet other MMs of opposite charges. In this way, they would self-annihilate and produce a burst of lighter SM spectrum via the following process

\[
m\overline{m} \to \text{SM}. \tag{20}
\]

By virtue of the magnetic charge \( M \) conservation \( 11 \), MMs would always be produced in north–south pairs from SM particles. This can be happened if the collision energy is higher than the combined mass of the two MMs, that is \( E_{\text{Collision}} \geq 2m_m \). However, if MMs are sufficiently light, it is envisaged that they would be produced in experiments using a process occurring especially in SM particle collisions. Concretely, they could have the following scheme

\[
q\overline{q} e^+ e^- \to \gamma' \to n\overline{m}. \tag{21}
\]

These kinds of searches are still going on at the powerful accelerators, especially LHC with a maximum collision energy of the order of \( E_{\text{CM}} \sim 10^3 \text{GeV} \). Whilst, the main emphasis of MMs searches is clearly concentrated on high-mass low velocity cosmic MMs. Assuming that the \( U(1)_M \) symmetry breaking scale is high \( \langle S \rangle \gg \langle H \rangle \sim 10^2 \text{GeV} \), this would make the MMs heavy \( m_m \sim \langle S \rangle^2 / M'_s \) and far to be produced at any accelerator if \( M'_s \) is not so huge, that is \( M'_s \sim M_{\text{Planck}} \). In the case where MMs are as heavy as expected, the best hope is observing them in cosmic rays, inspected by the actual telescopes, for
instance Icecube and ANTARES [34, 35, 4]. Using the fact that
in the present Universe no process occurring is sufficiently ener-
getic to produce MMs, any MMs today must be produced when
higher energies were available, in the very early Universe. As
the universe cooled down, the MMs density would have initially
decreased by pair annihilation given in (20). Once they were
sufficiently reduced, the MMs would no longer be able to find
annihilation partners and they would be survived indefinitely.
This means that the abundance of MMs is a cosmological is-
issue. According to astrophysical arguments, the flux of MMs in
 cosmos is probably quite small. Moreover, the heavy MMs
traversing the Earth are likely to be moving relatively slowly,
with a typical speed of the order of $10^{-3}c$. Experimentally, the
detection of such rare and slow particles is considered as a chal-
 lenging problem of modern physics.

In the intergalactic medium, acceleration of MMs by magnetic
fields can give them a kinetic energy up to $10^{14}$GeV to
reach the terrestrial detectors [3, 4, 5]. Considering this data
and using [19], the kinetic energy of MMs could be written as

\[ k_{M} = \frac{-\lambda_{SM} \left[ \mu_{S}^{2} + \mu_{M}^{2} + (2\lambda_{H} + \lambda_{SH}) \langle H \rangle^{2} \right]}{2\lambda_{S} + \lambda_{SH}} \lesssim 10^{14} \text{GeV}, \]

which, for $\lambda_{SM} \sim \lambda_{S} \leq 1$, corresponds to the MMs mass bound

\[ m_{M} = \frac{-\lambda_{SM} \left[ \mu_{S}^{2} + \mu_{M}^{2} + (2\lambda_{H} + \lambda_{SH}) \langle H \rangle^{2} \right]}{2\lambda_{S} + \lambda_{SH}} \lesssim 10^{8} \text{GeV}. \]

This MMs mass bound allows one to approach the breaking scale
of the magnetic symmetry $U(1)_{M}$ as well as the mass of the
associated scalar. Concretely, we have

\[ m_{M} \sim \langle S \rangle = \sqrt{-\frac{\mu_{S}^{2} + \mu_{M}^{2} + (2\lambda_{H} + \lambda_{SH}) \langle H \rangle^{2}}{2\lambda_{S} + \lambda_{SH}}} \gtrsim 10^{8} \text{GeV}. \]

It follows that the breaking of the magnetic symmetry $U(1)_{M}$
and the mass of the scalar field $S$ overtake, as expected, the SM
scale. According to the MMs higher mass bound [23], however,
the hope for a lighter MM mass to be seen in current powerful
accelerators remains plausible. In this picture, the MMs can ap-
pear at the moment of corresponding to the spontaneous break-
ning of the a high-scale magnetic symmetry of a large symmetry
group $G_{S}$ into subgroups, one of which is the $U(1)_{Q}$ of
electromagnetism. In a group theory language, we end up with the
following scale transitions

\[ G_{S} \rightarrow G_{SM} \otimes U(1)_{M} \rightarrow (S) \rightarrow G_{SM} \rightarrow SU(3)_{C} \otimes U(1)_{Q}. \]

Unfortunately, the too many free parameters involved in the
present study and the approximations of some of them do not al-
low a precise result and profound predictions, whether the MMs
in this model do or do not match the theoretical and observa-
tional constraints.

5. Summary and outlook

In this work, motivated by recent high energy detector
activities, we have attempted to give as an origin of MMs
a new $U(1)_{M}$ symmetry being hidden through a high-scale
spontaneous symmetry breaking. A new scalar field $S$ having
a non-zero VEV has been introduced to break such a new
abelian symmetry. The conserved quantum number, specified
as the magnetic number $M$, has been associated with the
MMs, being charged together with the scalar field $S$ under
this magnetic symmetry unlike the SM particles. Under this
suggestion, the communication between the MMs sector and
the SM sector is ensured indirectly by such a scalar field $S$
interacting with the electroweak SM Higgs field $H$ through a
weak mixing, governed by $\lambda_{SH} \ll 1$. Breaking the magnetic
symmetry and assigning the magnetic numbers to the spectrum
of the extended-SM, we have given allowed interaction terms
of the new fields. Then, we have given an explicit statement
of the corresponding MMs mass in terms of the involved
scales in the model. After deriving the mass of MMs, we
have discussed their searches by means of direct or indirect
detections. In particular, if there is a hope for detecting of
the lightest MM, it would be absolutely stable. Thus, they must
be seen in the Universe as cosmic relics after the end of their
self-annihilating into lighter SM particles. In current large
accelerators, these lighter MMs would always be produced
in north-south pairs from SM particles as stated by magnetic
charge $M$ conservation. Then, we have given an important
attention to heavy MMs, as incited by most GUT theories.
Such MMs must have to be produced at the very early Universe
when higher energies were available and would have survived
today as cosmic relics, to be detected in current high-energy
particle telescopes. According to the theoretical data and the
astrophysical constraints on the typical speed and likely kinetic
energy of heavy MMs, we have approached the involved scales
associated with the magnetic symmetry $U(1)_{M}$ by bounding
its breaking scale $\sim \langle S \rangle \gtrsim 10^{8} \text{GeV}$ and the mass of MMs
$m_{M} \lesssim 10^{8} \text{GeV}$. It has observed that this mass is weighted by
the underling mass scale $M_{S}$ supporting the existence of MMs.
Though these mass scales lie beyond the present accessible
scale $\sim TeV$, the expectancy of lighter MMs to be seen in the
running powerful accelerators remains reasonable.

This work opens up for further studies. In connection with
the compactification of string theory, one could consider
stringy models with several scalar fields $S_{i}$. These scalar
fields could be associated with R-R and NS-NS fields on 2-cycles
of the Calabi-Yau manifolds. The number of such fields which
can be given in terms the size and the shape deformations
of the Calabi-Yau manifold can provide a statistical analysis.
However, the corresponding physics deserves a better under-
standing. We hope to report elsewhere on these open questions.

In spite of their elusiveness, MMs still attract much of our
attention and push us to unveil some of their hidden properties
and explore others. Both theorists and experimenters will
continue to follow MMs without tiredness.

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