SCIENCE OBSERVER

HAVE YOU SEEN THIS PARTICLE?

"The Standard Model is too good. It predicts too well." This remark on the prevailing theory of the fundamental particles and forces of nature was made at a recent conference by Burton Richter, the director of the Stanford Linear Accelerator Center and a major contributor to the development of the very model whose success he laments. Richter's comment might be taken to suggest that all of nature's secrets have been laid bare, and physics is nearing its end. Younger physicists, take heart! There *are* a few particles yet to be discovered, phenomena to be explained, experiments to be done. What follows is a brief list, compiled from conversations with particle physicists, of questions for which answers are still wanting.

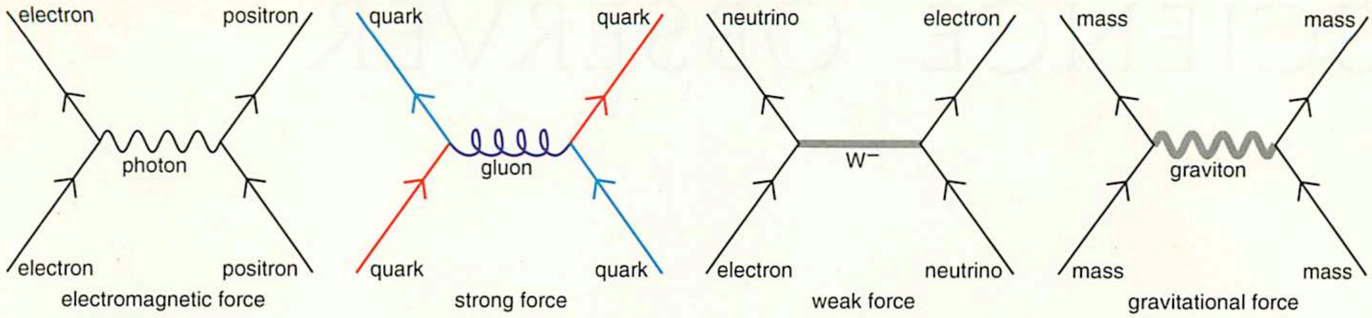
Underpinning the Standard Model are a few guiding principles. All matter is thought to be made up of two kinds of particles: quarks and leptons. The quarks come in six "flavors": up, down, strange, charmed, bottom and top. They all have the peculiar property that they are never seen in isolation but only as components of more familiar particles such as the proton and the neutron. There are also six varieties of leptons: the electron, the muon, the tau and three types of neutrinos. These particles interact with one another through four fundamental forces of nature, each of which is transmitted by its own set of carrier particles. Electromagnetism is transmitted by the photon, the weak force by the *W* and *Z* particles, the strong force by gluons, and gravity by the graviton. The Standard Model unifies electromagnetism and the weak force, thereby establishing a deep connection between the photon and the *W* and *Z* particles. The model also includes a theory of the strong force.

One element of the model that stands in urgent need of verification is the existence of the top quark, which is the only one of the six quarks that has not yet been seen in any experiment. The status of the search for the top quark was summarized in the September–October issue of *American Scientist* by John Huth of the Fermi National Accelerator Laboratory. Briefly, the top quark is apparently far more massive than any of

Excavation of the 54-mile tunnel begins at the Texas site of the Superconducting Super Collider.

the other quarks, and so larger and more energetic instruments are needed to produce it. Whereas the bottom quark has a mass of about 5 giga-electron-volts (GeV), the current lower limit on the top-quark mass is 91 GeV. This makes it heavier than the *W* and *Z* particles (80 and 91 GeV respectively), a fact that in turn has a strong influence on what kind of signal the quark will produce in a detector. There is widespread optimism that the top quark will be discovered with the current generation of particle accelerators. And even if it should elude the several hundred physicists who are currently on its trail, few would be prepared to consider the possibility that it simply does not exist; a world with a bottom quark but no top is all but unthinkable.

After the top quark, the next major quarry of particle hunters is the Higgs boson. This is the particle that in the simplest versions of the Standard Model accounts for the dramatic difference in mass between the photon (whose mass is



Four forces of nature govern the known interactions of matter. Each force is transmitted by its own carrier particle.

zero) and the *W* and *Z* particles. In fact, the Higgs boson is a key to understanding the origin of mass in all particles. The Higgs boson is the embodiment of a field that is thought to permeate all space; a particle's mass is determined by how strongly it interacts with the Higgs field. The mass of the Higgs particle itself can be estimated from the known masses of the *W* and *Z*. Based on current knowledge and assumptions, the Higgs mass should lie somewhere between 45 and 1,000 GeV. This is the territory to be explored by the Superconducting Super Collider being built in Texas. Part of the range will also be accessible to the Large Hadron Collider, the next-generation accelerator planned for CERN, the European Laboratory for Particle Physics in Geneva. Both of those devices are expected to be running by the end of the decade.

Some version of the Higgs mechanism is an inescapable part of the Standard Model, but it need not be the single Higgs boson predicted by the earliest formulation of the theory. Other variations on the Higgs mechanism could also explain the origin of mass. For example, instead of a single Higgs particle there could be a series of them, differing in a variety of properties such as electric charge. Or the Higgs particle could be a composite object made up of more fundamental entities. Some theorists would be disappointed if the simplest Higgs model were now confirmed, because other ideas are considered to have greater elegance and explanatory power.

One of the most intriguing alternatives to the original Higgs model is called supersymmetry, which brings about a reunion of two great families of particles, the fermions and the bosons. All particles can be classified according to their spin angular momentum, which for an elementary particle is a fixed, quantum-mechanical property. Particles whose spin is a half-integer are fermions; those with integer spin are bosons. All the quarks and leptons are fermions, whereas the various force-carrying particles are bosons. In conventional theories fermions and bosons are forever estranged, but supersymmetry forges a link between them. In doing so, it neatly doubles the number of elementary particles. All of the quarks and leptons acquire supersymmetric companions called squarks and sleptons; likewise the various bosons have companions with names such as photino, wino, zino and higgsino. All of these exotic states of matter become candidates for experimental search.

Experimenters at the new accelerators will also have an eye out for signs of a deeper level in the structure of matter. Just as the atomic nucleus is made up of protons and neutrons, and the protons and neutrons are made up of quarks, it seems possible that quarks and leptons could be composite objects made up of still smaller-scale entities.

Another realm that particle physicists are eager to explore in greater detail concerns a symmetry principle labeled CP, for charge conjugation and parity. Most interactions of elementary particles conserve CP symmetry: If you imagine converting all particles into antiparticles, and at the same time reflecting the event in a mirror, the result is an equally plausible event. CP symmetry is violated, however, in a few rare decays of the neutral kaon, a "strange" particle (that is, a particle whose constituents include a strange quark). The Standard Model can be made to account for the observed CP violation, but in a rather ad hoc and unsatisfying way. More precise measurements of the kaon decays might give a better clue to the underlying mechanism, but physicists are also eager to observe CP violation in particles other than kaons, most notably particles that incorporate a bottom quark.

Strange doings among neutrinos are also attracting a great deal of attention. For more than 20 years the flux of neutrinos emitted by the sun has been measured by a series of underground detectors, and the results have consistently come up short of expectations. It is still not clear whether the cause is something odd about the sun or something odd about the neutrino. If the answer lies with the neutrino, one possibility is that some of the electron-type neutrinos emitted by nuclear reactions in the sun may be spontaneously converting into muon-type or tau-type neutrinos, which would not be registered in the detectors. It so happens that if neutrinos are capable of such mixing, they cannot be massless particles, as was once thought. Recent experiments have hinted at a neutrino with a mass of 17 kilo-electron-volts, but that mass is much too large to solve the solar-neutrino puzzle. Other experiments have failed to confirm the 17-keV finding.

One thing that physicists definitely do *not* expect to discover is more types of neutrinos. The lifetime of the Z particle sets tight bounds on the number of neutrino types in nature, and measurements of the Z at CERN have produced strong evidence that the number is exactly three. (There is one loophole in this line of argument: More neutrinos could exist if their mass is greater than half the Z mass, or about 45 GeV.)

Any discussion of missing particles should not fail to mention the magnetic monopole, which has been on the most-wanted list since the 1930s. Monopoles are the magnetic counterparts of electrons and positrons; instead of an electric charge, they carry a magnetic charge, either north or south. (All ordinary magnets are dipoles, with inseparable north and south poles.) The existence of magnetic monopoles follows from very basic principles rooted in quantum mechanics and the special theory of relativity, and few doubt that they must exist somewhere. On the other hand, few are disturbed that no confirmed examples have turned up after 60 years of searching. The monopoles are very likely so massive and so rare that terrestrial detectors have a negligible chance of catching one.

The graviton, the carrier of the gravitational force, is unlikely ever to be seen in a conventional particle detector (gravitational interactions are too weak), but there is hope of detecting the related phenomenon of gravitational radiation. Indeed, gravity-wave detectors have been operating for more than 30 years. Most of these instruments are delicately suspended large masses, which should resonate to faint distortions of space-time propagating away from cataclysmic events such as supernovas and collisions of black holes. So far, no unambiguous signals have been detected. A sterling opportunity was missed five years ago, when the most sensitive detectors were not taking data at the time of supernova 1987a in the nearby Large Magellanic Cloud.

While waiting for various particles to make an appearance, physicists have also been waiting for one particle to *dis*appear. In the Standard Model the proton is an absolutely stable particle; it cannot decay because it is the lowest-mass combination of three quarks. But the next step beyond the Standard Model will be a theory that unifies the strong force with the weak and electromagnetic forces. Any such unification almost inevitably predicts that the proton can decay—and thus all matter is perishable. Initial analyses suggested that the proton lifetime might be shorter than 10^{30} years, which offered hope of detecting the decay by watching over a very large collection of protons. Several such vigils were undertaken in the 1980s, with disappointing results. Recently an independent analysis of a Japanese experiment has argued that a few proton decays were seen after all, but the verdict on this proposal is not yet in.

From this long recitation of the missing and misplaced, it may seem that particle physicists cannot be trusted to find anything at all they go looking for. They can take consolation in the far worse predicament of astrophysics. It appears that astronomers and astrophysicists have lost 90 percent of *everything*. On looking at galaxies and at the universe at large, they are able to discern only a tenth of the mass that must be present. All the rest remains to be discovered.

It is also a comfort to physicists that very general and noncontroversial principles argue that *something* must be seen in the mass range between 50 GeV and about 2,000 GeV, so that the experiments now being planned for this range have a "can't lose" guarantee. If the Higgs boson is not found, then something else—perhaps something even more interesting—ought to turn up. If it doesn't—if the entire region is a barren wasteland—then the Standard Model must be seriously flawed, which in itself would be a fascinating discovery.—*Brian Hayes*

THE ENEMY OF MY ENEMY IS MY FRIEND

Boxing lore includes hundreds of stories of fixed fights and mismatches set up by shady fight promoters trying to skew the odds or smooth the way for an up-and-coming prizefighter. And occasionally an instance so arouses public outrage that it threatens to end the sport for good. Yet the abuses in our most brutal sport pale beside nature's own inequities.

The matchup between a plant and its predators would seem as lopsided as a boxing match in which one contender is bound in a straitjacket. Plants can't run or strike, pinch or bite, but the mites, caterpillars, beetles and other insects that feed on them can do all that and more. When you think about it, says Alexander Enyedi, a plant molecular biologist at Rutgers University, plants are pretty passive. But Enyedi wastes no pity on the plant world. Plants appeared on earth long before their predators, and Enyedi predicts they will outlast their attackers. The question, nevertheless, is intriguing: With the odds so overwhelmingly stacked against them, how is it that plants have managed not only to survive, but thrive, in Nature's boxing ring? The answer lies in the wide array of plant defenses that have evolved during many years of struggle.

Some plants are just so heavily padded or armed that most pests don't even bother with them. Others prefer to poison or sabotage their predators. But scientists are learning that there are plants that have evolved defenses so sophisticated that they don't have to go one-on-one with their opponents. Rather, corn and many other plants have their fighting done for them, by their enemy's foe.