

Search for magnetic monopoles at the Tevatron sets new upper limit on their production

Paul Dirac showed in 1931 that the existence of even a single monopole, anywhere, would suffice to explain the universal quantization of electric charge.

Electric charges are everywhere, but there is still no evidence of magnetic monopoles. That remains true even after a new report of the most sensitive search to date for monopole production at accelerator energies.¹ The report, by the CDF-detector collaboration at the Fermilab Tevatron collider, concludes that more than 10^{12} proton-antiproton collisions over several months in the world's highest-energy collider produced not even one pair of magnetic monopoles.

In 1894 Pierre Curie pointed out that the absence of monopoles is all that mars the symmetry of the Maxwell equations with regard to electric and magnetic fields (see the box below). Serious modern interest in the possible existence of magnetic monopoles began with a famous 1931 paper by Paul Dirac.² He showed that a consistent quantum mechanical treatment of a system comprising an electron of electric charge $-e$ and a monopole of magnetic charge g required that

$$ge = n\hbar c/2,$$

where n must be an integer.

Dirac pointed out that this surprising quantum condition has a profound consequence: The existence of at least one magnetic monopole, anywhere, would explain the universal quantization of electric charge. Electric-charge quantization is an overwhelming fact of nature. The equality of the magnitudes of the proton and electron charges has been verified to very high precision. But, then as now, charge quantization doesn't follow from any established theory. Explaining it was for a long time the principal motive for monopole searches. In recent decades, searches have also been spurred by theories that explicitly predict the existence of monopoles with enormous masses comparable to the energies at which the different elementary-particle forces are expected to become unified.

Dirac's quantization condition says that the smallest possible value of the monopole charge g is $e/2\alpha$, where α , the fine-structure constant $e^2/\hbar c$, is close to $1/137$. That makes g at least 68.5 times bigger than e . This great disparity implies that the passage of a monopole through matter would leave much more ionization in its wake than would

a singly charged ordinary particle. That unusually high ionization is the basis of the CDF collaboration's search and for many earlier searches.

Superconducting loops

The other principal search mode, called the monopole-induction method, exploits the putative monopole-current ($\mathbf{j}_m$) term in the expanded Maxwell equations (see the box). The extra term says that even a steady current of monopoles threading a conducting loop would impose an electromotive force on the loop just as an electric current generates a magnetic field around itself.

In the 1960s and 70s, Luis Alvarez and coworkers at the Lawrence Berkeley National Laboratory tested various promising materials for the telltale emf of trapped monopoles. They passed castoff accelerator scraps and bits of rock from meteorites, the Antarctic, and the Moon through superconducting loops. Because magnetic charge, like electric charge, would be strictly conserved, a monopole trapped in metal or rock could not decay away. For the same reason, monopoles could only be produced in pairs of opposite polarity. By convention, g is positive for a lone north pole.

Two years ago, Alvarez's former student George Kalbfleisch (University of Oklahoma in Norman) led an effort that yielded a significant upper limit on the abundance of monopoles trapped over the years in metal structures near the Tevatron's collision regions. Kalbfleisch and company passed nonferrous bits of superannuated detector components through superconducting loops connected to SQUID probes.³

They found no monopoles, but if they had, the precious finds, securely trapped, could have been tested again and again to satisfy the rightly wary. Such was not the case on St. Valentine's Day in 1982, when a lone free monopole—perhaps a cosmic ray—appeared to pass through Blas Cabrera's superconducting-loop detector at Stanford University (see PHYSICS TODAY, June 1982, page 17). The absence of any further such traversals over a subsequent long exposure eventually convinced Cabrera that the St. Valentine's Day signal was almost certainly an instrumental fluke.

How massive?

At the Tevatron, countercirculating beams of 1-TeV protons and antiprotons collide head-on. Production of monopole pairs in the collider is energetically possible only if the monopole's mass is less than 1 TeV. That's more than a thousand times the proton's 0.94-GeV mass, but it's still very much smaller than most theoretical expectations. In the mid-1970s, Gerard 't Hooft and Alexander Polyakov pointed out that monopoles arise easily in theories that unite electromagnetism with other interactions. The so-called grand unified theories, which seek to unite the electroweak and strong-force sectors of particle theory's standard model, predict the existence of monopoles with a mass of something like 10^{13} TeV.

No conceivable accelerator could produce such ultraheavy monopoles. But cosmologists argue that they were profusely made in the first moments of the Big Bang. It was, in fact, largely to

The Maxwell equations with monopole terms

If magnetic monopoles exist, the Maxwell equations, shown here in Gaussian units, would be made symmetric with regard to the electric and magnetic fields $\mathbf{E}$ and $\mathbf{B}$ by the addition of the highlighted terms involving the monopole charge density ρ_m and current density $\mathbf{j}_m$. The force $\mathbf{F}_m$ on a single monopole of magnetic charge g is analogous to the usual Lorentz force $\mathbf{F}_e$ on an electron.

$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$

$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$

$$\nabla \times \mathbf{B} = \frac{1}{c} \frac{\partial}{\partial t} \mathbf{E} + \frac{4\pi}{c} \mathbf{j}_e$$

$$-\nabla \times \mathbf{E} = \frac{1}{c} \frac{\partial}{\partial t} \mathbf{B} + \frac{4\pi}{c} \mathbf{j}_m$$

$$\mathbf{F}_e = e(\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B})$$

$$\mathbf{F}_m = g(\mathbf{B} - \frac{1}{c} \mathbf{v} \times \mathbf{E})$$

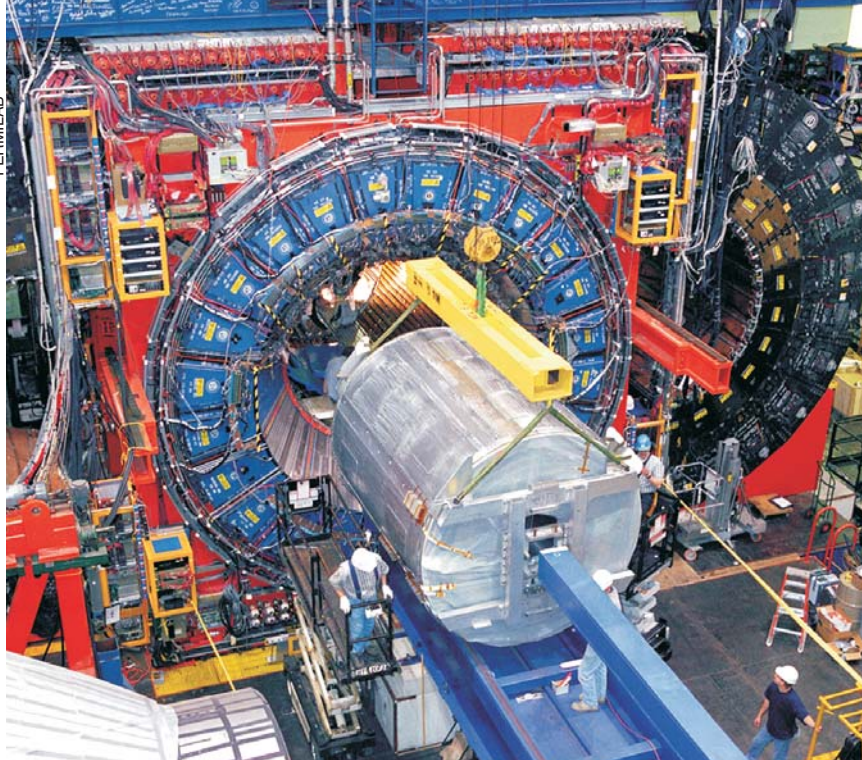


Figure 1. The CDF detector at Fermilab's Tevatron collider is shown here in 1999 as the new central outer tracker (the silvery cylinder) was about to be installed into a space surrounded by the 216 scintillation bars of the time-of-flight counter array. Beams of TeV protons and antiprotons coming from opposite directions along the cylindrical-symmetry axis collide in the detector's center. Anomalous bright scintillation pulses were used to trigger the search for evidence of the passage of highly ionizing monopoles through the tracker.¹

explain the present scarcity of monopoles that Alan Guth in 1979 introduced the idea of cosmic inflation. The high primordial density of monopoles would have dwindled to almost nothing during the inflationary expansion of the first 10^{-30} second.

Some theorists have raised the possibility of a more modest monopole mass on the TeV energy scale of electroweak unification. But given the detailed experimental verification of electroweak calculations—unadorned by virtual-monopole exchanges—for electron-positron collisions up to 200 GeV, it seems unlikely that there are monopoles lighter than 10 TeV. That's still too heavy even for the Large Hadron Collider, which is scheduled to begin hurling 7-TeV protons at each other next year. But the appeal of the monopole idea is so great, says theorist David Jackson (University of California, Berkeley), "that the search is renewed whenever a new energy region or a new source of matter becomes available."

Searching for tracks

During the summer 2003 Tevatron collider run, a special hardware trigger and an off-line selection program were

imposed on the CDF detector complex to ferret out any plausible monopole-production candidates from among the millions of proton-antiproton collisions that take place every second in the detector's heart. The monopole search, which ran in tandem with other scattering studies, was led by Christoph Paus and Michael Mulhearn from the CDF collaboration's MIT contingent.

The two detector components that were crucial to the search are visible in figure 1: The new central outer tracker (COT) was about to be slotted into the also-new cylindrical time-of-flight (TOF) scintillator array when the photo was taken in 1999. The TOF array's 216 bars of plastic scintillator, surrounding the COT like the staves of a barrel, are monitored by photomultiplier tubes that provided the monopole hardware trigger.

Proton and antiproton beams coming from opposite directions along the detector's cylindrical symmetry axis collide at its center and subject the TOF bars to an intense barrage of charged particles, mostly pions. But any monopole, because of its extraordinary ability to knock out atomic electrons, is expected to produce a scintillation light signal more than 500 times brighter

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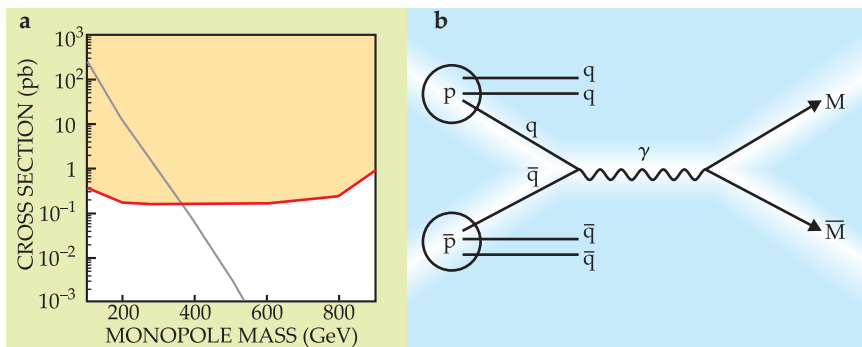


Figure 2. Monopole production at the Tevatron collider. (a) The absence of any surviving monopole candidate from a specially triggered sample of collision events yielded an upper limit, shown as a function of monopole mass by the red curve, on the cross section for the production of monopoles in 2-TeV proton-antiproton collisions. The shaded region is excluded with 95% confidence. The diagonal line shows the predicted mass dependence of the cross section for monopole production by the proposed Drell-Yan mechanism. (Adapted from ref. 1.) (b) Feynman diagram for the Drell-Yan production of pairs of opposite-polarity monopoles (M). A quark from a proton collides with an antiquark from an antiproton to form a virtual photon (γ) that decays into the monopole pair.

than that of any ordinary high-energy charged particle. The actual hardware trigger that initiated the storage and analysis of tracking data from the COT was more conservative. It required only that one of the scintillation bars produce a photomultiplier signal at least 30 times brighter than a relativistic charged pion or proton would yield. Nonetheless, the TOF hardware trigger picked out barely 100 000 candidate events from the total of 2×10^{12} proton-antiproton collisions that occurred during the harvesting of that sample.

The COT is a cylindrical tracking array consisting of 96 coaxial layers of sensor wires that monitor the ionization of the surrounding gas caused by a passing charged particle. Much like the light signal in the scintillator, an ionization pulse generated by a passing monopole would be more than 500 times higher than that of a relativistic pion or proton.

A monopole has an additional way of distinguishing itself in the tracking chamber. The COT sits in a 1.4-tesla magnetic field parallel to the beam axis. The Lorentz force of this strong field bends ordinary charged particles in the $\mathbf{v} \times \mathbf{B}$ direction perpendicular to the field, but it cannot accelerate them. A monopole, by contrast, would be immune to the azimuthal Lorentz-force bending, but it would be accelerated in the beam direction.

The off-line search of the COT data from the 100 000 triggered events for possible monopole tracks required, first of all, that any candidate track have recorded unusually high ionization pulses in more than half the sensor-

wire layers. Furthermore, it demanded that the track maintain a roughly constant azimuthal bearing. The search was complicated by the profusion of charged pions spewed through the tracking chamber in a typical Tevatron collision.

As the track-reconstruction algorithm gradually raised the minimum required ionization-pulse height on every sensor-wire hit by a putative monopole, more and more of the 100 000 triggered events fell away. The last surviving candidate was rejected when the ionization cutoff was raised above 15 times the ionization level for ordinary charged particles. And that final cutoff was still far below the ionization intensity expected for a monopole.

Having found no monopole tracks in its analyzed sample, the CDF collaboration concludes, at the 95% confidence level, that the cross section for producing monopoles at the energy of the Tevatron collider is less than 0.2 picobarns. (1 pb is 10^{-36} cm^2 .) For comparison, the total proton-antiproton scattering cross section at that energy is almost 100 millibarns.

As shown in figure 2a, the 0.2-pb upper limit is claimed only for monopole masses between 200 and 800 GeV. Because Monte-Carlo simulations indicate that the detector's efficiency for finding monopoles decreases as the putative mass approaches either zero or the kinematic limit of 1 TeV, the collaboration quotes correspondingly looser cross-section limits for those mass regions.

The standard model cannot specify an explicit mechanism for monopole pair production at the Tevatron. But a

simple guess is that they would be produced, much like muon pairs, by the so-called Drell-Yan mechanism, in which a quark-antiquark collision produces an intermediate virtual-photon state (see figure 2b). Because the Drell-Yan cross section for monopole production is calculable, it serves as something of a benchmark, even though some theorists argue that the mechanism would be strongly suppressed because monopoles cannot be point charges.⁴ The diagonal line in figure 2a, showing the Drell-Yan cross section's dependence on monopole mass, intersects the CDF experiment's upper limit at 360 GeV. Therefore, if one assumes that monopole pairs are indeed produced by the Drell-Yan mechanism, 360 GeV becomes the new lower limit on the monopole mass.

Even stronger monopoles

The Dirac quantization condition requires only that g equal $ne/2\alpha$. The quoted CDF cross-section and mass limits assumed that n is 1. If n is larger, monopoles would be even more ionizing and, in that sense, easier to see. Furthermore, the production cross section would likely be proportional to n^2 . But the enhanced ionization is more than offset by the greater probability that stronger monopoles would be swept out of the tracker's view by the 1.4-T magnetic field.

Julian Schwinger in 1969 imposed symmetry considerations on Dirac's argument to conclude that n should be a multiple of 2. If, despite the strong presumption that free quarks don't exist, it were appropriate to apply Dirac's quantization argument to the fractional charges of quarks, n would be some multiple of 3.

Because the induction-method search by Kalbfleisch and company did not suffer from CDF's rapid loss of detection efficiency with increasing n , they were able to quote cross-section upper limits for the production of $n = 1, 2, 3$, and 6 monopoles at the Tevatron.³ Their tightest upper limit was 0.07 pb for the production of $n = 3$ monopoles. Would the discovery of an $n = 3$ monopole be evidence that free quarks really do exist?

Bertram Schwarzschild

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