Magnetic monopoles — a scientific mystery

Single north and south magnetic poles are predicted to exist but haven't yet been found. Could this be because of their unexpected properties: massive, slow-moving and rare?

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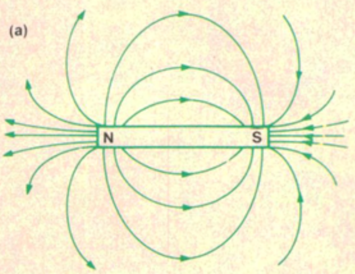
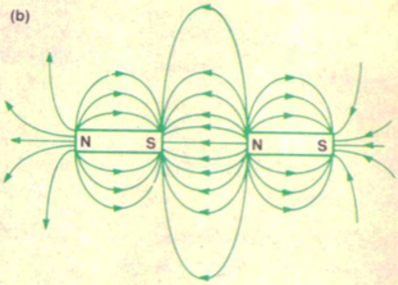
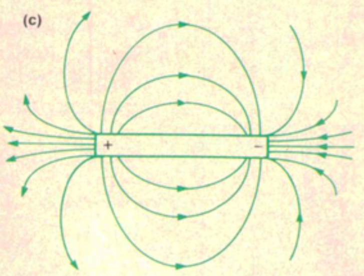


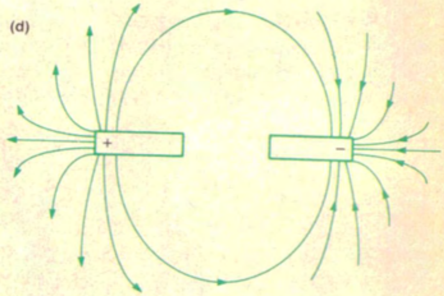
Dipole fields. Set up by a bar magnet.



Magnet cut in half. Two smaller dipoles are created.



An electric structure analogous to the above. Opposite electric charges are deposited at the ends.



Electric analogue cut in half. The field remains dipolar because the electric charges that generate the field remain in place.

FOR MORE THAN 50 years physicists have been looking for magnetic monopoles, elementary particles which carry a single magnetic pole.

They are predicted to exist but so far no one has produced enough conclusive evidence of an observation. A new theory explains that this may be because the monopoles are too massive, slow-moving and rare.

Blas Cabrera, a researcher at Stanford University, thought that he might have found one early in 1982. But he has yet to verify an effect he has observed only once in six months. Theory suggests that there are not enough monopoles around today to explain why one should have been found in such a relatively short space of time.

As early as 1269 Petrus Peregrinus, a French investigator of the magnetic properties of materials, noted that magnetic objects have paired regions of opposite polarity; that is, all magnets are dipoles. It seems that magnetic 'charges' or poles always occur in pairs, unlike electric charges which can occur as isolated positive or negative charges.

If you cut a bar magnet in half you end up with two smaller magnets, each with a north and south pole, rather than two pieces with opposite poles. This is because every atom in a magnetic material behaves as a tiny magnet, each atomic field being generated by electrons orbiting the atomic nucleus (just as an electromagnet is created by an electric current looping round a coil).

Speculation about the possible existence of magnetic monopoles has been going on for a long time. However, in the theory of electromagnetic phenomena, formulated by James Clerk Maxwell in 1864, the possibility of isolated magnetic charges was ignored since none had ever been observed. Over the past century Maxwell's theory has been put to many experimental tests and has never been found wanting. That fact alone severely limits the contexts in which magnetic monopoles might be found.

Interest in the idea intensified in 1931 when the British physicist Paul A.M. Dirac showed that an important observed property of electrically charged particles could be explained by assuming the existence of single magnetic poles.

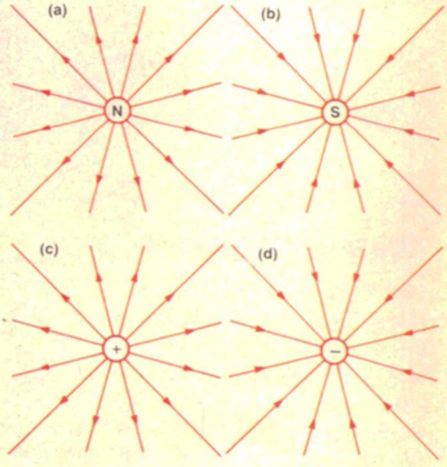
Dirac was trying to explain the quantisation of electric charge; the fact that electric charge appears only in multiples of the charge of the electron and the proton. Dirac showed that if an isolated magnetic pole exists anywhere in the universe, electric charge must be quantised everywhere. Until recently, Dirac's magnetic monopole hypothesis was the only explanation of the observed quantisation of the electric charge.

Dirac's monopole has a minimum unit of magnetic charge about 70 times as large as the corresponding unit of electric charge. He also predicted that the magnetic monopole would be matched by a magnetic antimonopole. However, his theory made no prediction about the mass or size of the magnetic monopoles, or about their abundance in the universe.

Dirac's predictions stimulated a rush of theoretical papers on the expected properties of the hypothetical monopoles, and several experiments were undertaken to detect them. Physicists searched for them in particle accelerators, cosmic rays and even moon rocks, but with no luck. However, they may not have been looking for the right effects.

Some interesting properties of magnetic monopoles arise when Maxwell's equations of electromagnetism are augmented to include magnetic charges and magnetic currents.

For example, as the velocity of a moving electric charge approaches the speed of light, its properties should increasingly resemble those of a magnetic charge. Similarly, a mov-



Symmetry exists. A north monopole (a) would have as its antiparticle a south monopole (b), just as the proton (c) has as its antiparticle the antiproton (d).

ing magnetic monopole would begin to take on the properties of an electric charge at a speed approaching the speed of light.

These transformations, which follow from Einstein's special theory of relativity, have been confirmed experimentally for moving electric charges but not of course for moving magnetic charges.

A moving electric charge can lose energy by ionising matter; that is, it detaches electrons from their atoms. Because of the much stronger charge of the magnetic monopole, it would ionise atoms some 10 000 times more effectively. Thus a magnetic monopole passing through a photographic emulsion of the type employed by physicists to detect electrically charged particles would leave a track thousands of times darker than the track left by an electric charge moving at the same speed.

Because the monopole would lose energy to the ionisation process so quickly, it would slow down much sooner on entering a substance than does an electrically charged particle with the same kinetic energy.

A magnetic monopole traversing a superconducting coil one metre long would gain more energy than a proton acquires in the largest particle accelerator yet built.

The physics of magnetic monopoles has another curious feature which can only be made apparent by imagining that the flow of time can be reversed. This is a thought experiment suggested by Robert K. Adair of Yale University.

A proton is in a magnetic field which arises not from an electric current but from the presence of a magnetic monopole. Reversing time does not alter the polarity of the monopole and therefore leaves the direction of the magnetic field unchanged. The proton's path in the field of a monopole depends on the direction of time, an effect that violates the principle of time-reversal invariance.

The predicted effects of a magnetic monopole when time is reversed were for many years viewed as a serious argument against its existence.

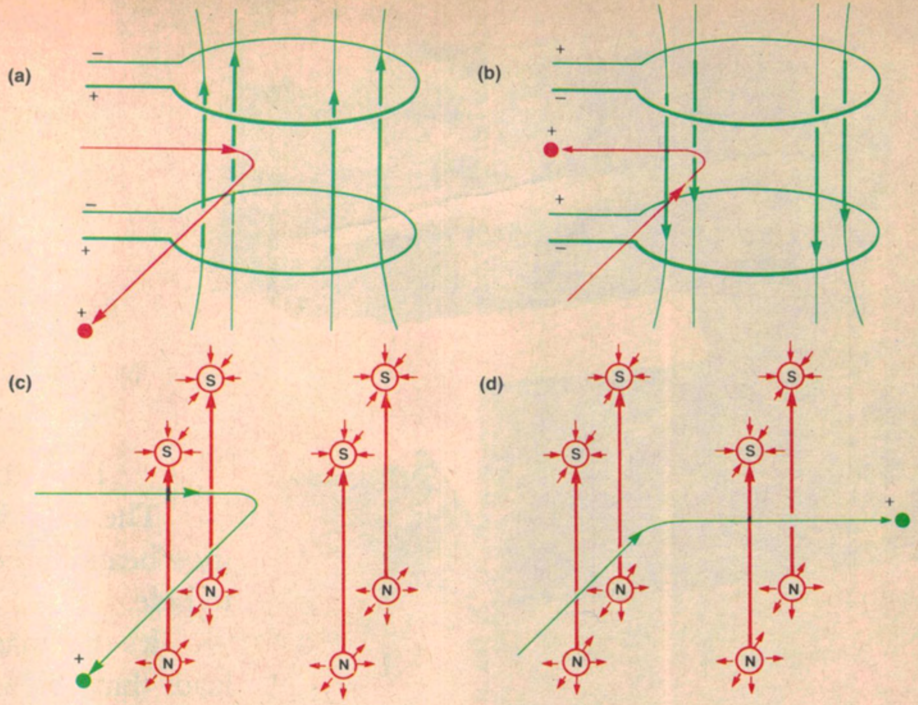
In 1964, however, an experiment was done at Princeton University which discovered an effect much like a violation of time-reversal invariance in the decay of the particles called neutral kaons. As this finding has become better understood some of the opposition to the idea of magnetic monopoles has abated.

Searching north and south

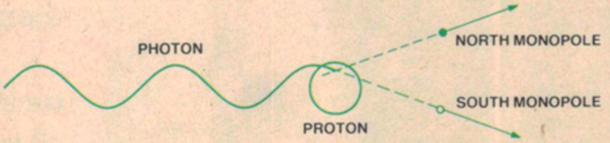
Knowing something of the properties of magnetic monopoles means that the experimental search for their existence can take a more positive direction. Soon after every new particle accelerator is commissioned magnetic monopoles are looked for in the debris of the initial high-energy particle collisions.

Monopoles have also been sought among the by-products of collisions between cosmic rays and atoms in the atmosphere. Other experiments have tried to detect them among the atoms of terrestrial and extraterrestrial substances. Samples of iron ore collected from the rocky outcroppings of old mountains are another potential source of material.

One detection method, first discussed in the 1960s, was implemented in the 1970s by Luis W. Alvarez and his colleagues at the Lawrence Berkeley Laboratory of the University of California. In their device a sample of material suspected of harbouring magnetic monopoles is passed repeatedly through a superconducting coil. On each pass of a magnetic monopole the electric current in the coil would presumably increase by a small amount. Because the coil is superconducting the incremental induced current would persist indefinitely. It's then a matter of measuring the extremely small signal induced by the multiple passes of a single monopole.



Time reversal. In (a) a proton is moving through a perpendicular magnetic field generated by electric currents. If the direction of time is reversed (b) everything is reversed, the particle retracing its path in the opposite direction. In (c) the magnetic field is produced by an idealised array of north and south monopoles. Reversing time would leave the magnetic field unchanged (d). Although the proton would reverse direction, it would not retrace its path; a violation of the principle of time-reversal invariance.



Particle-antiparticle pair. A north monopole and a south monopole could be created when a high-energy photon interacts with an electrically charged particle such as a proton. The mutual attraction between the monopoles, however, would cause them to collide, converting their mass back into photons.

By means of this technique Alvarez and his colleagues were able to show that the density of magnetic monopoles in rock samples recovered from the surface of the moon is less than one for every 10^{28} protons. Even at this limiting abundance, however, there could still be an average of one monopole in every 20 kilograms or so of matter.

A less direct way of hunting for magnetic monopoles is to look for signs of the creation and destruction of a monopole-antimonopole pair. In theory a pair of this type could be created when a high-energy photon passes near a proton, just as an electron-positron pair is known to be produced. The oppositely charged monopoles would exist for only a moment, however, as they would soon come together and annihilate each other, converting their mass into additional photons.

In 1975 investigators at the University of California at Berkely and the University of Houston announced that they had discovered a magnetic monopole. Their evidence was an anomalously thick, dark track, presumably of cosmic ray origin, recorded on a stack of photographic emulsions and plastic sheets.

The detector had been exposed to cosmic rays while it was suspended from a balloon flown at high altitude for two and a half days. The area-time factor of the detector was roughly a million times smaller than that attained in previous searches in which no monopole had been seen.

Other problems with the monopole interpretation of the event subsequently led the experimenters to suggest instead that the track might have been caused by the passage of a superheavy atomic nucleus or a massive antiparticle.

One benefit of this episode is that it inspired a careful evaluation of how a magnetic monopole would lose energy through ionisation. Even so, the question still remains unsettled.

Superheavy particles

The prospects for magnetic monopole hunters suddenly brightened in the mid-1970s as a result of the independent work of Gerard 't Hooft in Utrecht in the Netherlands and Alexander M. Polyakov in Moscow. They both found that a certain class of theories of elementary particle interactions not only allows magnetic monopoles but also demands them.

These grand unification theories attempt to unify the four basic forces in nature — gravity, electromagnetism, and the strong and weak nuclear forces — into one graspable mathematical structure. According to this theory monopoles are 'superheavy', 10^{16} times the mass of the proton or ten nanograms, which is about as heavy as an amoeba.

Such a particle is so much heavier than any other elementary particle yet discovered that it could well explain why previous searches for monopoles have been unsuccessful.

Such heavy particles cannot be created at even the highest energies particle accelerators can reach, but they could have been produced copiously in the aftermath of the big bang with which, cosmologists generally believe, the universe began.

Up to times as little as 10^{-35} seconds after the big bang, the universe would have been hot enough (almost 10^{30} degrees Kelvin) to generate such particles. Both north and south magnetic monopoles would have been formed, and a small fraction of them would have recombined, annihilating each other. Most of the superheavy monopoles would have escaped an early death, however, and there is no reason to think they would not have survived to the present.

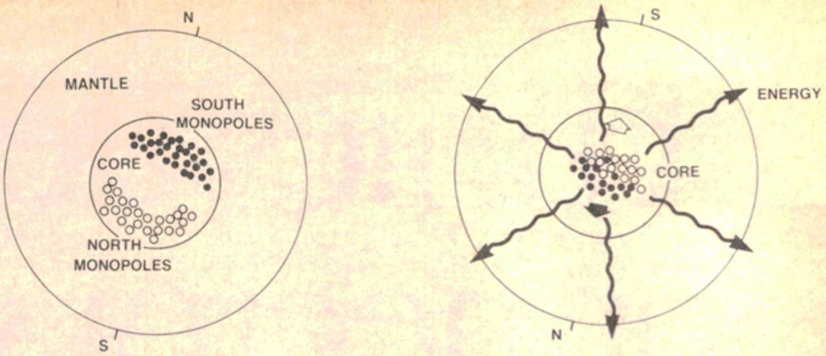
Researchers at the European Organisation for Nuclear Research (CERN) in Geneva decided that the interaction of monopoles with the galactic magnetic field sets a limit on the ratio of magnetic monopoles to protons of about one to 10^{20}. Given that abundance, some 200 monopoles per year would be expected to pass through an area of one square kilometre. A more conservative estimate, based on a more uniform distribution of monopoles in the universe, would result in a flux of a few monopoles per year per square kilometre.

So for the first time the theory of magnetic monopoles provides estimates of the expected mass and flux of magnetic monopoles. At least these estimates, even if they are rough, provide a fresh field for experimenters to explore.

One place to look for superheavy monopoles is in large-scale natural effects. So what was the fate of monopoles in the material which collected together to form the solar system? One could speculate that as the earth condensed the monopoles would have sunk toward the centre under the influence of the planet's gravitational and magnetic fields. North monopoles would have collected near the south geomagnetic pole and vice versa.

From the geologic record it is known that the earth's magnetic field has reversed many times. Such a field reversal would cause the two separated populations of monopoles to migrate toward and then through each other. During their journey some monopoles and antimonopoles would be annihilated, liberating the enormous energy embodied in their mass.

From the measured heat flow at the surface of the earth one can set a rough limit on the number of monopoles trapped in the core; the number calculated in this way is consistent with other experimental limits on the abundance of superheavy monopoles.



Monopoles trapped in the earth. They tend to collect at two places in the earth's core near their opposite geomagnetic poles. Following a reversal of the earth's magnetic field (an event observed repeatedly in the geological record) the two segregated populations of monopoles would migrate through each other. Some would meet and annihilate each other, converting their mass into energy, which could be observed in the outflow of heat at the earth's surface.

But how do you find them?

The design of a detector to search for these heavy, rare particles is, however, not obvious. But there are a lot of ideas around, many of them quite bizarre.

The massive monopoles are expected to travel slowly, at speeds far below the velocity of light. The collision of a superheavy monopole and a stationary atomic nucleus would be like a steamroller hitting an ant. A cosmic ray monopole could lose a huge amount of energy to such encounters as it ploughed its way ponderously through the earth, and it might still emerge virtually unscathed from the other side.

So under these circumstances it is difficult to predict what degree of ionisation would be observed in a detector. Whatever happens, it's obvious that an extremely large detector is required if the experimenter is to observe a monopole event in his lifetime.

One detector which records the light generated by ionisation and covers many square kilometres has been developed at the University of Utah. The device, called the fly's-eye detector, is an array of photomultiplier tubes directed at the night sky; it registers the light given off by secondary particles produced by rare ultra-high-energy cosmic ray interactions in the upper atmosphere. As the secondary particles shower down toward the earth they collide with nitrogen atoms in the atmosphere, causing them to scintillate. However, the passage of a magnetic monopole, even with the most optimistic estimate of its ionisation rate, would give rise to less than a ten-thousandth of the light needed to set-off the detector.

The ability of such a detector to respond to particle-induced scintillations is limited by background illumination from stars, overflying aircraft and other sources such as beacon lights on distant radio towers. Perhaps a fly's-eye detector could be installed in a large cave or salt mine such as those now being used to look for proton decay.

Another large-volume detector is the Deep Underwater Muon and Neutrino Detector which will be sensitive to events within a cube of ocean about a kilometre on a side. This detector will respond to the Cerenkov radiation emitted when a particle moves through the seawater faster than the speed of light in water. Unfortunately superheavy magnetic monopoles would probably move too slowly to give off Cerenkov radiation.

Some of the largest existing scintillation detectors are too small by a factor of about 100 to have a good chance of observing magnetic monopoles if the flux is limited by the galactic magnetic field.

The contrary view holds that all searches with ionisation detectors are doomed to failure because the slow-moving, superheavy monopoles will cause no ionisation.

Another possible means of detection is based on the fact that the passage of any charged particle through metal is accompanied by eddy currents. These eddy currents are independent of the particle's speed and whether its charge is electrical or magnetic. A spherical metal detector has been designed but the signal can only be detected above the background noise if the detector is cooled to a few millidegrees above absolute zero; a difficult technical requirement with a large detector.

One comparatively simple strategy for detecting superheavy monopoles, which does not rely on assumptions about mass, calls for a superconducting coil similar to the one used by Alvarez and his colleagues.

Blas Cabrera claimed to have detected a monopole with a superconducting niobium coil five centimetres in diameter, kept in liquid helium at a temperature only 4.2 degrees above absolute zero.

Another plan is to mount a superconducting detector under an iron-ore processing plant which heats more than a million tons of ore per year to a temperature of 1700°C. At this temperature any magnetic monopoles trapped in the iron would be released, allowing them to fall through the detector.

The discovery of a magnetic monopole would rank as one of the finds of the century, comparable to the discovery of the positron, Dirac's other great prediction. If the monopole was found to be very massive, the case for some form of grand unified theory of elementary particle interactions would be strengthened.

Even if no magnetic monopoles are found, physicists, being what they are, will not view the negative evidence as conclusive.

References

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