# MAGNETIC MONOPOLES

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The symmetry between electric and magnetic fields in the sourcefree Maxwell's equations naturally suggests that electric charges might have magnetic counterparts, known as magnetic monopoles. Although the greatest interest has been in the supermassive monopoles that are a firm prediction of all grand unified theories, one cannot exclude the possibility of lighter monopoles, even though there is at present no strong theoretical motivation for these.

In either case, the magnetic charge is constrained by a quantization condition first found by Dirac [1]. Consider a monopole with magnetic charge $Q_M$ and a Coulomb magnetic field

$$\mathbf{B} = \frac{Q_M}{4\pi}\frac{\hat{\mathbf{r}}}{r^2}\,. \tag{1}$$

Any vector potential $\mathbf{A}$ whose curl is equal to $\mathbf{B}$ must be singular along some line running from the origin to spatial infinity. This Dirac string singularity could potentially be detected through the extra phase that the wavefunction of a particle with electric charge $Q_E$ would acquire if it moved along a loop encircling the string. For the string to be unobservable, this phase must be a multiple of $2\pi$. Requiring that this be the case for any pair of electric and magnetic charges gives the condition that all charges be integer multiples of minimum charges $Q_E^{\rm min}$ and $Q_M^{\rm min}$ obeying

$$Q_E^{\rm min} Q_M^{\rm min} = 2\pi\,. \tag{2}$$

(For monopoles which also carry an electric charge, called dyons, the quantization conditions on their electric charges can be modified. However, the constraints on magnetic charges, as well as those on all purely electric particles, will be unchanged.)

Another way to understand this result is to note that the conserved orbital angular momentum of a point electric charge moving in the field of a magnetic monopole has an additional component, with

$$\mathbf{L} = m\mathbf{r}\times\mathbf{v} - 4\pi Q_E Q_M \hat{\mathbf{r}} \tag{3}$$

Requiring the radial component of **L** to be quantized in half-integer units yields Eq. (2).

If there are unbroken gauge symmetries in addition to the U(1) of electromagnetism, the above analysis must be modified [2,3]. For example, a monopole could have both a U(1) magnetic charge and a color magnetic charge. The latter could combine with the color charge of a quark to give an additional contribution to the phase factor associated with a loop around the Dirac string, so that the U(1) charge could be the Dirac charge $Q_M^D \equiv 2\pi/e$, the result that would be obtained by substituting the electron charge into Eq. (2). On the other hand, for monopoles without color-magnetic charge, one would simply insert the quark electric charges into Eq. (2) and conclude that $Q_M$ must be a multiple of $6\pi/e$.

The prediction of GUT monopoles arises from the work of 't Hooft [4] and Polyakov [5], who showed that certain spontaneously broken gauge theories have nonsingular classical solutions that lead to magnetic monopoles in the quantum theory. The simplest example occurs in a theory where the vacuum expectation value of a triplet Higgs field $\phi$ breaks an SU(2) gauge symmetry down to the U(1) of electromagnetism and gives a mass $M_V$ to two of the gauge bosons. In order to have finite energy, $\phi$ must approach a vacuum value at infinity. However, there is a continuous family of possible vacua, since the scalar field potential determines only the magnitude $v$ of $\langle\phi\rangle$, but not its orientation in the internal SU(2) space. In the monopole solution, the direction of $\phi$ in internal space is correlated with the position in physical space; *i.e.*, $\phi^a \sim v\hat{r}^a$. The stability of the solution follows from the fact that this twisting Higgs field cannot be smoothly deformed to a spatially uniform vacuum configuration. Reducing the energetic cost of the spatial variation of $\phi$ requires a nonzero gauge potential, which turns out to yield the magnetic field corresponding to a charge $Q_M = 4\pi/e$. Numerical solution of the classical field equations shows that the mass of this monopole is

$$M_{\rm mon} \sim \frac{4\pi M_V}{e^2}\,. \tag{4}$$

The essential ingredient here was the fact that the Higgs fields at spatial infinity could be arranged in a topologically nontrivial configuration. A discussion of the general conditions under which this is possible is beyond the scope of this review, so we restrict ourselves to the two phenomenologically most important cases.

The first is the electroweak theory, with $\mathrm{SU}(2)\times\mathrm{U}(1)$ broken to U(1). There are no topologically nontrivial configurations of the Higgs field, and hence no topologically stable monopole solutions.

The second is when any simple Lie group is broken to a subgroup with a U(1) factor, a case that includes all grand unified theories. The monopole mass is determined by the mass scale of the symmetry breaking that allows nontrivial topology. For example, an SU(5) model with

$$\mathrm{SU}(5) \xrightarrow{M_{\mathrm{X}}} \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1) \xrightarrow{M_W} \mathrm{SU}(3)\times\mathrm{U}(1) \tag{5}$$

has a monopole [6] with $Q_M = 2\pi/e$ and mass

$$M_{\mathrm{mon}} \sim \frac{4\pi M_{\mathrm{X}}}{g^2}\,, \tag{6}$$

where $g$ is the SU(5) gauge coupling. For a unification scale of $10^{16}$ GeV, these monopoles would have a mass $M_{\mathrm{mon}} \sim 10^{17}$ – $10^{18}$ GeV.

In theories with several stages of symmetry breaking, monopoles of different mass scales can arise. In an SO(10) theory with

$$\mathrm{SO}(10) \xrightarrow{M_1} \mathrm{SU}(4)\times\mathrm{SU}(2)\times\mathrm{SU}(2) \xrightarrow{M_2} \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1) \tag{7}$$

there is monopole with $Q_M = 2\pi/e$ and mass $\sim 4\pi M_1/g^2$ and a much lighter monopole with $Q_M = 4\pi/e$ and mass $\sim 4\pi M_2/g^2$ [7].

The central core of a GUT monopole contains the fields of the superheavy gauge bosons that mediate baryon number violation, so one might expect that baryon number conservation could be violated in baryon–monopole scattering. The surprising feature, pointed out by Callan [8] and Rubakov [9], is that these processes are not suppressed by powers of the gauge boson mass. Instead, the cross-sections for catalysis processes such as $p + \text{monopole} \to e^+ + \pi^0 + \text{monopole}$ are essentially geometric; *i.e.*, $\sigma_{\Delta B}\beta \sim 10^{-27}$ cm$^2$, where $\beta = v/c$. Note, however, that intermediate mass monopoles arising at later stages of symmetry breakings, such as the doubly charged monopoles of the SO(10) theory, do not catalyze baryon number violation.

***Production and Annihilation:*** GUT monopoles are far too massive to be produced in any foreseeable accelerator. However, they could have been produced in the early universe as topological defects arising via the Kibble mechanism [10] in a symmetry-breaking phase transition. Estimates of the initial monopole abundance, and of the degree to which it can be reduced by monopole-antimonopole annihilation, predict a present-day monopole abundance that exceeds by many orders of magnitude the astrophysical and experimental bounds described below [11]. Cosmological inflation and other proposed solutions to this primordial monopole problem generically lead to present-day abundances exponentially smaller than could be plausibly detected, although potentially observable abundances can be obtained in scenarios with carefully tuned parameters.

If monopoles light enough to be produced at colliders exist, one would expect that these could be produced by analogs of the electromagnetic processes that produce pairs of electrically charged particles. Because of the large size of the magnetic charge, this is a strong coupling problem for which perturbation theory cannot be trusted. Indeed, the problem of obtaining reliable quantitative estimates of the production cross-sections remains an open one, on which there is no clear consensus.

***Astrophysical and Cosmological Bounds:*** If there were no galactic magnetic field, one would expect monopoles in the galaxy to have typical velocities of the order of $10^{-3}c$, comparable to the virial velocity in the galaxy (relevant if the monopoles cluster with the galaxy) and the peculiar velocity of the galaxy with respect to the CMB rest frame (relevant if the monopoles are not bound to the galaxy). This situation is modified by the existence of a galactic magnetic field $B \sim 3\mu$G.

A monopole with the Dirac charge and mass $M$ would be accelerated by this field to a velocity

$$v_{\rm mag} \sim \begin{cases} c, & M \lesssim 10^{11}\text{GeV} \ , \\ 10^{-3} c \left(\frac{10^{17}\,\text{GeV}}{M}\right)^{1/2}, & M \gtrsim 10^{11}\text{GeV} \ . \end{cases} \tag{8}$$

Accelerating these monopoles drains energy from the magnetic field. Parker [12] obtained an upper bound on the flux of monopoles in the galaxy by requiring that the rate of this energy loss be small compared to the time scale on which the galactic field can be regenerated. With reasonable choices for the astrophysical parameters (see Ref. 13 for details), this Parker bound is

$$F < \begin{cases} 10^{-15}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{sec}^{-1}\,, & M \lesssim 10^{17}\,\text{GeV} \ , \\ 10^{-15}\left(\frac{M}{10^{17}\,\text{GeV}}\right)\text{cm}^{-2}\,\text{sr}^{-1}\,\text{sec}^{-1}\,, & M \gtrsim 10^{17}\,\text{GeV} \ . \end{cases} \tag{9}$$

Applying similar arguments to an earlier seed field that was the progenitor of the current galactic field leads to a tighter bound [14],

$$F < \left[\frac{M}{10^{17}\text{GeV}} + (3\times 10^{-6})\right] 10^{-16}\,\text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1}. \tag{10}$$

Considering magnetic fields in galactic clusters gives a bound [15] which, although less secure, is about three orders of magnitude lower than the Parker bound.

A flux bound can also be inferred from the total mass of monopoles in the universe. If the monopole mass density is a fraction $\Omega_M$ of the critical density, and the monopoles were uniformly distributed throughout the universe, there would be a monopole flux

$$F_{\rm uniform} = 1.3\times 10^{-16}\Omega_M \left(\frac{10^{17}\,\text{GeV}}{M}\right)\left(\frac{v}{10^{-3}c}\right)\text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1}. \tag{11}$$

If we assume that $\Omega_M \sim 0.1$, this gives a stronger constraint than the Parker bound for $M \sim 10^{15}$ GeV. However, monopoles with masses $\sim 10^{17}$ GeV are not ejected by the galactic field and can be gravitationally bound to the galaxy. In this case their flux within the galaxy is increased by about five orders of magnitude for a given value of $\Omega_M$, and the mass density bound only becomes stronger than the Parker bound for $M \sim 10^{18}$ GeV.

A much more stringent flux bound applies to GUT monopoles that catalyze baryon number violation. The essential idea is that compact astrophysical objects would capture monopoles at a rate proportional to the galactic flux. These monopoles would then catalyze proton decay, with the energy released in the decay leading to an observable increase in the luminosity of the object. A variety of bounds, based on neutron stars [16–20], white dwarfs [21], and Jovian planets [22] have been obtained. These depend in the obvious manner on the catalysis cross section, but also on the details of the astrophysical scenarios; *e.g.*, on how much the accumulated density is reduced by monopole-antimonopole annihilation, and on whether monopoles accumulated in the progenitor star survive its collapse to a white dwarf or neutron star. The bounds obtained in this manner lie in the range

$$F\left(\frac{\sigma_{\Delta B}\beta}{10^{-27}\mathrm{cm}^2}\right) \sim (10^{-18} - 10^{-29})\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{sec}^{-1}. \qquad (12)$$

It is important to remember that not all GUT monopoles catalyze baryon number nonconservation. In particular, the intermediate mass monopoles that arise in some GUTs at later stages of symmetry-breaking are examples of theoretically motivated monopoles that are exempt from the bound of Eq. (12).

***Searches for Magnetic Monopoles:*** To date there have been no confirmed observations of exotic particles possessing magnetic charge. Precision measurements of the properties of known particles have led to tight limits on the values of magnetic charge they may possess. Using the induction method (see below), the electron's magnetic charge has been found to be $Q_e^m < 10^{-24} Q_M^D$ [23](where $Q_M^D$ is the Dirac charge). Furthermore, measurements of the anomalous magnetic moment of the muon have been used to place a model dependent lower limit of 120 GeV on the monopole mass [1] [24]. Nevertheless, guided mainly by Dirac's argument and the predicted existence of

[1] Where no ambiguity is likely to arise, a reference to a monopole implies a particle possessing Dirac charge.

monopoles from spontaneous symmetry breaking mechanisms, searches have been routinely made for monopoles produced at accelerators, in cosmic rays, and bound in matter [25]. Although the resultant limits from such searches are usually made under the assumption of a particle possessing only magnetic charge, most of the searches are also sensitive to dyons.

***Search Techniques:*** Search strategies are determined by the expected interactions of monopoles as they pass through matter. These would give rise to a number of striking characteristic signatures. Since a complete description of monopole search techniques falls outside of the scope of this minireview, only the most common methods are described below. More comprehensive descriptions of search techniques can be found in Refs. [26,27].

The induction method exploits the long-ranged electromagnetic interaction of the monopole with the quantum state of a superconducting ring which would lead to a monopole which passes through such a ring inducing a permanent current. The induction technique typically uses Superconducting Quantum Interference Devices (SQUID) technology for detection and is employed for searches for monopoles in cosmic rays and matter. Another approach is to exploit the electromagnetic energy loss of monopoles. Monopoles with Dirac charge would typically lose energy at a rate which is several thousand times larger than that expected from particles possessing the elementary electric charge. Consequently, scintillators, gas chambers and nuclear track detectors (NTDs) have been used in cosmic ray and collider experiments. A further approach, which has been used at colliders, is to search for particles describing a non-helical path in a uniform magnetic field.

***Searches for Monopoles Bound in Matter:*** Monopoles have been sought in a range of bulk materials which it is assumed would have absorbed incident cosmic ray monopoles over a long exposure time of order million years. Materials which have been studied include moon rock, meteorites, manganese modules, and sea water [28]. A stringent upper limit on the monopoles per nucleon ratio of $\sim 10^{-29}$ has been obtained [28].

***Searches in Cosmic Rays:*** Direct searches for monopoles in cosmic rays refer to those experiments in which the passage of the monopole is measured by an active detector. Catalysis processes in which GUT monopoles could induce nucleon decay are discussed in the next section. To interpret the results of the non-catalysis searches, the cross section for the catalysis process is typically either set to zero [29] or assigned a modest value (1mb) [30]. Searches which explicitly exploit the expected catalysed decays are discussed in the next section.

Although early cosmic ray searches using the induction technique [31] and NTDs [32] observed monopole candidates, none of these apparent observations have been confirmed. Recent experiments have typically employed large scale detectors. The MACRO experiment at the Gran Sasso underground laboratory comprised three different types of detector: liquid scintillator, limited stream tubes, and NTDs, which provided a total acceptance of $\sim 10000\text{m}^2$ for an isotropic flux. As shown in Fig. 1, this experiment has so far provided the most extensive $\beta$-dependent flux limits for GUT monopoles with Dirac charge [30]. Also shown are limits from an experiment at the OHYA mine in Japan [29], which used a $2000\text{m}^2$ array of NTDs.

In Fig. 1, upper flux limits are also shown as a function of mass for monopole speed $\beta > 0.05$. In addition to MACRO and OYHA flux limits, results from the SLIM [33] high-altitude experiment are shown. The SLIM experiment provided a good sensitivity to intermediate mass monopoles ($10^5 \lesssim M \lesssim 10^{12}$ GeV). In addition to the results shown in Fig. 1, a limit of $\sim 9 \times 10^{-16}$ cm$^{-2}$s$^{-1}$sr$^{-1}$ was obtained for monopoles with $\beta = 0.76$ by The AMANDA-II experiment [34]. This limit extends to $\sim 4 \times 10^{-17}$ cm$^{-2}$s$^{-1}$sr$^{-1}$ for $\beta \sim 1$. The most stringent constraints on the flux of ultra-relativistic monopoles have been obtained by the RICE [35] and ANITA-II experiments [36] at the South Pole which were sensitive to monopoles with $\gamma$ values of $10^7 \lesssim \gamma \lesssim 10^{12}$ and $10^9 \lesssim \gamma \lesssim 10^{13}$, respectively, and which produced flux limits as low as $10^{-19}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. In addition to the aforementioned flux limits for monopoles with the Dirac charge, the OHYA experiment also presented limits for monopoles with charges up to $3Q_M^D$, as did the the SLIM experiment.

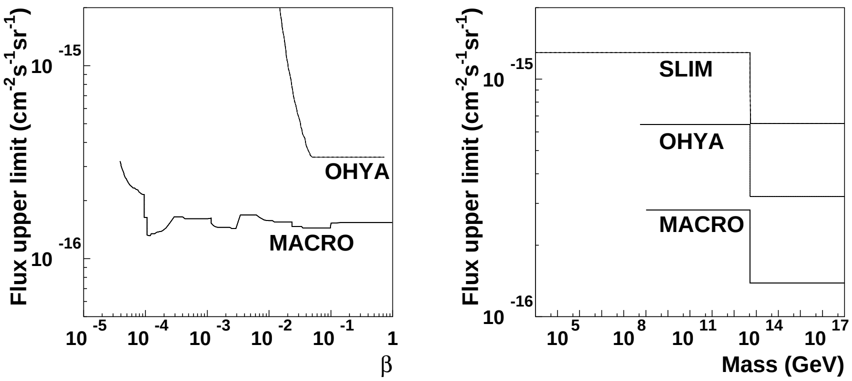


**Figure 1:** Upper flux limits for (a) GUT monopoles as a function of $\beta$ (b) Monopoles as a function of mass for $\beta > 0.05$.

***Searches via the Catalysis of Nucleon-Decay:*** Searches have also been performed for evidence of the catalysed decay of a nucleon, as predicted by the Callan-Rubakov mechanism. Searches have been made at a range of experiments which are sensitive to the induced nucleon decay of a passing monopole. For example, searches have been made with the Soudan [37] and Macro [38] experiments, using tracking detectors. Searches at Kamiokande [39], IMB [40] and the underwater Lake Baikal experiment [41] which exploit the Cerenkov effect have also been made. The resulting $\beta$-dependent flux limits from these experiments, which typically vary between $6 \times 10^{-17} - 9 \times 10^{-14}$cm$^{-2}$sr$^{-1}$s$^{-1}$ [25], are sensitive to the assumed values of the catalysis cross sections.

***Searches at Colliders:*** Searches have been performed at hadron-hadron, electron-positron and lepton-hadron experiments. Collider searches can be broadly classed as being direct or indirect. In a direct search, evidence of the passage of a monopole through material, such as a charged particle track, is sought. In indirect searches, virtual monopole processes are assumed to influence the production rates of certain final states.

***Direct Searches at Colliders:*** Collider experiments typically express their results in terms of upper limits on a production cross section and/or monopole mass. To calculate these limits, ansatzes are used to model the kinematics of monopole-antimonopole pair production processes since perturbative field theory cannot be used to calculate the rate and kinematic properties of produced monopoles. Limits therefore suffer from a degree of model-dependence, implying that a comparison between the results of different experiments can be problematic, in particular when this concerns excluded mass regions. A conservative approach with as little model-dependence as possible is thus to present the upper cross-section limits as a function of one half the centre-of-mass energy of the collisions, as shown in Fig. 2 for recent results from high energy colliders.

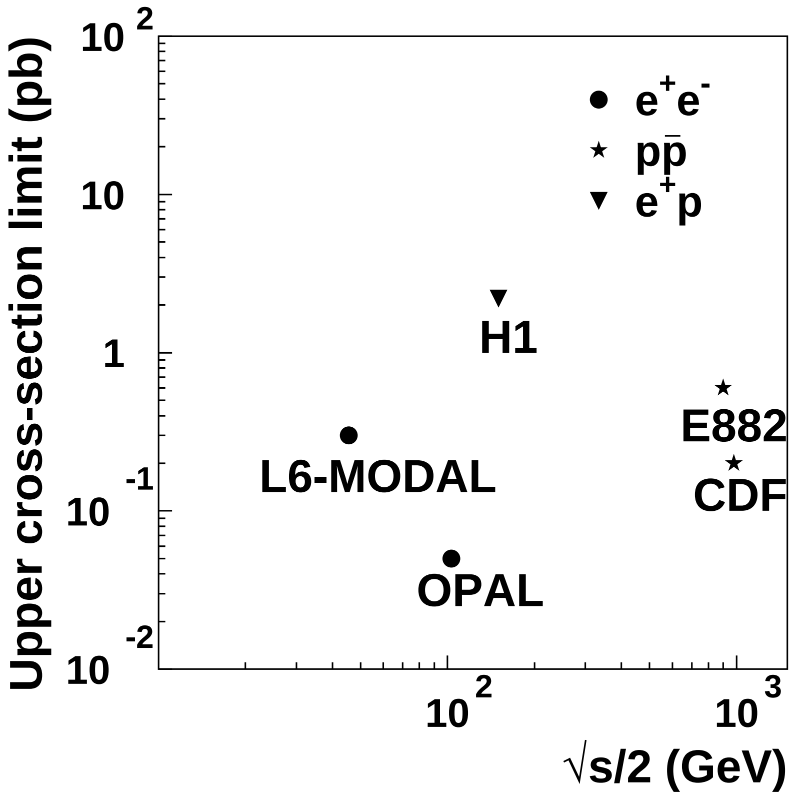


**Figure 2:** Upper limits on the production cross sections of monopoles from various collider-based experiments.

Searches for monopoles produced at the highest available energies in hadron-hadron collisions were made at the Tevatron by the CDF [42] and E882 [43] experiments. Complementary approaches were used; the CDF experiment used a dedicated time-of-flight system whereas the E882 experiment employed the induction technique to search for stopped monopoles in discarded detector material which had been part of the CDF and D0 detectors using periods of luminosity. Considered together, the searches provide a sensitivity to monopoles with charges between $Q_M^D$ and $6Q_M^D$ and masses up to around 900 GeV. Earlier searches at the Tevatron, such as Ref. 44, used NTDs and were based on comparatively modest amounts of integrated luminosity. Lower energy hadron-hadron experiments have employed a variety of search techniques including plastic track detectors [45] and searches for trapped monopoles [46].

The only LEP-2 search was made by OPAL [47] which quoted cross section limits for the production of monopoles possessing masses up to around 103 GeV. At LEP-1, searches were made with NTDs deployed around an interaction region. This allowed a range of charges to be sought for masses up to $\sim$ 45 GeV. The L6-MODAL experiment [48] gave limits for monopoles with charges in the range $0.9Q_M^D$ and $3.6Q_M^D$, whilst an earlier search by the MODAL experiment was sensitive to monopoles with charges as low as $0.1Q_M^D$ [49]. The deployment of NTDs around the beam interaction point was also used at earlier $e^+e^-$ colliders such as KEK [50] and PETRA [51]. Searches at $e^+e^-$ facilities have also been made for particles following non-helical trajectories [52,53].

There has so far been one search for monopole production in lepton-hadron scattering. Using the induction method, monopoles were sought which could have stopped in the aluminium beampipe which had been used by the H1 experiment at HERA [54]. Cross section limits were set for monopoles with charges in the range $Q_M^D - 6Q_M^D$ for masses up to around 140 GeV.

***Indirect Searches at Colliders:*** It has been proposed that virtual monopoles can mediate processes which give rise to multi-photon final-states [55,56]. Photon-based searches were made by the D0 [57] and L3 [58] experiments. The D0 work led to spin-dependent lower mass limits of between 610 and 1580 GeV, while L3 reported a lower mass limit of 510 GeV. However, it should be stressed that uncertainties on the theoretical calculations which were used to derive these limits are difficult to estimate.

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