Primaeval magnetic monopoles

from P. C. W. Davies

One of those curious apparent imperfections of nature is the lopsidedness of electricity and magnetism. The world abounds with electric particles (all atoms are made of them) but nobody has ever seen a pure magnetic particle. Magnetic fields can, it seems, only be produced by moving electricity, that is, electric currents. Consequently, when magnetism occurs, magnetic charge always appears in tandem (north and south), never singly. Tandem charges are called dipoles and single charges, if they exist, are known as monopoles. Matter is built out of subatomic electric monopoles, but magnetic monopoles elude us. This is all the more surprising because of the celebrated mathematical symmetry built into our theory of electromagnetism.

The great nineteenth century physicist James Clerk Maxwell unified electric and magnetic fields, and discovered the principles which govern their interplay, but his beautiful theory is marred by the asymmetry of the monopoles. In the 1930s Paul Dirac gave an argument, subsequently developed by Julian Schwinger, that if magnetic monopoles exist they will have magnetic charge only in fixed multiples of a fundamental unit, simply related to the fundamental unit of electric charge, such as we find on the electron. A few years ago the Soviet and Dutch physicists A. M. Polyakov and G. 't Hooft argued that magnetic monopoles could exist on subatomic particles with masses in excess of five thousand proton masses.

There has always been room in theory for magnetic monopoles, but elaborate searches among ordinary matter have persistently failed to detect any. Despite a recent flurry of excitement that one had been found in cosmic ray debris, the monopole remains perhaps the most significant non-discovery of the century.

Sometimes negative evidence can be useful in revealing information about other physical systems. The non-detection of quarks, for example, has been used as a motivation for theories of subatomic particle structure. In a recent paper (*Phys. Lett.* **79**3, 239; 1978) the Soviet mathematical physicist and astronomer Ya. B. Zeldovich, and a colleague at the Institute of Applied Mathematics in Moscow, M. Yu. Khlopov, have argued that the experimental absence of magnetic monopoles raises serious doubts either about their existence or the popular understanding of the origin of the Universe. The central idea is the theory that the Universe began with an intensely hot big bang. Indeed, so energetic was this event that we can be sure that any subatomic particles that can exist would have existed at sufficiently early moments (that is, sufficiently high temperatures). And this includes magnetic monopoles, despite their predicted enormous masses.

Zeldovich and Khlopov calculate that inside the first 2×10^{-11}s the monopoles would have been in thermodynamic equilibrium at a certain concentration among all the other matter, but that as the explosive expansion rapidly cooled the primaeval cosmological material, the temperature fell too low to sustain the monopoles, and they started to annihilate each other. The annihilation is a consequence of fundamental physics that a magnetic north pole is the antimatter image of a south pole, and close encounters between them result in mutual destruction.

In the subsequent phases of the expanding fireball, most of the monopoles would have disappeared as a result of this mechanism. But not all. Merely on statistical grounds some monopoles would have avoided their opposite numbers and escaped this demise. This is because both the density of matter, hence monopoles, was falling rapidly, and the temperature, hence speed, of subatomic particles also plummeted. The authors calculate the residue of relic monopoles coughed out of the big bang which should still exist. The annihilation ceases after about 10 ms, leaving a total concentration today of around 4×10^{-19} cm^{-3}, or less than one monopole per million million atoms. Small though this is, it is enormously greater than the experimental upper limits already set ($10^{-30}-10^{-38}$ cm^{-3}) from examination of lunar and terrestrial matter, and cosmic ray studies.

There seem to be two alternative explanations of this inconsistency. One is that nature truly is lopsided, and that magnetic monopoles simply do not exist in isolation. (There is still the possibility that for some obscure reason monopoles exist in permanently confined multiplets, like quarks.) The second is that the standard hot big bang model of the Universe is badly wrong, at least in some of its details. We thus have an additional motivation for seeking out monopoles, for their discovery as free particles would, unless the previous abundance estimates are a fluke, tell us much about the first micromicrosecond of the Universe.

One of the ironies about papers of this type concerns the central role played by aesthetics. Belief in magnetic monopoles stems primarily from a deep-rooted desire that nature should be elegant and symmetrical. Similarly in cosmology, sweeping assumptions are made about the structure of the primaeval Universe which, once again, stem from the yearning for simplicity. Now we see that cosmic simplicity (primaeval thermodynamic equilibrium) and subatomic symmetry are in conflict. The resolution cannot be found by aesthetics alone. Only experiment can decide which assumption is wrong.

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the muon diffuses faster and faster as the temperature rises, and the rate at which it samples different internal magnetic fields affects the depolarisation rate and can be measured. This regime ends at a temperature fixed by the trap density, and in region III, the muon monitors properties of the trapping site. Finally, in region IV, release from traps and motional-narrowing occur. Obviously, behaviour gets more complicated when several distinct traps are involved, but the principles are the same. Many workers have obtained results fitting this qualitative description of the temperature dependence.

For this picture to be useful, it is important that the muon can indeed diffuse to the traps of interest. The muon lifetime sets a limit here. In most metals studied (V, Nb, Ta, Cu, Fe) at accessible temperatures the muon hopping time between diffusive jumps is in the range 10^{-5}–10^{-7} s corresponding to a mere 0.2 to 20 jumps in a lifetime. Diffusion from a random stopping site to any trap present in low concentration is negligible. And indeed the irradiation of Cu and the doping of Nb by Ta have little observable effect on muon properties. Two metals are different, and appear to show very fast diffusion: Cr, with a hopping time around 10^{-11} s and Al, where motional narrowing appears to be complete even at the lowest temperatures, with times such as 10^{-10} s at 10 K and 10^{-12} s at 50 K indicated.

Several groups have studied trapping

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