

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 minimum magnetic charge. The existence of magnetic charge required electric charge to be quantized. He de-

rived 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 $(10\text{--}30) \times 10^6$ K). In the latest experiments, performed this past July, plasma density in 2XIIB was about 4×10^{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). □