Do Monopoles Catalyze Proton Decay?

The two most famous predictions of the grand unified theories seem to be intertwined, but the relationship will be tough to verify

For the most part the Grand Unified Theories (GUT's) of particle physics deal with the behavior of matter at extraordinarily high energies and extraordinarily short distances—the kind of conditions that prevailed at the Big Bang, for example, when temperatures exceeded 10^{27} K and particles jostled each other at ranges of 10^{-30} centimeter.

But the theories also predict low-energy phenomena that might just barely be testable in the laboratory. It now appears that two of these phenomena, proton decay and the existence of magnetic monopoles, are much more closely intertwined than anyone had realized. Specifically, magnetic monopoles may be powerful catalysts for proton decay.

If true (and not everyone believes it), the proton decay detectors now starting up around the world will turn out to be excellent monopole detectors. Wandering cosmic monopoles will mark their passage through the apparatus with chains of decaying protons, dozens of them, each detonating in a precisely timed sequence—"a monopole speedometer," as one physicist puts it.

On the other hand, there may be precious few monopoles to find. Cosmologists have used the new calculations to put very strong limits on the cosmic abundance of monopoles. In fact, it is apparent that rapid monopole catalysis is grossly inconsistent with the monopole event announced last spring by Stanford physicist Blas Cabrera (*Science*, 4 June, p. 1086). One or the other is wrong.

Monopole catalysis of proton decay has been independently pointed out during the last year by V. A. Rubakov of the Institute of Nuclear Research, Academy of Sciences of the U.S.S.R., Curtis G. Callan of Princeton University, and Frank Wilczek of the Institute for Theoretical Physics at the University of California, Santa Barbara.

As Callan explains it, the grand unified theories predict that magnetic monopole has an onionskin structure centered on a tiny core about 10^{-30} centimeter across. Within that core is a state of symmetry that has not existed in the outside universe since the instant of the Big Bang. Quarks are identical to electrons and electrons are identical to neutrinos. Massless photons mix with massive vector bosons and merge with the elusive colored gluons. "Then as you go out from the core," says Callan, "you get less and less symmetry at each layer." The gauge hierarchy, as it is known, gets broken in stages, and the various particles begin to develop their own personalities. Finally, he says, on the outside of the monopole the only remnant of the internal symmetry transformations is a long-range magnetic field.

In most situations, of course, the magnetic field is all that matters. The core is essentially a dimensionless point, even on the subnuclear scale, and in most cases it can be ignored. But as it turns out, says Callan, a charged, spin one-half particle such as a quark is a special case: such a particle will interact with the core with a probability that is independent of the size of the core.

"It's a free ride into very short distances," he notes. "You automatically get a window into physics at the grand unified scale."

The fate of the interacting quark depends on the details of the particular grand unified theory that describes the monopole. However, what Callan, Rubakov, and Wilczek realized is that any theory allowing for proton decay—or more technically, any theory allowing for baryon number violation—will also allow a quark that interacts with the core to transform into a positron or an antiquark. This means in turn that a monopole wandering into a proton or neutron can swallow one of the quarks there, reemit it as an antiquark, and trigger the detonation of the larger particle into a spray of leptons and mesons. The proton or neutron decays, and the monopole, like any proper catalyst, emerges unscathed to repeat the process elsewhere.

There are a number of caveats to this conclusion, Callan warns. In some versions of GUT's, for example, there are monopoles but no proton decay, which means that there is no catalysis, either. "If you found monopoles but they didn't catalyze the protons," says Callan, "that would give you some information on which theory is correct."

A more difficult and controversial question is the rate of catalysis. Callan, like Rubakov, believes that the process is extremely vigorous. "We have only solved the problem in a certain approximation," he admits, "but we believe the rate is determined by strong interaction physics. That's about 30 orders of magnitude difference from the GUT cross section!"

Wilczek, however, uses a very different mathematical approach to the problem and argues that the relevant scale is set by the weak interactions. He opts for a cross section at least 10^{-4} smaller than that of Callan and Rubakov. He also wonders if their process is really a true catalysis. Perhaps the monopole undergoes some internal rearrangement in the course of the interaction. "It is not clear to me that this question has been sufficiently addressed," he says.

Whatever the theoretical quandaries, however, monopole catalysis offers experimental physicists a rarity in GUT physics: a phenomenon that might actually be observed. And for that reason it has generated considerable enthusiasm. If Callan and Rubakov are correct about the rates, for example, a monopole would show up vividly in the new proton decay experiments. "Detection of either a monopole or a proton decay would be a revolution," says Lawrence R. Sulak of the University of Michigan. "This is revolution squared."

Sulak spends much of his time underground these days as a principal investigator at the Irvine/Michigan/Brookhaven proton decay detector, a 10,000-tonne tank of water sitting in a vault of a salt mine near Cleveland, Ohio. According to standard GUT estimates, he says, the phototubes surrounding the tank should pick up perhaps a few hundred proton or neutron decay events per year. But, if a Callan-Rubakov monopole traversed the 20-meter tank, it would trigger a string of some 60 decays all at once. "You'd have to be blind to miss it," he says.

Better still, he says, cosmic monopoles are probably very slow by particle physicists' standards, with speeds no greater than a few hundred kilometers per second. Each decay in the string would thus come many microseconds after the one before it. The electronics could easily measure such a delay, says Sulak, which means that the speed and direction of the monopole could be measured very precisely.

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On the other hand, neither the Irvine/Michigan/Brookhaven experiment nor any of the other proton decay experiments have had the slightest hint of such a signal. And suggestions have recently come from other quarters that they never will, even if Wilczek, Callan, and Rubakov are right about catalysis. The problem is that the rate of catalyzed proton decay in any given detector is given by the product of two unknown quantities: the catalysis cross section and the cosmic flux of monopoles. Astronomical observations have now been used to place extremely stringent limits on this product, limits so low that the search for monopole catalysis on the earth may well prove hopeless.

Two independent groups have reached essentially the same conclusions: Wilczek, together with Savas Dimopoulos and John Preskill at Harvard, and Edward W. Kolb and Stirling A. Colgate of Los Alamos, together with Jeffrey A. Harvey of Princeton University. Both groups start from the observation that the effects of monopole catalysis will be greatest where matter is at its densest: in neutron stars.

"If monopoles exist with some galactic flux," explains Kolb, "they will be accreted onto neutron stars and trapped. [GUT monopoles are extraordinarily massive—10^{16} times the mass of the proton—and would sail right through an ordinary star.] The density of neutrons around the monopole would be very large, and so the rate of neutron decay would be very high. We estimate that one-half to two-thirds of the rest mass of each decaying neutron would go into heat and x-rays, and the rest would go into neutrinos that escape. So the neutron star has an x-ray luminosity per monopole that is proportional to the cross section [for monopole catalysis]."

Next, says Kolb, the number of monopoles in a given neutron star is proportional to the unknown flux of monopoles times the age of the star. Since neutron stars are the cores of supernovas, and since supernovas have presumably been going off since the galaxy formed, most neutron stars will be roughly as old as the galaxy: 10 billion years. Moreover, there are probably about one billion of them scattered through the galaxy at random.

Multiplying everything together, one finds that the total x-ray luminosity of a given neutron star depends on only one unknown quantity: the product of the catalysis cross section and the cosmic monopole flux.

"Recently we have had x-ray satellites that could place upper limits on the x-ray luminosity of neutron stars," says Kolb. Not only has there never been any clear-cut x-ray signal from an isolated neutron star, he says, but there is no x-ray background that can be attributed to randomly scattered billions of neutron stars.

The limit this implies for the cosmic monopole flux is by far the most severe ever found. Suppose, for example, that Callan and Rubakov are correct in their estimate: "If you put in a typical strong cross section [for catalysis], then the flux has to be less than 10^{-22} monopole per square centimeter per second per steradian," says Kolb.

To get a feel for that number, consider that Blas Cabrera's monopole detector at Stanford was 5 centimeters across. (He is now building one with 50 times the collecting area.) If Callan and Rubakov are correct, the neutron star limit says that Cabrera should have seen about one monopole in a trillion years. In fact, he recorded a strong monopole candidate event after 185 days.

"To put it another way," says Kolb, "the Callan-Rubakov cross section times the Cabrera flux is 12 orders of magnitude too large. At least one of them is wrong. Even with [Wilczek's] weak cross section it still misses by a lot."

As for monopoles showing up in proton decay detectors, he adds, "our limits indicate you'd never see them. Experiments would have to probe to proton lifetimes of 10^{42} years"—many orders of magnitude beyond anything now contemplated.

On the other hand, Kolb, like many others, finds the prospect of catalytic monopoles tremendously exciting. Quite aside from their scientific importance as a laboratory for GUT physics, he says, they would provide for the total conversion of matter into energy.

—M. Mitchell Waldrop

Proton Decay: Not Yet

The Kolar Gold Field proton decay experiment in India has seen at least three events and perhaps as many as six. The Mont Blanc tunnel experiment found one event on 23 July, after only 3 weeks of operation. So is it safe to say that proton decay has now been confirmed?

Not yet. "The events are intriguing, but not definitive," says Maurice Goldhaber of Brookhaven National Laboratory, a participant in the Irvine/Michigan/Brookhaven (IMB) experiment now starting up in a salt mine near Cleveland. "The Mont Blanc and Kolar events are candidates, but not all candidates get elected. You cannot exclude the possibility that they were caused by neutrinos."

The particular neutrinos that bedevil proton decay experiments are the ones formed by cosmic ray interactions high in the atmosphere. They penetrate through any amount of shielding, and sometimes have sufficient energy to imitate a proton decay should they interact with a nucleus in the detector. One way to sort things out is with statistics: a plot of the number of neutrino-induced events versus their total energy should have a broad peak at about one-third of a proton mass. A smaller, sharper peak right at the proton mass would be evidence for proton decay. But a single event, even one at precisely the right energy, does not prove anything.

Lawrence R. Sulak of the University of Michigan, a principal investigator on the IMB experiment, points out that a real proton decay event must also have the right geometry: to conserve momentum the decay products—a positron and a neutral pi-meson, for example—must be emitted back to back. Only one in a thousand neutrino events would imitate that. But neither the Kolar nor the Mont Blanc experiments can provide definitive information on the direction of the decay products.

That kind of information is what the IMB experiment is designed to provide. It is essentially a 10,000-tonne tank of water surrounded by Cherenkov detectors that will measure both energy and direction of the decay products. A similar detector, built by workers from Harvard, Purdue, and the University of Wisconsin, is also coming online in Utah.

Within 6 months, says Sulak, he and his colleagues should have finished initial measurements on their neutrino background. "Then we can ask if we have any proton-decay candidates," he says. Goldhaber adds: "This is too important an experiment to be left dangling. We want to be able to say something one way or another."—M.W.