Cabrera counts flux quanta to find a Dirac monopole

Take a superconducting loop, place it in an ultralow magnetic-field device, and monitor the current with a Superconducting Quantum Interference Device for many months. That was the experiment that Blas Cabrera of Stanford University did in his search for a moving magnetic monopole. On Valentine's Day he found a single event consistent with one Dirac unit of magnetic charge. When rumors of the observation spread, the organizers of the Third Workshop on Grand Unification phoned Cabrera in Blacksburg, Virginia (where he was giving a colloquium), and asked him to address the Workshop the next morning (16 April). After a long, wee-hours-of-the-morning drive to Chapel Hill, N. C., Cabrera electrified the workshop participants with his careful, low-key account of his possible monopole discovery.

One noted theorist remarked, "We came to scoff and stayed to praise. It was a very impressive glitch. One shouldn't be convinced by one event. But it's about as impressive as one event can be."

By using a superconducting ring, the Cabrera experiment can detect a moving magnetic charge solely from the long-range electromagnetic interactions between the magnetic charge and the macroscopic quantum state of the ring. Such a detector is insensitive to the monopole velocity, mass, electric charge or magnetic dipole moment.

A similar approach was used in 1970 by Philippe Eberhard, Ronald Ross and Luis Alvarez (Berkeley) and Robert Watt (SLAC). They circulated moon dust (collected by the Apollo 11 astronauts, Neal Armstrong, Edwin Aldrin and Michael Collins) through a superconducting solenoid and looked for the emf generated. Cabrera's paper was published in the 17 May issue of *Physical Review Letters.*

The existence of magnetic monopoles was proposed by Paul Dirac in 1931 in an attempt to explain the existence of the smallest electric charge, e. Dirac's quantization condition said that the strength of a single magnetic pole, g, would be restricted by the relation

$$eg = \hbar c/2$$

In 1948 Dirac showed that if a magnetic charge exists, the integrity of quantum mechanics, and in particular the quantization of angular momentum, is violated unless there is a smallest electric charge.

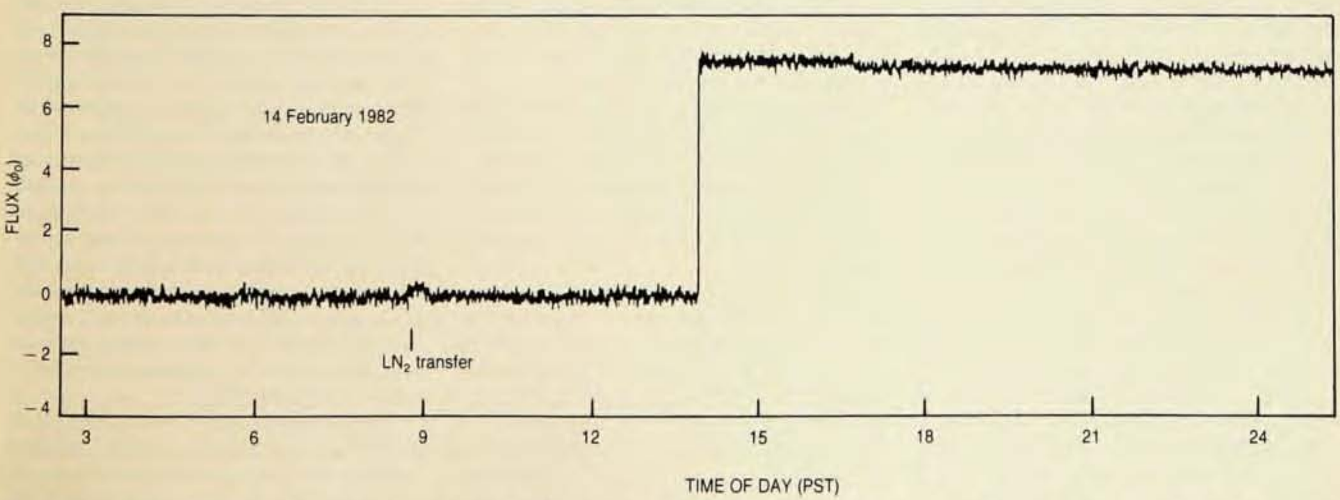
In remarks prepared for the Monopole Meeting held in Trieste last December, Dirac said, "I am inclined now to believe that monopoles do not exist. So many years have gone by without any encouragement from the experimental side."

But practically all previous searches for monopoles—in cosmic rays, at particle accelerators, and in matter—would not have detected an extremely massive monopole. Currently popular grand unified theories predict the existence of monopoles, which are indeed extremely massive—10^{-8} grams or 10^{16} GeV.

In 1975 P. Buford Price, Edward Shirk (Berkeley), Zack Osborne and Lawrence Pinsky (University of Houston) reported finding in cosmic rays a monopole with twice the Dirac strength and a mass at least 200 proton masses (PHYSICS TODAY, October 1975, page 17). The Price group later withdrew its claim to have found a monopole.

Cabrera's way to detect a monopole is to use the quantized flux in a superconductor. The flux quantum $\phi_0 = hc/2e$ gives a direct measurement of magnetic charge.

Cabrera's apparatus is a four-turn, 5-cm-diameter loop made of niobium, positioned with its axis vertical; the loop is connected by twisted pair leads to the superconducting input coil of a SQUID magnetometer. If a single Dirac charge passes through the loop, one would expect an $8\phi_0$ change in the flux through the superconducting circuit,



Candidate monopole event found by Blas Cabrera of Stanford University. If a single Dirac magnetic charge passes through the detection loop, one would expect an $8\phi_0$ change in the flux through the superconducting circuit.

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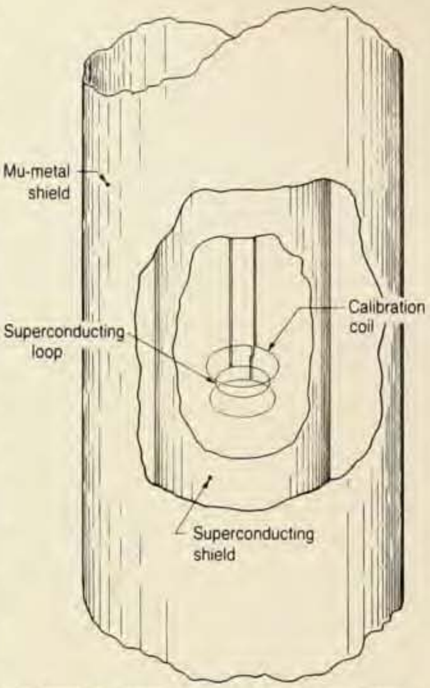
consisting of the detection loop and the SQUID input coil (a factor of 2 from $4\pi g = 2\,\phi_0$ and of 4 from the number of turns in the pick-up loop).

The SQUID and loop are mounted inside a 20-cm-diameter, 1-meter-long cylindrical superconducting shield closed at the bottom. Surrounding the superconducting shield is a single mu-metal cylinder that reduces the Earth's field to a few milligauss. The combined shielding provides 180 db isolation from external magnetic-field changes and an ambient field of 5×10^{-8} gauss. A flux quantum in this size cylinder would produce a field of about 3×10^{-9} gauss. So, Cabrera told us, the cylinder has a few unpaired vortices. Cabrera had used a similar ultralow field device for his PhD research (which he earned in 1974 under William Fairbank's direction).

[Blas Cabrera is a third-generation physicist. His father, Nicolas, is a solid-state physicist who spent 23 years at the University of Virginia (where his son earned his BS), and is now at the Autonomous University of Madrid. The father of Nicolas, also named Blas, specialized in magnetism and was an organizer of the 1930 Solvay Congress, along with Niels Bohr, Marie Curie and Albert Einstein. He is sometimes credited with founding modern experimental physics in Spain.]

To make the superconducting shield, Cabrera takes an expandable lead foil, 60 microns thick, and cools it to liquid-helium temperature while it is accordion-pleated into a long, thin ribbon. When the foil container becomes superconducting, it has trapped the ambient field. Then Cabrera uses a mechanical plunger to expand the foil into a cylinder, still keeping it at liquid-helium temperature. During the expansion, the magnetic field that occupied the volume of cylinder before expansion is expelled from the volume by induced supercurrents on the surface, leaving a lower magnetic field inside the foil container. Although some trapped field remains inside the shield because of the folded configuration, the inside of the cylinder has a field a factor of 10–100 lower than the field outside.

Then Cabrera takes a second folded shield ribbon, placed inside a cooling tube, which can be thought of as a vacuum jacket with a long, glass tube. The tube allows him to control the temperature of the inner shield while the outer shield is kept superconducting. He lets warm helium gas flow through the glass tube, then slowly reduces the flow so that the inner shield is cooled through its transition temperature. Because the inner shield is in the lower magnetic field provided by the previously expanded shield, a still lower field is trapped. He continues this bootstrap process, so that after



Monopole-search apparatus. The loop is connected to the input coil of a SQUID magnetometer. The combined shielding provides 180 db isolation from external field changes and an ambient field of 5×10^{-8} gauss.

three or four expansions, the field inside the apparatus is down to 5×10^{-8} gauss. Then Cabrera lowers his apparatus into the ultralow field region through an airlock. (Stanford has four such ultralow field devices operating; two of them are used for the gyro relativity experiment.) The Dewar is maintained continuously at liquid-helium temperature.

The four-turn loop is a flip coil that can be rotated 180° in the plane of the coil (to allow calibration of the absolute magnetic field). Cabrera had been using the facility for an experiment to measure h/m_e. In his monopole search, he left the coil in a fixed position with its axis coincident to the shield axis.

By mid-May, Cabrera had been monitoring the dc current in the superconducting loop continuously for over 200 days and had seen only one candidate event—recorded at 1:53 PM on Sunday, 14 February, when the lab was unoccupied. Cabrera found the event an hour and a half later, when he read his strip chart recorder.

In his *Phys. Rev. Letter*, Cabrera reports that the event is consistent with the passage of a single Dirac charge within a combined uncertainty of $\pm 5\%$. It is the largest event of any kind in the record. He found a total of 27 events exceeding a threshold of 0.2 ϕ_0, which remain after excluding known disturbances such as transfers of liquid helium and nitrogen. He defines an event as a sharp offset with well-defined stable levels for at least one hour before and after. Only six events were recorded during the 70% of the running time when the lab was unoccupied.

Sources of error. Discussing possible sources of spurious detector response, Cabrera says line-voltage fluctuations caused by two power outages and accompanying transients did not cause detectable offsets. Radio-frequency interference from the motor brushes of a heat gun failed to produce any offsets when operated close to the detector. The critical current of the loop is not reached for currents 1000 times greater. No seismic disturbance occurred on 14 February.

Could an energetic cosmic ray hitting the wire cause a piece of it to go normal? Cabrera says that such rays could deposit as much as 1 GeV/cm in traversing the wire, raising the local wire temperature by about 0.01 K. But a 5-K change would be needed to reach the critical temperature.

Cabrera has intentionally generated mechanically induced offsets by hitting the detector with a screwdriver handle, for example. Out of 25 attempts, two produced offsets up to $6\phi_0$, but the signal was not clean enough to mimic a monopole event, Cabrera told us. There was always an overshoot and settling-in period lasting several hours.

The only reasonable occurrence that would mimic a monopole passage, Cabrera feels, is a spontaneous internal stress-release mechanism. If the turns in the loop shifted with respect to each other, the inductance would change and produce a current change. A 1% shift in inductance could mimic the event.

Cabrera says his signal-to-noise level approaches 15:1 for the passage of a single Dirac charge. The 1970 experiment of Alvarez and his collaborators was not sensitive to a single Dirac charge in a single pass. So they circulated their moon-rock samples several times through the superconducting coil to increase the signal-to-noise ratio. Cabrera told us that the advantage of this type of experiment, compared to other monopole searches, is that a particle with any velocity or mass carrying a magnetic charge affects the experiment in the same way. The coupling is only through long-range electromagnetic fields. Although his present system, with its low bandwidth, is unable to discern the expected monopole velocity (about 10^{-3} c), some SQUID systems built for research have been made with sufficient bandwidth.

Improved experiment. Cabrera, Michael Taber, Susan Felch, Robert Gardner and John Bourg are building a new detector with three mutually orthogonal loops wound on a spherical Pyrex bulb. Unlike the flip coil, the three-loop arrangement is highly stable mechanically. For hypothetical monopoles passing through the loops, about 70% of the trajectories will intersect at least two of the loops, providing coincidence information. The total area is ten times that of the flip coil. An additional factor of five in effective detecting area is gained because Cabrera also will be able to detect near-miss trajectories that do not pass through because they would cause a field change within the ultralow-field shield. Cabrera expects that the group will be taking data with the new equipment beginning this month.

Cabrera stresses that the event he has reported is "not yet a discovery. It's an interesting event. We're working hard with new apparatus to see definitively if there are such particles. It's tough to be very extravagant with only one data point. But it's also difficult to make it go away. We're caught on a knife edge."

Theory. In 1974 Gerard 't Hooft (University of Utrecht) and A. M. Polyakov (Landau Institute for Theoretical Physics, Moscow) independently showed that if you have a non-Abelian gauge group that is semisimple and that spontaneously undergoes a breakdown of scale, such theories have solutions corresponding to Dirac magnetic monopoles. They further showed that the mass of the monopole would be the characteristic scale of symmetry breaking divided by the fine-structure constant. That same year Howard Georgi, Helen Quinn and Steven Weinberg (all then at Harvard) showed that for a large class of grand unified theories, the unification scale—the region where strong, weak and electromagnetic couplings become equal—is about 10^{14} GeV. All the grand unified theory predictions for monopole mass are in the ballpark of a hundred times the unification scale, that is 10^{16} GeV.

If any monopoles exist now, presumably they would have been produced in the very early Universe, about 10^{-35} sec after the Big Bang, at a time when the unified interactions break apart into strong, weak and electromagnetic.

Cabrera cites an observational upper bound on the mass density of monopoles to be given by the local "missing mass." This limit is in the range 0.03–0.05 solar masses/cubic parsec. One can assume that because the monopoles are so massive their velocities would be no greater than about 300 km/sec (as Alvarez says, just sauntering by an atom so that little or no ionization takes place). Then Cabrera estimates that the number of monopoles passing through the Earth's surface would be 4×10^{-10} cm^{-2} sec^{-1} ster^{-1}. Such a flux would yield 1.5 events per year through his loop.

In 1969 Eugene Parker (University of Chicago) pointed out that if monopoles are distributed throughout the galaxy, they would leach energy out of the galactic magnetic field and soon destroy the field. Some argue that monopoles are concentrated locally, but it's difficult to produce a mechanism for this concentration. At the GUT workshop in April, Glashow mentioned an idea developed by him, Savas Dimopoulos, Edward Purcell (Harvard) and Frank Wilczek (University of California, Santa Barbara). They speculate that the monopole flux arriving on Earth originates in the Sun. Alvarez has called attention to measurements of the Sun's magnetic field for the last five "quiet periods" that once led John Wilcox (Stanford) to write a 1972 paper called, "Why does the Sun sometimes look like a magnetic monopole?" A few months ago Alvarez calculated, assuming those measurements are correct, that the monopoles in the Sun must have masses greater than 10^{12} GeV to keep them together by gravitational attraction in spite of their mutual repulsion.

Perhaps monopoles collect at the center of the Earth, too, Alvarez speculates. You couldn't hope to put a monopole on a table and experiment with it. As Paul Frampton (University of North Carolina) points out, "Because of its enormous mass, the thing would be unimpressed by a table. Earth's gravitational pull could be greater than the electromagnetic force between a monopole and a typical atom. So the monopole would go straight through."—GBL

Hunting neutron–antineutron oscillation

When Murray Gell-Mann and Abraham Pais predicted in 1955 that the K^0 meson should exhibit an oscillating probability for metamorphosis into its antiparticle, the $\bar{K}^0$, they cited the neutron as a counterexample. The conservation of baryon number, they pointed out, would prevent the neutron–antineutron analog of neutral-kaon oscillation. But nowadays, with grand unified theories of the elementary particles very much in favor, all bets based on baryon-number conservation are off. A prodigious experimental effort (PHYSICS TODAY, January 1980, page 17) attests to the widespread expectation that proton decay will be seen with a lifetime of about 10^{31} years.

But the same SU(5) grand unified theory that predicts this finite proton lifetime does not (in its simplest form) permit neutron oscillation. The SU(5) unification of quarks and leptons in a single gauge-theoretic framework, proposed by Howard Georgi and Sheldon Glashow (both at Harvard) in 1974, replaces baryon conservation by the conservation of $B-L$, the difference between baryon and lepton number, thus forbidding $n \rightleftarrows \bar{n}$, the neutron-oscillation transition.

There are, however, rival unification theories. Robert Marshak (Virginia Polytechnic Institute) and Rabindra Mohapatra (City College of New York) have recently put forward[1] a "partial (as distinguished from grand) unification theory" based on a left–right symmetric electroweak scheme which, when joined to the usual color-SU(3) group of quantum chromodynamics, yields a color-SU(4) group structure mathematically similar to an earlier proposal of Jogesh Pati (University of Maryland) and Abdus Salam (International Centre for Theoretical Physics, Trieste, and Imperial College, London). In contrast to the SU(5) grand unification, the Marshak–Mohapatra theory predicts neutron oscillation on a time scale that may well be accessible to experiment. Proton decay, on the other hand, is not permitted in the Marshak–Mohapatra partial unification scheme.

One could complicate the spontaneous-symmetry-breaking mechanism in the SU(5) theory to get neutron oscillations at an observable level. But such departures from "minimal SU(5)" would deprive the theory of much of its simple elegance, Georgi contends. "I would be greatly surprised if we find neutron oscillation," he told us. "But if we do, it will be most instructive."

Aesthetic prejudices notwithstanding, Lay-nam Chang (Virginia Polytechnic Institute) and Ngee-pong Chang (City College of New York) have proposed[2] a modification of SU(5) that would permit *both* neutron oscillation and proton decay at observable levels by extending the theory's minimal symmetry-breaking mechanism to include Higgs bosons with masses around 10^4 or 10^5 GeV.

Because neutron oscillation plays such a central role in choosing among competing unification theories, a number of experimental attempts to look for this exotic phenomenon are now in various stages of planning, and one group has recently announced preliminary results. At the International Conference on Baryon Nonconservation, held in Bombay in January, Milla Baldo-Ceolin (University of Padua) reported the first results obtained by a CERN, Laue–Langevin, Padua, Rutherford, Sussex collaboration using the cold-neutron facilities of the Laue–Langevin Institute at Grenoble. Their first null finding—that the characteristic neutron oscillation time is greater than