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F The search for magnetic monopoles

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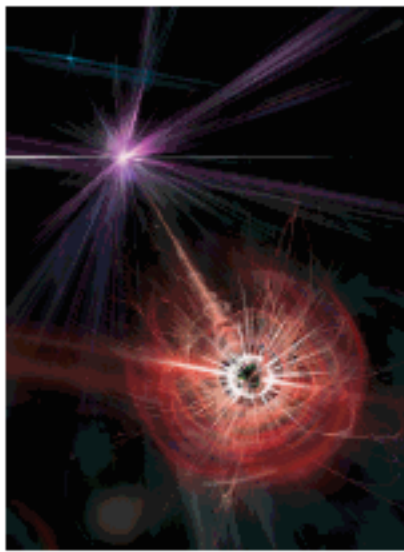


The discovery of the mysterious hypothetical particles would provide a tantalizing glimpse of new laws of nature beyond the standard model.

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Electricity and magnetism appear everywhere in the modern world and form the basis of most of our technology. Therefore, it would be natural to assume that they are already fully understood and no longer pose unanswered fundamental physics questions. Indeed, for most practical purposes they are perfectly well described by classical electrodynamics, as formulated by James Clerk Maxwell in 1864. At a deeper level, a consistent quantum mechanical account is given by quantum electrodynamics, part of the standard model of particle physics. The theory works so well that it predicts the magnetic dipole moment of the electron accurately to 10 significant figures. Nevertheless, there is still an elementary aspect of electromagnetism that we do not understand: the question of magnetic monopoles.¹

That magnets always have two poles—north and south—seems like an obvious empirical fact. Yet we do not know any theoretical reason why magnetic monopoles, magnets with a single north or south pole, could not exist. Are we still missing some crucial fundamental aspect of the theory? Or do [magnetic monopoles](#) exist and we simply have not managed to find them yet?



HEIKKA VALJA/MoEDAL COLLABORATION

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Magnetic mystery

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Nothing in classical electrodynamics prohibits magnetic monopoles; in fact, they would make the theory more symmetric. As Maxwell noted, the laws governing electricity and magnetism are identical. That can be seen in the Maxwell equations of electrodynamics, which in vacuum have a duality symmetry—the electric terms can be replaced with magnetic terms, and vice versa, in such a way that the equations are left unchanged. That symmetry is broken only in the presence of electric charges and currents, which have no magnetic counterparts. If magnetic monopoles existed, they would carry the magnetic equivalent of an electric charge, and they would restore the duality symmetry (see figure 1). On aesthetic grounds, one would therefore expect their existence.

$$\begin{array}{l}
 \mathbf{E} = -\nabla\phi - \dot{\mathbf{A}} \\
 \nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \\
 \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} - \nabla \times \mathbf{B} = -\mu_0 \mathbf{J} \\
 \nabla \times \mathbf{E} = -\dot{\mathbf{B}} \\
 \mathbf{B} = \nabla \times \mathbf{A} \\
 \nabla \cdot \mathbf{B} = \mu_0 \rho_M \\
 \frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = -\mu_0 \mathbf{J}_M \\
 \nabla \times \mathbf{B} = \mu_0 (\mathbf{J} + \dot{\mathbf{A}}) \\
 \nabla \cdot \mathbf{B} = \mu_0 \rho_M \\
 \nabla \times \mathbf{E} = -\dot{\mathbf{B}} \\
 \nabla \times \mathbf{E} = -\dot{\mathbf{B}} \\
 \nabla \times \mathbf{B} = \mu_0 (\mathbf{J} + \dot{\mathbf{A}})
 \end{array}$$

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Figure 1. Maxwell's equations of electrodynamics, amended to include magnetic monopoles. The terms on the right-hand sides of the equations at right arise due to magnetic monopoles. The arrows indicate transformations that obey duality symmetry. Here,

\mathbf{E} and \mathbf{B}

\mathbf{B} are the electric and magnetic fields, respectively; ϵ_0

ϵ_0 and μ_0

μ_0 are the permittivity and permeability of vacuum; c

c is the speed of light; ρ

ρ and \mathbf{J}

\mathbf{J} are the electric charge and current densities; and ρ_M

ρ_M and \mathbf{J}_M

\mathbf{J}_M are the magnetic charge and current densities.

The duality symmetry provides clues to the likely traits of the hypothetical magnetic charges and currents. They would behave in exactly the same way as electrically charged particles: The magnetic charge would be conserved, so the lightest magnetic monopole would be a stable particle; opposite monopoles would attract each other and like monopoles would repel each other; their trajectories would bend in an electric field, and so forth. Indeed, a hypothetical universe in which all electric charges were replaced by magnetic charges of the same strength would be completely indistinguishable from ours. The word “electric” is simply a label for the type of charge that exists, and the word “magnetic” for the type that apparently does not. Of course, if they both existed, there would be genuinely new electromagnetic phenomena.

If Maxwell's theory of electrodynamics is perfectly compatible with magnetic charges, why did he not include them? Simply because experiments at the time suggested that the charges didn't exist. Those experiments were simple by today's standards—they involved things like floating magnets and cutting long magnets to pieces. But in spite of vast improvements in technology and experimental techniques, his assumption still seems to hold. And despite equally dramatic advances in our understanding of fundamental physics, we still don't understand why.

Quantum quandary

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At first sight, magnetic monopoles seem to be incompatible with quantum mechanics. That is because in quantum mechanics, electromagnetic fields have to be described in terms of a scalar potential ϕ and vector potential \mathbf{A}

\mathbf{A} . The magnetic field is given by the curl of the vector potential, $\mathbf{B} = \nabla \times \mathbf{A}$

$\mathbf{B} = \nabla \times \mathbf{A}$, and it follows from elementary vector calculus that the field must then be sourceless, $\nabla \cdot \mathbf{B} = 0$

$\nabla \cdot \mathbf{B} = 0$. In other words, magnetic field lines cannot end. So how can there be magnetic monopoles?

The same problem appears in classical electrodynamics, where potentials are often used as mathematical tools. But in classical physics the use of potentials is optional, because any system can be described using electric and magnetic fields instead. By contrast, in quantum physics the potentials couple directly to the complex phase of the quantum wavefunction—with real physical consequences—and therefore their use cannot be avoided.

In 1931, however, British physicist Paul Dirac ingeniously showed that the requirement for unbroken magnetic field lines doesn't rule out monopoles.² Quantum mechanics allows them to exist, but only if their magnetic charge has exactly the right strength.

In Dirac's model, illustrated in figure 2, each magnetic north pole is connected to a magnetic south pole by a line of singularity called a Dirac string. That string is effectively an idealized solenoid with zero thickness, and it carries magnetic flux from the south pole to the north pole so that the field lines remain continuous. In classical physics, such a string would be easily observable because of the effect it would have on electrically charged particles. But in quantum physics, if the magnetic charge g of the poles has exactly the right value, electrically charged particles are unaffected by the string's presence. That value is given by the so-called Dirac quantization condition

$$g = \frac{2\pi\hbar}{\mu_0 e} n$$

$$g = \frac{2\pi\hbar}{\mu_0 e} n$$

where e

e is the electric charge of a particle used to probe the string, \hbar

\hbar is Planck's constant, and n

n is any integer. If the Dirac condition is satisfied by the electric charges of all particles, no experiment can observe the string. Thus, Dirac argued, the string is not really there: It is a mathematical artifact, a consequence of the variables chosen for the theoretical description. Only the two poles at the ends of the string are real, and physically they appear as two separate particles—free magnetic monopoles.

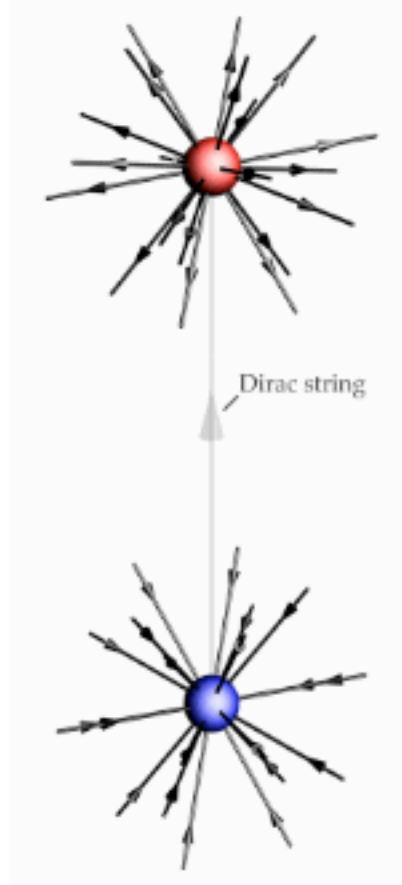


Figure 2. Dirac monopoles. The north monopole (red) is connected to a south monopole (blue) by a line singularity known as a Dirac string, which carries magnetic flux and preserves the continuity of the magnetic field lines. If the magnetic charge of the monopoles satisfies the Dirac quantization condition, the Dirac string is unobservable and does not affect the motion or behavior of the monopoles it connects.

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The quantization condition has important consequences. First, it tells us what the charge g of a magnetic monopole should be, which turns out to be very strong: The magnetic force between two monopoles, each with a single Dirac charge g_D of $2\pi\hbar/\mu_0 e$, would be 4700 times as strong as the Coulomb force between two electrons.

Second, the condition implies that if monopoles exist, the electric charge must be quantized. In other words, all particles must have an electric charge that's an integer multiple of the elementary charge $e_0 = 2\pi\hbar/\mu_0 g_D$. And indeed, experiments show that all particle charges are integer multiples of the electric charge of the electron. The only exceptions are quarks, which have fractional charges but aren't subject to the quantization condition because they are permanently confined. The observed quantization of electric charge can therefore be seen as evidence for the existence of magnetic monopoles.

Fiendish fields

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Dirac's construction does not imply that magnetic monopoles must exist, only that they may. It was not a prediction in the same sense as his famous prediction of the positron, which he showed to be an unavoidable consequence of relativistic quantum mechanics. Nor did it show how to describe the monopole as a dynamical, quantum mechanical particle. That problem turns out to be thorny.

One complication is the monopole's strong magnetic charge. Quantum field theory calculations in particle physics can use perturbation theory whenever interactions are weak. For electrically charged particles, the interaction strength is characterized by the fine-structure constant

$$\alpha = e^2/4\pi\hbar c\epsilon_0 \approx 1/137$$

$$\alpha = e^2/4\pi\hbar c\epsilon_0 \approx 1/137. \text{ Because } \alpha$$

α is much smaller than one, perturbation theory works well. By contrast, the Dirac quantization condition implies a magnetic fine-structure constant that is much greater than one: $\alpha_M = \mu_0 g^2/4\pi\hbar c = 1/4\alpha \approx 34$

$\alpha_M = \mu_0 g^2/4\pi\hbar c = 1/4\alpha \approx 34$. Perturbation theory is therefore not applicable. That said, the same is true for strong nuclear forces, but physicists have made progress on that front nonetheless; instead of perturbation theory, they use numerical lattice Monte Carlo simulations. Similar methods are being developed for magnetic monopoles.³

Another, deeper problem is that monopoles must be attached to Dirac strings. Quantum fields describe point-like elementary particles, but the Dirac string is a line-like extended object. Including it in the theory in a way that respects its fundamental symmetries—the Lorentz invariance of special relativity and the gauge invariance of electrodynamics—is difficult. Furthermore, the Dirac string has to be included in such a way that it becomes completely unobservable if the Dirac quantization condition is satisfied. Although theoretical formulations dating back to the 1960s satisfy those criteria, they are cumbersome and haven't been studied much.

Could the difficulty of finding a field theoretical description of magnetic monopoles reflect some deeper fundamental incompatibility with quantum field theory? Again, the answer is no. In 1974 Gerard 't Hooft and Alexander Polyakov found so-called hedgehog solutions for quantum field theories in which the electromagnetic field is a part of a larger unified interaction.⁴ Such solutions are "lumps" of field with finite, nonzero size, each lump consisting of a large number of elementary quanta. At the center of the lump, the electromagnetic field loses its identity, which allows magnetic field lines to end; consequently, the lump acquires a magnetic charge. If the lumps are small enough, they appear as point-like magnetic monopoles. Figure 3 shows a 't Hooft–Polyakov monopole simulated using lattice field theory.

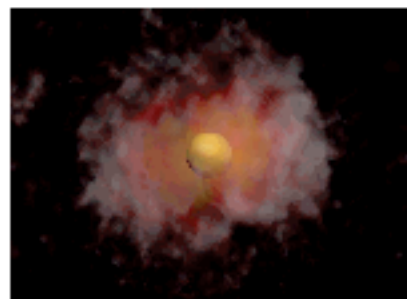


Figure 3. A 't Hooft–Polyakov monopole surrounded by a quantum field cloud, simulated using lattice field theory.

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The 't Hooft–Polyakov solutions demonstrate that magnetic monopoles are compatible with renormalizable, relativistic quantum field theory. In fact, the theory in which they were found is similar to the electroweak sector of the standard model of particle physics. The only difference is that the theory's Higgs field had three real components, whereas the standard model Higgs has two complex components. As a result, the standard model does not have 't Hooft–Polyakov monopole solutions and does not predict the existence of monopoles. We know perfectly well, however, that the standard model cannot be the complete theory of everything, because it does not include gravity and does not account for dark matter, cosmological inflation, or the origin of the preponderance of matter over antimatter. There must be undiscovered physics beyond the standard model.

One widely studied hypothesis is grand unification. According to grand unified theories (GUTs), the strong and electroweak forces merge at very high energies into a single unified force. Remarkably, one can show that every GUT has 't Hooft–Polyakov monopole solutions, and therefore, magnetic monopoles are an inevitable consequence of grand unification.

The mass of GUT monopoles is determined by the energy scale of grand unification and is thus very high, around 10^{17} GeV/ c^2 . (The mass of the proton is approximately 1 GeV/ c^2 .) That makes the monopoles far too heavy to be produced in experiments. The Large Hadron Collider (LHC), the world's largest particle accelerator, has a maximum proton–proton collision energy on the order of 10^4 GeV.

On the other hand, we do not know what new physics lies waiting beyond the standard model. It is perfectly possible that there are monopoles unrelated to grand unification. And if they are elementary particles, not lumps of quanta, they could be much lighter than GUT monopoles.

Cosmic conundrum

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One important difference between magnetic monopoles and most other elementary particles is that monopoles, if they exist, would be absolutely stable. Whereas the Higgs boson, for example, has a lifetime of just 10^{-22} s, a magnetic monopole could be destroyed only if it came in contact with another monopole of opposite charge. In that case they would annihilate each other and produce a burst of lighter elementary particles and radiation.

The monopoles' stability means that if they were produced at any time in the history of the universe, they would still be present. Such a scenario is by no means far-fetched. In the same way that nucleosynthesis in the early universe yielded light elements, thermal processes would have produced magnetic monopoles if ever the temperature was high enough. As the universe cooled down, the monopoles' density would have initially decreased by pair annihilation. But once they were sufficiently depleted, the monopoles would no longer have been able to find annihilation partners, and they would have survived indefinitely.

The present-day number density of the relic monopoles would depend on their mass. According to traditional Big Bang theory—in which the temperature of the universe was initially close to the Planck scale of quantum gravity and there was no inflationary epoch—the monopoles would have to have a relatively light mass, M , of no more than 10^{10} GeV/ c^2 ; otherwise, they would exceed the observed matter density of the universe.⁵

The fact that the upper limit on mass is well below the GUT monopole masses rules out grand unification in the context of the traditional Big Bang. That so-called monopole problem was one key motivation for the theory of cosmological inflation, which posits that the early universe went through a phase of accelerating expansion. The expansion would have diluted any preexisting monopole density to unobservably low levels, and provided the universe didn't subsequently reheat to temperatures high enough to produce new ones, at most a few monopoles would remain in the observable universe today. The monopole problem would be solved.

Today the theory of inflation is strongly supported by observed temperature anisotropies in the cosmic microwave background and by other cosmological observations. Those observations show that the reheat temperature, the maximum temperature of the universe after inflation, was less than approximately 10^{16} GeV/ k_B , not high enough to produce typical GUT monopoles. (Here, k_B is the Boltzmann constant.) The reheat temperature may even have been much lower, as low as 1 to 100 GeV/ k_B , in which case even significantly lighter monopoles would pose no problem.

Lowered limits

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Several physicists have attempted to improve on the matter-density constraints by searching for monopoles both directly and indirectly, through their astrophysical implications. One of the best constraints is the Parker bound, which is based on observed traits of galactic magnetic fields and named after the astrophysicist Eugene Parker.⁶ Observations indicate that galaxies typically have magnetic fields of around a few microgauss. Sufficiently light magnetic monopoles would be accelerated by such fields to high velocities. That process would gradually drain energy from the field and cause it to dissipate. Therefore, the strength of present-day galactic magnetic fields gives an upper bound (see figure 4) on the monopole flux \mathcal{F}

\mathcal{F} through a unit area per unit time per unit solid angle. The flux can be related to the number density n

n of monopoles through $\mathcal{F} \approx nv/(4\pi)$

$\mathcal{F} \approx nv/(4\pi)$, where v

v is the typical monopole velocity and is close to the speed of light for monopoles of mass 10^{11} GeV/ c^2 or less accelerating in galactic magnetic fields.

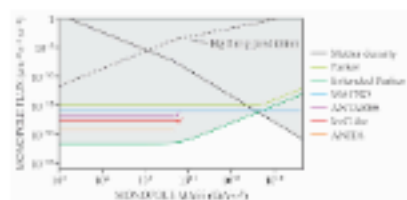


Figure 4. Astrophysical observations and cosmic-ray experiments have placed stringent upper bounds on the cosmic monopole flux. The dotted line shows the predicted monopole density according to the traditional Big Bang theory; that prediction lies entirely within the gray shaded area representing the densities that have been excluded by observations. The conflict between theory and observation is solved by introducing cosmological inflation, which reduces the predicted flux to an unobservable level. (Data from refs. 6, 7, 10, and 11.)

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The Parker bound can be tightened further by considering how the galactic magnetic fields were generated from a small initial seed field.⁷ The resulting extended Parker bound is so stringent that it excludes all monopoles at cosmic densities predicted by traditional Big Bang theory (see figure 4).

If magnetic monopoles are present in the universe today, we should be able to find them in cosmic rays hitting Earth. In 1973 a team at the University of California, Berkeley, led by P. Buford Price, appeared to find one in a balloon-based cosmic-ray experiment.⁸ The team's stack of nuclear track detector (NTD) sheets had an unusual track corresponding to a highly ionizing particle moving downward at relativistic speed. The track seemed consistent with a magnetic monopole having the Dirac charge, g_D , and a mass of no more than 200 GeV/ c^2 . However, closer analysis showed that the track was probably produced instead by a platinum nucleus.

Another monopole candidate was seen in 1982 in an experiment with a superconducting ring carried out by Blas Cabrera of Stanford University.⁹ The current in the ring jumped by exactly the amount that would be induced by the passage of a magnetic monopole with a Dirac charge.

Cabrera's result has since been cast into doubt by subsequent, more extensive searches that found no further candidate monopoles.^{10,11} The MACRO experiment in Gran Sasso, Italy, ran from 1989 to 2000 and gave an upper bound on the monopole flux of 10^{-16} cm⁻² s⁻¹ sr⁻¹ over a wide range of monopole masses, and the ANITA, ANTARES, and IceCube neutrino detectors have provided even stricter limits on relativistic monopoles (see figure 4). Researchers have also attempted to find monopoles trapped in polar rocks, moon rocks, and seawater and through the tracks they might leave in mica, all to no avail. Because of highly uncertain systematics, however, it is not possible to turn those studies into precise limits on the monopole flux. Some GUT monopoles are predicted to catalyze nucleon decay, and the effects on the interiors of white dwarfs, neutron stars, and even the Sun place strong bounds on their number density.

Taken together, the above experiments and observations thoroughly rule out the monopole densities predicted by traditional Big Bang theory, for all realistic masses. Therefore, if monopoles exist, the reheat temperature would have to be so low that they would not be produced after inflation. Whether magnetic monopoles exist in principle, in practice they cannot be present in the universe today.

Even if magnetic monopoles aren't present in the cosmos, one might be able to produce them in collider experiments, just as one would produce, say, Higgs bosons. Because of magnetic charge conservation, monopoles would always be produced in north–south pairs, and only if the collision energy is higher than the combined mass of the two monopoles. Therefore, the LHC, with its maximum proton–proton collision energy of 13 TeV, could produce monopoles only if their mass is at most a few TeV/c^2 . That's many orders of magnitude too small to observe GUT monopoles, but elementary magnetic monopoles could have masses within the accessible range.

That collider experiments have yet to find magnetic monopoles places an upper bound on the probability of producing them in a single collision. Because of quantum uncertainty in the position of the colliding particles, that probability is most naturally expressed as the production cross section σ

ϕ . For realistic monopole masses, experiments currently place the upper bound on pair production at just a few femtobarns. In other words, the probability of a single collision producing a monopole is, at most, about the same as the likelihood that the centers of two colliding particles will pass within 10^{-22} m of one another.

Unfortunately, one cannot apply perturbation theory to calculate the monopole pair production cross section. To get a rough estimate, however, one can consider the Drell–Yan mechanism, in which a quark and an antiquark annihilate, forming a short-lived virtual photon that decays into a monopole–antimonopole pair. That picture rather accurately describes the production of electrically charged particles, but because of the strength of the magnetic charge, it cannot be very accurate for monopoles.

For 't Hooft–Polyakov monopole pairs, which consist of a large number of elementary quanta, theoretical arguments suggest that the production cross section is exponentially small—suppressed by the factor $\exp(-1/\alpha) \sim 10^{-60}$. That would make them practically impossible to produce even if enough energy was available. Any monopoles found at the LHC would likely be elementary particles, not semiclassical 't Hooft–Polyakov monopoles.

Since 2010 the ATLAS experiment at the LHC has sought magnetic monopoles in the debris of 8 TeV proton–proton collisions by looking for highly charged particles captured in an electromagnetic calorimeter.¹² That search is sensitive only to monopoles with charge equal to the Dirac magnetic charge; monopoles of higher charge would stop before reaching the calorimeter. Assuming a leading-order Drell–Yan production cross section, the ATLAS results constrain the monopole mass to be no less than $1340 \text{ GeV}/c^2$ for spin- $1/2$ monopoles with a single Dirac charge and no less than $1050 \text{ GeV}/c^2$ for spin-0 monopoles with a single Dirac charge. However, the Drell–Yan result relies on perturbation theory, whose applicability to monopoles is questionable.

Now upgraded to 13 TeV, the LHC experiments can reach even higher monopole masses. There is also a new, dedicated experiment called MoEDAL—for Monopole and Exotics Detector at the LHC—located next to the LHCb experiment and designed specifically to look for magnetic monopoles and other stable, highly ionizing particles¹³ (see figure 5). It uses two passive methods: plastic NTD sheets and aluminum trapping detectors.



Figure 5. The MoEDAL experiment, pictured here in a panoramic photo, looks for monopoles and other exotic, highly charged particles in the debris of proton–proton collisions at CERN's Large Hadron Collider. After a brief test run in 2012, the experiment began collecting data last year. (Image courtesy of CERN.)

Altogether, 400 six-sheet stacks of NTDs, each 25 cm × 25 cm, have been placed around LHCb's Vertex Locator (VELO) detector. If a monopole is produced in a collision and flies through the sheets, it will leave a track that should be observable when the sheets are later etched and analyzed with an optical scanning microscope. The search for monopole tracks will be carried out with the help of a new citizen science project hosted by the Zooniverse web platform.

The MoEDAL trapping detector consists of some 800 kg of Al bars placed around the VELO detector. When a monopole travels through the Al, it loses energy and eventually binds to an Al nucleus, because of the atom's anomalously high magnetic moment. The monopole can then be detected by scanning the Al bars through a sensitive superconducting magnetometer. A passing magnetic monopole would induce a telltale jump in the magnetometer's electric current. If such a jump is observed, the measurement can be repeated multiple times to eliminate any possibility of a false detection.

MoEDAL began full operation in June 2015 with the start of the LHC's second science run. It has not yet published results from 13 TeV collisions, but in 2012 a smaller, 160 kg test array of trapping detectors was exposed to 8 TeV proton–proton collisions for a short period.¹⁴ The results, shown in figure 6, indicate that MoEDAL can search for monopoles of higher mass and magnetic charge than could ATLAS. The test run also demonstrated that the scanning method should be more than sensitive enough to detect a single magnetic monopole trapped in the aluminum. The full installation of trapping detectors will have a larger trapping volume, cover a larger solid angle, and be supplemented by NTDs, all of which should strengthen the bounds on monopole production even further.

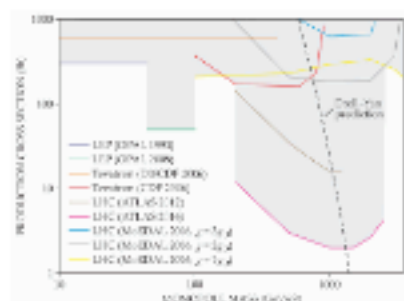


Figure 6. Collider experiments have placed upper bounds on the monopole production cross section, expressed here in conventional units of femtobarns ($1 \text{ fb} = 10^{-43} \text{ m}^2$). With the exception of the MoEDAL test-run results, the observations apply to spin- $\frac{1}{2}$ monopoles with a single Dirac magnetic charge g_D . (The MoEDAL experiment also applies to higher charges.) The dotted line shows a crude theoretical prediction for the cross section from proton–proton collisions, and the gray shaded area corresponds to cross sections that have been excluded by observations. Because the cross section depends on both the energy and type of collider, however, results from different colliders are not directly comparable. (Data from refs. 11, 12, 14, and 17.)

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The search continues

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The discovery of magnetic monopoles would have a huge effect on physics. Not only would monopoles provide the first glimpse of the new laws of nature beyond the standard model, but their special properties would allow us to explore that new physics in ways not possible with other particles. Because monopoles are stable and interact with the electromagnetic field, they could easily be extracted from the trapping detectors and used for a wide range of further experiments. Furthermore, their interactions with electrically charged fermions, including the possible catalysis of proton decay, would depend sensitively on physics at very high energies. Given the technological importance of electricity and magnetism, it also seems likely that magnetic monopoles could have real practical applications, although they would necessarily be specialized because of the very high cost of producing the particles.

Even without a discovery, magnetic monopoles have already influenced fields ranging from high-energy physics to condensed-matter physics. They have provided new insight into the problem of quark confinement by the strong nuclear force, and they've shed light on properties of superstring theory and supersymmetric quantum field theories, where generalizations of the concept of duality have proven useful.

Magnetic monopoles have also inspired condensed-matter physicists to discover analogous states and excitations in systems such as spin ices¹⁵ and Bose–Einstein condensates.¹⁶ However, despite the importance of those developments in their own fields, they do not resolve the question of the existence of real magnetic monopoles. Therefore, the search continues.

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