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[Columbia University, New York, NY, and Institute for Advanced Study, Princeton, NJ]

The requirement that *P* and *T* be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one that would give a remarkable new kind of very light, long-lived pseudoscalar boson. [The *SCI*® indicates that this paper has been cited in more than 605 publications.]

The Birth of Axions

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The basic idea of axions occurred to me as a result of my wife's ear infection. This was in the summer of 1975, when we were visiting Fermilab with a small baby daughter in tow. My wife was ill and confined to bed, and I had a rather difficult day trying to cope. Finally, both wife and daughter were safely asleep and it was a beautiful midwestern night with a gorgeous clear sky, and I decided to take a long walk.

Turning with relief from the cares of the day, I decided to think about the Higgs sector. At that time, what is now called the standard model of particle physics, although less than three years old, was already established as far as I was concerned. Therefore, it made sense to look at this model in a critical spirit, to see how to go beyond it. A critical spirit did not find great difficulty in locating soft spots. Although the standard model gave an excellent account of the gauge interactions among elementary particles (quarks and leptons), it gave a very poor account of the pattern of their masses and weak mixing angles. These masses and mixing angles were all blamed on the coupling of the quarks and leptons to the Higgs field. A condensate of its quanta (Higgs particles) was supposed to permeate all space and destroy the orderly symmetry of the model, which is too good for this world. On the other hand, there was no direct experimental evidence for the existence of the Higgs field or its quanta, and the postulated couplings were quite arbitrary and ugly. (By the way, the story is essentially the same, and just as unsatisfactory, today.)

I had two worthwhile ideas that night. One was a practical method for trying to detect Higgs particles from their emission in heavy quark decays—a technique that has since been used in connection with b-quark decays and may turn up again in connection with t-quark decays when that quark is finally located.

Following these rather mundane considerations on how the elusive particles might get discovered, I was musing on how peculiar it was to replace masses and mixing angles, which we think of as fixed and tangible things, by fields that could vary in space and time. I was idly tossing around ideas—that these things were fixed historically; how our particular Universe happened to evolve; that each mass had its own private Higgs fields instead of there being just one shared by all (as in the standard model). These remain possibilities even now, but not compelling ones.

But suddenly, I made a connection to a paper by C.W. Bernard and E. Weinberg[1] that I had been reading, which suggested that the θ parameter of quantum chromodynamics could be viewed as a coupling constant. It struck me that here was a case where having a coupling constant as a dynamical variable might actually buy you something. It was a big mystery, why the θ parameter is so small in reality. If it were a dynamical variable, it might be *forced* to be zero, or nearly so, to minimize the energy.

It was not too difficult to construct rather simple and attractive extensions of the standard model that realized this idea. As I constructed such models in detail, however, I was reminded of some models that appeared in a paper written by R.D. Peccei and H.R. Quinn[2] that spring that I hadn't understood at the time. So with some trepidation, I went back to re-read their paper and found to my horror that they had the essential idea already. However, I had realized several little things and one big thing they hadn't: the big thing was that these models inevitably contained a very un-

usual, very light particle. I called this particle the *axion*, after the laundry detergent, because that was a nice catchy name that sounded like a particle and because this particular particle solved a problem involving *axial* currents.

At first I suspected, without thinking very hard about it, that this particle couldn't possibly have escaped detection, and so it destroyed the whole circle of ideas. Since the result was negative, I dithered about writing it up, trying to see if one could somehow make the axion or find some plausible alternative. None of these attempts came to anything.

I talked with several of my friends about these things. Late that fall, one of them, Robert Shrock, heard Steven Weinberg talking about very similar ideas and told him I had been thinking along similar lines. Weinberg very graciously called me, and we shared our thoughts, which were indeed closely related. However, to my amazement, he didn't think the particle was necessarily ruled out. We decided to continue independently, although keeping in touch to avoid errors, and arrived at very similar models and conclusions.[3] It was truly natural and effective to extend the standard model to include axions, and these particles might just barely have escaped detection, although experiments specifically designed to find them were certainly feasible.

This was a very exciting time; probably the most exciting I have experienced in my physics career. We were making a specific and well-motivated suggestion for the existence of a new particle with truly spectacular properties. Many experimentalists took up the challenge, and within a few weeks...the axion no longer seemed a live possibility.

The situation languished in this unsatisfactory state for several years, with the axion apparently ruled out. But no alternative idea for solving the problem it addressed was even remotely as compelling. Then M. Dine, W. Fischler, and M. Srednicki[4] made the very important observation that Weinberg and I had assumed in our models—that the axion was associated with the Higgs field of the weak interaction, which was a natural assumption but not necessary. It was at least equally natural to have axions associated with Higgs fields of grand unified interactions. Such axions would be much more feebly interacting and elusive than the ones we originally contemplated; in fact, they seemed hopelessly so and were called "invisible axions."

Later developments have changed the picture and raised the stakes. It turns out that (following standard Big Bang cosmology) axions would have been copiously produced in the early Universe;[5] in fact, so copiously that they are a plausible candidate—perhaps, at present, the most plausible—to provide the "dark matter" astronomers seem to observe through gravitational influences but have been unable to detect directly. Also, P. Sikivie[6] has devised ingenious but technologically demanding axion antennas that promise to be capable of sensing the cosmic axion background. It will take heroic efforts to detect this background (even though it's most of the Universe by weight); but there do seem to be heroes rising to the challenge.

One other development that should be mentioned is that axions play a central and crucial role in superstring theory.

Axions have joined the select company of magnetic monopoles as theoretically compelling, unobserved particles. Indeed, like monopoles, they have become more compelling theoretically while the possibility of their experimental detection has become more tenuous. Instead of the nice little bird-in-the-hand I originally hoped for, we have a flock of pteranodons in the bush. Still, there is hope.

[Editor's note: Frank Wilczek was elected to the National Academy of Sciences in April 1990.]

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