search & discovery

Mixed reception for magnetic monopole announcement

The possibility that a fundamental magnetic charge might exist has intrigued physicists over the years. After the quantum theory of the magnetic monopole was developed in 1931 by P. A. M. Dirac, experimenters began looking for them. They have searched in cosmic rays, at particle accelerators, in iron ore, ocean sediment, meteorites and lunar rock.

Now a group of four cosmic-ray observers have announced finding an event that they interpret as being caused by a moving magnetic monopole. The team consists of P. Buford Price and Edward K. Shirk (University of California at Berkeley), W. Zack Osborne and Lawrence S. Pinsky (University of Houston). Their results appeared in the 25 August issue of *Phys. Rev. Letters.*

The Berkeley–Houston team says they have found a magnetic monopole of strength $g = 137\ e$. (Dirac had predicted integral multiples of 68.5 e.) It had a velocity of 0.5 c with error bars of +0.1 and −0.05 c. Their paper says its mass must exceed 200 proton masses. Since then further calculation puts a lower limit on the mass of about 600 proton masses.

The announcement made headlines in many newspapers and magazines throughout the world and is being widely discussed in the physics community. Many observers were openly skeptical of the report, particularly since only one event was found. Some are arguing that the event could be interpreted instead as a high-Z nucleus.

The detector was flown in a balloon 130 000 feet above Sioux City, Iowa for 2.6 days beginning 18 September 1973 to look for heavy cosmic rays. It consisted (from top to bottom) of a Lexan detector, a Cerenkov detector, a G-5 nuclear emulsion and finally a stack of 32 Lexan detectors.

The routine followed was for the Houston group to scan the nuclear emulsion and then instruct the Berkeley group how best to process the Lexan sheets. During the nearly two years of scanning the Houston group found the unique event. By measuring the core and halo of the track, they estimated that if the cause were a charged particle, it had a Z of about 80 and a β of about 0.5 c. From the distribution of delta rays, one can tell the particle was moving downward.

Then the Berkeley experimenters, guided by the estimates of charge and velocity, decided how long they would chemically etch the Lexan sheets. Etching essentially develops the track

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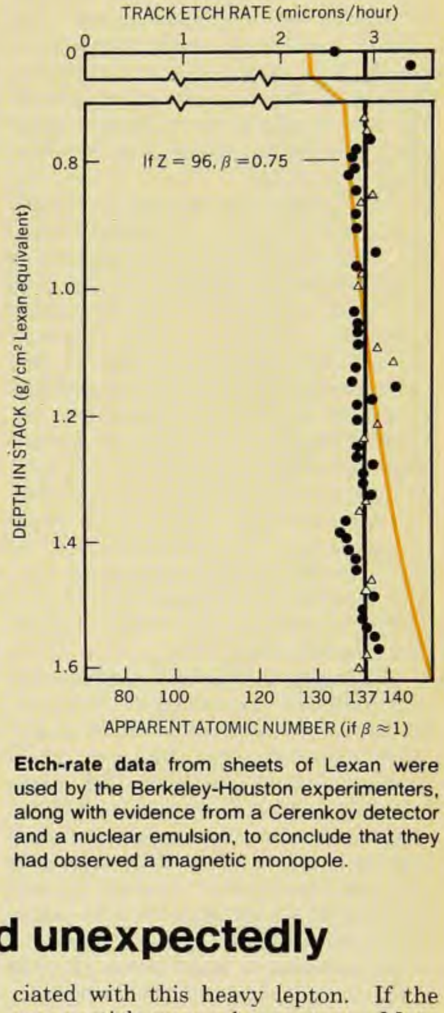

Etch-rate data from sheets of Lexan were used by the Berkeley-Houston experimenters, along with evidence from a Cerenkov detector and a nuclear emulsion, to conclude that they had observed a magnetic monopole.

SPEAR shows electron-muon pair produced unexpectedly

In a year full of surprises in high-energy physics, an experiment at the SPEAR colliding-electron-beam facility has uncovered yet another unexpected phenomenon: A significant number of events have been seen in which an electron and positron collide and produce one electron and one muon plus some missing energy. The experimenters can find no conventional explanation for this anomalous production of leptons and postulate that this reaction could proceed through the production of a pair of new particles. Each of the U particles, as they have been tentatively called, would then decay into an electron or a muon plus one or two neutrinos.

This work was done by a collaboration consisting of two groups from SLAC led by Martin Perl and Burton Richter and groups from the Lawrence Berkeley Laboratory and the University of California headed by William Chinowsky, Gerson Goldhaber and George Trilling. Perl discussed the results at a Summer Institute on Particle Physics held at Stanford University in late July.

Although the data suggest the production of a pair of particles with strong leptonic decay modes, they cannot determine the exact nature of such particles. The most popular candidates are a heavy lepton, a heavy meson and an elementary boson. If the new particle is a heavy lepton l it might have the purely leptonic decay modes

$$l^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_l$$

or

$$l^- \rightarrow e^- + \bar{\nu}_e + \nu_l$$

and similar decay modes for the l^+, where ν_l would be a new neutrino associated with this heavy lepton. If the new particle were a heavy meson M, to explain the signal it must have relatively large leptonic decay modes such as

$$M^- \rightarrow e^- + \bar{\nu}_e$$

or

$$M^- \rightarrow \mu^- + \bar{\nu}_\mu$$

and similar decay modes for the M^+. This heavy meson would be a candidate to have the property of charm, a characteristic of a fourth type of quark that has been postulated by some theorists. If the U particle were an elementary boson it should have similar decay modes but would be distinguished from the heavy meson by being a point particle, with no form factor associated with it. However the new particle is probably not massive enough to be the hypothetical intermediate vector boson that would mediate weak interactions.

Experiment. This anomalous lepton production was seen as part of a study of electron–positron collisions at high energy—the same study that, together with an experiment by an MIT–Brookhaven team, produced the first evidence for two new particles at 3.1 and 3.7 GeV a year ago. Their apparatus consists of a cylindrical magnetic detector surrounding the beam axis. Inside the magnetic coil are cylindrical, magnetostrictive spark chambers and 48, 2.6-meter-long scintillation counters. Just outside are 24, 3.1-meter-long lead-plastic scintillator shower counters. Outside the 20-cm-thick iron magnetic-flux-return plates are magnetostrictive spark chambers referred to as the muon detection system.

The signature for an electron was a large pulse height in the shower counters. The requirements for a particle to be identified as a muon were that it be seen in at least one of the two muon chambers and that its pulse height in the shower counters be small. Any gamma rays seen in the shower counters were also noted. Within these muon–electron events, additional selection was made to reduce the contamination from pair production or from events where the muon or electron could be easily misidentified. This selection cut out events in which the muon and the electron were nearly coplanar and those in which the electron or muon has momentum less than 0.65 GeV/c.

The largest sample of data was taken at a center-of-mass energy of 4.8 GeV. At this energy the team found 24 muon–electron events that had no visible gamma rays. The SLAC–LBL team has tried to account for these events as hadrons that have been misidentified as leptons or as electrons that have been mistaken for muons and vice versa. However, these estimates fall far below the number of events actually seen.

The properties of these events are now being analyzed for clues to their origin. The plots of invariant mass and missing mass indicate that at least two particles are not detected. The momentum distribution predicts that, if the events are produced by the decay of a pair of particles, their mass lies between 1.6 and 2.0 GeV/c^2. The angular distributions are sensitive to whether the U particles decay into two or three bodies. Although the distinctions are not sharp, a two-body decay would most probably characterize a heavy meson or elementary boson, whereas a three-body decay mode is likely to signal a heavy lepton. Perl told us that the three-body decay fits the observed distribution but that the two-body decay fits only if the U particles have spin one and have some spin–spin correlations.

The observed cross section corrected only for background appears at 4 GeV, rises to a maximum at 5 GeV and then falls off with energy. A $1/s$ behavior (where $s^{1/2}$ is the total energy) would be expected from the production of a pair of pointlike particles rather than from the heavy meson, which is expected to have a form factor. Thus, some theorists are leaning toward the heavy-lepton explanation for the U particle rather than the charmed-particle hypothesis. However, cautions Perl, the cross section should be corrected for losses caused by the momentum and angle cuts. These correction factors depend on the production and decay mechanism; they may be large and they certainly are energy dependent.

Other strange phenomena have recently been observed in weak interactions, but no one knows whether or not they are related. Specifically, high-energy neutrino–nucleon collisions studied at the Fermi National Accelerator Laboratory (NAL), have produced a number of events with two muons in the final state (PHYSICS TODAY, March 1975, page 24). Members of the Harvard–Penn–Wisconsin–NAL collaboration that have studied these events feel they provide strong evidence for production of a hadron with a new quantum number. Other experiments have observed direct production of leptons in proton–proton interactions at a higher rate than was expected (PHYSICS TODAY, October 1974, page 18).

Other evidence for a heavy lepton was postulated earlier this year to explain four or five events that had been seen in neutrino interactions studied in the Kolar Gold Mines, India by a collaboration from the Tata Institute of Fundamental Research, India and the Osaka City University, Japan.[1] In these events, which constitute about 25% of the neutrino interactions seen within the rock wall of the mine, the experimenters measured several charged tracks, which they interpret as coming from the decay of a new neutral particle produced in the neutrino interaction. However, an NAL experiment, headed by Frank Nezrick and Byron Roe, to study neutrino interactions in the 15-foot hydrogen bubble chamber, reported no indications of the above effect. In another NAL experiment the Harvard–Penn–Wisconsin–NAL group looked for long-lived penetrating neutral particles produced by neutrinos. One member of this group, Alfred Mann (University of Pennsylvania), cautioned that comparison is difficult because the accelerator experiments are not really identical with the cosmic-ray ones. Still, his collaboration does not see an effect comparable in magnitude to that of the Indian–Japanese experiment.

Meanwhile, several more experiments are being planned to study the muon-electron channel with better muon detectors or with better hadron–lepton separation and also to look for other decay modes or other anomalous effects from this possible new particle. —BGL

Reference

1. M. R. Krishnaswamy, M. G. K. Menon, V. S. Narasimham, N. Ito, S. Kawakami, S. Miyake, Phys. Lett. **57B**, 105 (1975).

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left by a particle, which shows up as a cone. From the etch rate (microns per hour), one can determine the ratio of Z to β. In the figure, data are shown for both 20- and 30-hour etches. The experimenters say that the best fit to their data is given by a zero slope (rate of change of etch rate with depth). For the maximum slope consistent with the data the charge is about 125 and β about 0.92. Subsequent measurements, still in progress, indicate a Z/β about 121. A calculation by Steven Ahlen (Berkeley), using previously published estimates of ionization by monopoles, indicates that this value of Z/β is consistent with that expected for a monopole with $\beta = 0.5\,c$.

The colored curve, obtained with the original uncalibrated estimate, shows the best fit to the data for a nucleus of $Z = 96$; its velocity would be about 0.75 c. A similar curve with Z about 78 and β about 0.68 c would fit the scale of Z/β as revised. If one assumes that the event is caused by a magnetic monopole of strength g, one instead obtains the black line in the figure. It is consistent with a monopole of strength twice that calculated by Dirac; his minimum value was $\hbar c/2e = (137/2)e$. The monopole could have any velocity sufficient to penetrate the 1.6-g/cm^2 stack, the experimenters say. Arguing that the emulsion data do not allow the particle to have such a high velocity, the experimenters say that therefore the particle must be a monopole.

There is an additional restraint on the velocity of the particle. The fast-film Cerenkov detector does not show an elliptical Cerenkov image; such an image would indicate that the particle was moving at a velocity greater than or equal to 0.68 c. So the experimenters believe that the particle velocity was less than 0.68 c.

A further argument in favor of the monopole hypothesis, the Berkeley-Houston group says, is that the particle ionized heavily and at a constant rate, a property predicted by Dirac. They state that a particle with only electric charge and velocity 0.5 c would have to be more massive than 10^4 proton masses to fit the data.

In their paper, the group says that in order to penetrate the Lexan stack the monopole must have had a mass greater than 200 proton masses. Subsequent calculations indicate that the mass is greater than about 600 proton masses.

Criticism. When the results were announced, many observers were disbelieving. Some argued that because earlier, more sensitive experiments had not uncovered a monopole, it was unlikely that the Berkeley–Houston team had. One such critic was Luis Alvarez (also of Berkeley), who had looked for monopoles in moon rocks and failed to find them. On 27 August, at the International Conference on Lepton and Photon Interactions at Stanford University, Alvarez stated his case against the Berkeley–Houston claim. In examining their data, Alvarez thought he saw an obvious fragmentation of a heavy nucleus about ⅓ of the way up from the bottom of the stack. By rotating their etch-rate curve 90 deg counterclockwise, he noticed that the colored curve looked like a Bragg curve. The Bragg curve has a sudden glitch, drops down and then rises again, suggesting a fragmenting heavy nucleus. In addition, he says, the particle has the right value of dE/dx. Furthermore, he argues, in a balloon flight one expects to see heavy nuclei. The cause that fits best he says is a fragmenting platinum nucleus with a magnetic rigidity of 2.2 GeV/c, a value very close to the peak of the cosmic-ray spectrum at Sioux Falls, where the flight took place.

In doing his analysis, however, if Alvarez used the Berkeley–Houston limit on the velocity from the Cerenkov detectors, namely 0.68 c, the nucleus could not have penetrated the thickness of photographic material indicated by the group—0.74 g/cm^2, and subsequently behaved as it did in the Lexan stack; it would have been going so slowly that it would have been far up on its Bragg curve. He asked them if they were sure of their value. It turned out that they had erred in reporting the thickness. The relevant thickness was actually 0.37 g/cm^2. With that thickness, Alvarez says, the event could easily be explained as a fragmenting heavy nucleus.

The following week we discussed the Alvarez claim with Price, who had just returned from the 14th International Cosmic-Ray Conference in Munich, where he and his colleagues had presented their results. Price said he was not concerned that they used the wrong value for the thickness; he feels the new value makes little difference.

Peter Fowler (University of Bristol), who, like Price, also has been involved in cosmic-ray observations of high-Z nuclei, and Price (while sharing a room at the meeting) worked out a scenario that is similar to that of Alvarez: A particle, with Z of 78 and velocity of 0.68 c enters at the top. It undergoes a nuclear interaction one-third of the way down, losing two charges. The nucleus

Photomicrographs of the cosmic-ray track in (top) a Lexan sheet (epoxied, sliced and viewed edge-on) and a G-5 nuclear emulsion (viewed nearly vertically).

then travels another third of the way down, loses three more charges and passes through the bottom of the stack.

Price argues that such a saw-toothed ionization curve has a much smaller probability of fitting all the data points than a straight line of zero slope. Furthermore, he is bothered because he says that Alvarez has neglected 20 out of their 58 Lexan data points in drawing his conclusion and has summarily rejected the data from the emulsion. (Alvarez reports that the heavy-nucleus explanation fits the full set of points—he says he originally fit the 40 circles and omitted the 16 triangles, "in an effort to make what the Price group said was impossible, somewhat easier.")

Further tests. The group is checking on the validity of Osborne's range-energy estimates in the emulsions obtained for 40 ultraheavy cosmic rays on the same flight. Of the seven checked so far, Osborne either obtained the velocity precisely or overestimated. In analyzing data from previous flights, Osborne's technique yielded similar results. Thus, so far the velocity estimates would not allow a nuclear-reaction hypothesis, Price said. If Osborne's velocity estimates turn out to be right, Price feels the case for a monopole is "awfully close to compelling. If he got one of them wrong, I would say the case is very, very shaky."

Meanwhile Fowler, experienced in the ways of nuclear emulsions, plans to examine the crucial emulsion in Bristol and make a photodensitometer measurement of the radial distribution of optical density. Using his own theoretical curves, Fowler finds that particles with β greater than 0.45 c have shapes that are indistinguishable in practice. Thus he is unable to see how he can arrive at the velocity that the Berkeley–Houston experimenters claim. So, both Fowler and Alvarez agree that the velocity measurement from the emulsion should be rejected at the present time. But Fowler's new analysis should be ready in a few months. The curves of the Berkeley–Houston group differ quantitatively from those of Fowler. They conclude that a measurement of velocity can be made for β up to about 0.6 c. Their curves are based upon the track-structure model of Robert Katz and Edward Kobetich (University of Nebraska), which has recently been supported by cosmic-ray measurements done by O. Mathiesen and his collaborators at the University of Lund, Sweden, Price told us.

Two Lexan sheets out of the 32 in the stack remain unetched—one from the top and one from the bottom. The Berkeley–Houston group had believed they might be observing a historic event, referring to the unetched material as their "posterity sheets," which would be etched with possibly better methods at a later date. Because of the furor that has developed the group decided to etch them now. By the third week in September or so, they expected to know whether or not the new etchings support the zero-slope case. If they do, Price notes, the nuclear-reaction hypothesis will be difficult to maintain.

Another measurement the group was to do in the next few weeks is to see if the track has any deviation from a straight-line path. If the event were a nuclear reaction, a slow particle might deviate a total of 10–15 microns, Price says. If it were a monopole, no deviation should be observed.

A final measurement, which Price calls the *"coup de grace"* will, if positive, definitely demonstrate the existence of the monopole, he believes. During the balloon flight, each of the 32 Lexan sheets was actually three times as long as the sheets they have etched. When recovered, the Lexan sheets were split into thirds and stored in three piles, one on top of the other; the total stack was stored in Houston at sea level for four months. So if the event occurred at sea level and not in the balloon, the track will extend into the remaining sheets. If it does, Price feels that the case for a monopole will be clinched, because a high-Z nucleus could not penetrate Earth's atmosphere to reach the ground. If the track is not found, however, nothing will have been proven. Price expected to know the answer to this question in a few days.

Both Alvarez and Fowler (who raised his objections at the Munich conference) feel that before one can seriously mention monopoles at all, the case for a heavy nucleus must be thoroughly demolished.

Previous searches for monopoles date back at least as early as 1951, when W. V. R. Malkus (then at the University of Chicago) looked for monopoles produced in cosmic rays by making use of the drift of monopoles along field lines. A similar, more sensitive experiment was done by W. C. Carithers, R. Stefanski and Robert K. Adair (Yale University) in 1966.

Other groups have searched for monopoles in large masses of material. One would expect a monopole produced in cosmic rays to drift along a flux line of Earth until it reaches the surface. If the surface is the crust, the monopole could be found in paramagnetic or ferromagnetic substances. If the surface is the ocean, the monopole would be captured by magnetic material at the bottom.

In 1963 Eiichi Goto (University of Tokyo), Henry Kolm (MIT Magnet Laboratory) and Kenneth Ford (then at MIT) used a portable pulsed magnet to detect monopoles that might have accumulated in exposed magnetite outcrops; they also searched iron meteorites. Subsequently Kolm, Francesco Villa and Allen Odian (SLAC) searched deep-sea sediment and clay. Others have looked for evidence of monopole tracks in obsidian or mica—Robert L. Fleischer, Price and R. T. Woods (then all at General Electric). Later Fleischer and Price joined with other colleagues to look for monopoles in the manganese crust of the North Atlantic. A search of moon rocks from Mare Tranquillitatus was done by Alvarez, P. H. Eberhard, R. R. Ross and R. D. Watt (Berkeley) who looked for the emf generated in a superconducting link by the circulation of material containing the monopole. All the searches were negative, although many had sensitivities 10^4–10^6 times greater than the Berkeley–Houston experiment. However one can argue that each of the searches had to make some assumptions about the properties of a monopole. Furthermore Kolm notes that searches for monopoles that have accumulated would not find any that had energy greater than 10^{18} eV.

Experiments at accelerators generally assume that monopole pairs are produced in the very high-energy interactions of particles produced by the accelerators. Each time a new accelerator with higher energy is turned on, experimenters eagerly look for monopoles—at the AGS, CERN, Serpukhov and NAL. To no avail. Accelerators have an energy limitation that cosmic rays do not. And if the Berkeley–Houston group is correct, the monopole is massive indeed.

Theory. Maxwell's equations, more than a century old, assumed that although there are sources of the electric field, magnetic sources do not exist. This lack of symmetry between electricity and magnetism has troubled some people over the years.

Dirac's famous paper in 1931 showed that if a magnetic charge exists, in order to quantize angular momentum one must have a minimum electric charge and a mimimum magnetic charge. The existence of magnetic charge required electric charge to be quantized. He derived the relation $eg/\hbar c = n/2$ where n is an integer. From the experimental observation that e^2 is $\hbar c/137$, one can calculate that monopoles would have a magnetic charge of 68.5 e or multiples thereof.

If the monopole exists, quantum electrodynamics would of course have to be modified. However, this modification need only be done at very high energies because the monopole is expected to be much more massive than the electron. In the regime where careful comparison between theory and experiment has been made, the monopole's existence should make no difference.

About ten years ago Alfred Goldhaber (State University of New York at Stony Brook) developed the least restrictive set of conditions from which Dirac's quantization could be derived—that the correspondence principle and rotational invariance hold.

Many years ago Nicola Cabibbo and E. Ferrari attempted to develop a field theory of monopoles. Subsequently Julian Schwinger (then at Harvard University) developed a consistent field theory of monopoles. Later he proposed that monopoles might be the fundamental building blocks of matter in the form of so-called "dyons." A hadron would be composed of several monopoles with both magnetic charge and fractional electric charge. The theory involved integral rather than half-integral quantum numbers. This would of course be consistent with the Berkeley–Houston experiment and suggests that if one could see the end of the track, a fractional electric charge could be observed, Schwinger pointed out to us.

Malvin Ruderman (Columbia University) and Daniel Zwanziger (New York University) proposed that if monopoles are pair-produced by energetic photons, they might drag each other back as they are trying to escape and radiate so much that the monopoles could not escape.

Last year Gerard 't Hooft (CERN) showed (Nucl. Phys. **B79**, 276, 1974) that monopoles could arise in a natural way from a non-Abelian gauge theory. Monopoles would be themselves composed of various vector and scalar fields. The theory predicts that the monopole would be extremely massive, with a mass at least several thousand GeV. But both the mass and the magnetic charge are model-dependent. Their determination, 't Hooft told us, would be extremely important in connection with weak-interaction theory and the concept of charm. —GBL

Encouraging progress with Livermore mirror machine

The 2XIIB mirror device at Lawrence Livermore Laboratory has produced plasma temperatures of 10–14 keV, more than four times higher than temperatures reached in an earlier version of the device. Simultaneous with this achievement of reactor-level temperatures in a dense plasma was a tenfold increase in plasma confinement time, to about five milliseconds. Although these new results are not being taken to mean that magnetic-mirror confinement has suddenly become the favorite for producing a practical fusion reactor, they do show that the plasma produced in such a device continues to follow classical energy scaling at high temperatures. Confinement time, that is, does increase with energy, indicating that most of the plasma losses are caused by collision between plasma particles rather than by the more serious effects of internal instabilities. Moreover, notes Frederic Coensgen, leader of the California experimental group, the temperature reached was just that predicted two-and-one half years ago, and success was achieved within the predicted time and for the predicted cost. Other members of the experimental team are Thomas Simonen, William Cummins, Grant Logan, Arthur Molvik, William Nexsen Jr, Barry Stallard and William Turner.

The 2XIIB device is the immediate successor to 2XII, which was able to confine 1–3 keV plasmas (the equivalent of (10–30) $\times$ 10^6 K). In the latest experiments, performed this past July, plasma density in 2XIIB was about 4 $\times$ 10^{13} cm^{-3}, and β (the ratio of plasma pressure to magnetic-field pressure) was about 0.4. The Livermore group built the 2XIIB magnet system to exploit their good results with high-density plasmas in 2XII.[1] The plasma in 2XII had been found to be "beta-limited;" that is, the plasma energy was limited by the theoretically attainable β values (dependent on mirror ratio) rather than by the output of the plasma injector.

Both 2XII and 2XIIB are part of a series of magnetic-mirror plasma confinement systems built at the Livermore Laboratory over the past ten years or so.

Confinement times are still too short to approach the Lawson criterion for practical use as a fusion reactor. However, there is revived interest in mirror machines as neutron producers to test materials under reactor-like conditions. Still more speculative is talk centered around the possible use of mirror machines as neutron breeders in a fission economy. —MSR

References

1. F. H. Coensgen, W. F. Cummins, A. W. Molvik, W. E. Nexsen Jr, T. C. Simonen, B. W. Stallard in "Plasma Physics and Controlled Nuclear Fusion Research," page 323, IAEA, Vienna (1975). □