Particle Theorists in a Quandary

The "standard model" of elementary particles fits all the data, but it does not explain everything; so theorists ponder which way to go

Elementary particle theorists are not noted for their humility, but lately they have been frankly admitting they need help. Having constructed an admirable edifice, the "standard model," that accounts for almost all the experimental evidence, theorists find that a lot of questions remain unanswered. Moreover, with new accelerators with collision energies of 100 to 2000 billion electron volts (GeV) coming on line this decade, theorists cannot with confidence predict from the standard model what experimentalists will find in this newly accessible energy range.

One of the principal architects of the standard model, Steven Weinberg of the University of Texas, rather forcefully portrayed the current mood of the theoretical community in his presentation opening the International Conference on Unified Theories and their Experimental Tests last March in Venice. Weinberg recalled a period of rapid progress, lasting until the mid-1970's, during which steps were taken toward a rational understanding of the world of elementary particles. Most important was the development of quantum field theories that actually did describe observed behavior. But since around 1976 despite much effort progress has been far more difficult.

It is not that there are no ideas for how to go beyond the standard model. It is just that there is no clue as to which is the correct way to go. In speaking of one of the alternatives, the one most actively investigated at present, Weinberg noted, "It is interesting that there is not one iota of direct experimental evidence for supersymmetry, yet we study it because it looks so much like the sort of theory we would like to believe in. This is symptomatic of the terrible state we are in. . . . The salvation of elementary particle physics is, at least for the moment, in the hands of the experimentalists."

The standard model consists of two quantum field theories: quantum chromodynamics, which describes the strong nuclear force; and a unified theory, which combines the weak and electromagnetic forces. The fields come in two types, one for the forces between particles and one for the interacting particles. In the prototype quantum field theory, quantum electrodynamics, for example, photons are the quanta of the electromagnetic field and have the role of carrying the force between interacting electrically charged particles.

In quantum chromodynamics, there are eight force fields and their quanta are called gluons. Like photons, gluons have no rest mass. Unlike photons, which carry no electrical charge, the gluons are charged. However, the charge is of a different sort that physicists have dubbed color. In further analogy to quantum electrodynamics, the particles feeling the strong nuclear force must be color charged. These particles are the quarks, which come in three colors, red, green, and blue.

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The weak force is unique in that there is no satisfactory quantum field theory for it in isolation. It must be combined with electromagnetism in a unified theory. When this is done, there are four fields and four types of field quanta. One is the massless, chargeless photon. The other three, which carry the weak force, possess mass, and two of the three are charged. Just as there is an electric charge for electromagnetism and a color charge for the strong force, there is a weak charge. The intimate connection between electromagnetism and the weak force is perhaps suggested by the fact that the quanta of the weak force fields have the same electrical and weak charge. There is the Z^0, which has zero electrical and zero weak charge, the W^+, which has positive charge of both types, and the W^-, which has negative charge of both types.

Ordinarily, field quanta in quantum field theories of the type in question, which physicists call gauge theories, must be massless. This is effectively the case for interactions at energies considerably greater than 100 GeV, but at lower energies a mechanism called spontaneous symmetry breaking gives masses to the W's and the Z^0. The price of this is the creation of an altogether new particle, the Higgs boson. Whereas the unified theory gives quite explicit predictions for the masses of the W's (a little over 80 GeV) and the Z^0 (a little over 90 GeV), the mass of the Higgs does not fall out of the theory.

The particles that feel the weak force include both the quarks and the leptons (electron, muon, tau, and their respective neutrinos). The electric and the weak charges of a given particle are not identical, but there is a fixed relation between them, again suggesting the connection between the two forces. Even more striking is that the particles are grouped in families of four particles, and so far there seem to be three families or generations. The corresponding particles in successive generations have the same weak and the same electrical charges, but the masses progressively increase from one generation to the next. Physicists have coined the term flavor to specify both the weak charge and the generation number of the quarks. Quarks thus have electrical charge (+2/3 or −1/3), color, and flavor. The first generation consists of up and down quarks, electron, and electron neutrino; the second of charm and strange quarks, muon, and muon neutrino; and the third of top and bottom quarks, tau, and tau neutrino.

While it is true that the standard model accounts for most of the experimental data, it is also true that some of the features of the model remain to be verified. One of the highest priorities is the capturing of the W's and the Z^0 and a detailed study of their properties. The proton-antiproton collider that started running last year at the European Laboratory for Particle Physics (CERN) at a collision energy of 540 GeV, a similar machine at the Fermi National Accelerator Laboratory of 2000 GeV that will commence operations in early 1986, and 100-GeV electron-positron colliding-beam machines at the Stanford Linear Accelerator Center and at CERN that are planned for 1987 openings will all address this issue.

Recent results from lower energy electron-positron colliding-beam storage rings at the German Electron Synchrotron (DESY) laboratory and at Stanford have already resulted in tantalizing glimpses. In the experiments, beams of electrons and positrons of equal energy (17 GeV at DESY and 14.5 GeV at Stanford for total collision energies of 34

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and 29 GeV, respectively) collide. Some of the time, electrons and positrons annihilate, and the energy released reappears as a pair of muons, one positively charged (antimuon) and one negatively charged.

The intermediate state between the electron-positron and muon-antimuon pairs can be either a photon or a Z^0. If it is a photon, there is no preferential direction for the positively charged antimuon or for the negatively charged muon, whereas, if it is a Z^0, the components of the antimuon motions along the beam axis prefer to be in the direction of the electrons, and the components of the muon motions prefer to be in the direction of the positrons. A characteristic of the weak force is that its strength grows as the interaction energy increases, becoming comparable to the electromagnetic force when the energy equals the Z^0 mass. At the energies of the electron-positron experiments, the weak force is still "weak," but the asymmetry between the directions of the muons and antimuons is nonetheless predicted by the unified theory to be a few percent. The DESY and Stanford experiments (six groups in all) generally supported this forecast. The group with the most data and hence the best statistics is the Mark-J collaboration at DESY, which is led by Samuel Ting of the Massachusetts Institute of Technology. The Mark-J group published in June its finding of an asymmetry of (-8.1 ± 2.1) percent to be compared to the theoretical value of (-7.6 ± 0.6) percent.

Other particles that must be found include the top quark and the Higgs boson. G. G. Ross of the University of Oxford argued at the 1981 International School of Subnuclear Physics in Erice, Italy, that the top quark must almost certainly exist because details of the decay processes of particles containing its third generation companion, the bottom quark, as observed at Cornell University's CESR electron-positron storage ring are inconsistent with its absence. Ross also summarized the predictions of the top quark mass, which range from the present experimental limit of 17 GeV to a few hundred GeV.

The Higgs particle is even more uncertain. Ross also reviewed this particle and pointed out that general considerations lead to a Higgs mass lying between 6.4 GeV and 300 GeV, a rather broad range. If it were light enough, the Higgs could be produced when Z^0 or toponium particles decay.

But even if these particles are found, many questions remain unanswered by the standard model. Gordon Kane of the University of Michigan gave a partial list at a Brookhaven National Laboratory workshop held in May. The standard model does not explain the masses of the quarks and leptons. It does not explain why there are three generations of particles, with each generation apparently identical in all respects except for the masses of the particles. And it does not explain why quarks and leptons are different, why the forces are different, and how they can be unified in a single theory.

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Unification has already been addressed. The simplest grand unified theory that brings together the strong nuclear, weak, and electromagnetic forces is the 1974 model of Howard Georgi and Sheldon Glashow of Harvard University. Georgi and Glashow invoked a spontaneous symmetry-breaking mechanism similar to that in the unified theory of the weak and electromagnetic forces. At very high energies, there are four forces, all of which have comparable strengths. The fourth force is a new hyperweak force that permits quarks to transform into leptons and vice versa. At lower interaction energies, this highly symmetric situation is broken, and the standard model is what remains, along with a greatly attenuated hyperweak force. Also in 1974, Georgi, Helen Quinn, now at Stanford, and Weinberg calculated that for this and many other grand unified theories, the energy at which the forces become comparable is about 10^{15} GeV, an energy seen only in the earliest moments of the birth of the universe.

A consequence of the quark-lepton transformation is that protons (made of two up and one down quark) can decay, albeit exceedingly slowly. The principal decay mode for the Georgi-Glashow model is by way of a neutral pi meson (one up quark and one antiup quark) and a positron. The proton lifetime is expected to be about 10^{32} years. The long life expectancy is due to the mass of the field quanta of the hyperweak force (10^{15} GeV), which is so high that in our low-energy world such particles are created only rarely—when the quarks in a proton happen to approach to within 10^{-29} centimeter of one another.

Neither the Georgi-Glashow nor other grand unified theories address the questions of quark and lepton masses and of generations of particles. Moreover, in the intervening years, physicists have realized that the grand unified theories make no "natural" explanation for the huge difference in the energies at which symmetry is broken in the grand unified theory (10^{15} GeV) and in the unified theory (90 GeV). As Frank Wilczek of the University of California at Santa Barbara explained at the Venice conference on unified theories, "a fantastic cancellation is required in otherwise unrelated coupling constants" to generate the smaller energy. This is called the hierarchy problem.

A proposed solution to the hierarchy problem is supersymmetry. One of the most fundamental separations in physics is between fermions (particles with half-integer spin angular momenta) and bosons (particles with integer spin angular momenta). As it happens, quarks and leptons are fermions, whereas the field quanta that carry forces between these particles are bosons. Supersymmetry allows transformations between fermions and bosons. One of the consequences of supersymmetry is the generation of new particles. Every particle in the standard model has a "twin" with all the same properties except for spin angular momentum, which is increased or decreased by 1/2. There are photons and photinos, gluons and gluinos, quarks and squarks, leptons and sleptons, and so on. Since none of these twin particles have been sighted, theorists conclude that supersymmetry, in a now familiar picture, is obeyed only at high interaction energies but not in our low-energy world—that is, it is broken. Supersymmetry could solve the hierarchy problem because, when all the details are worked out, theorists find that breakdown of the weak-electromagnetic symmetry cannot occur at a higher energy than the breakdown of supersymmetry. Supersymmetry breaking at 1000 GeV or less would account for the 90 GeV energy for the breakdown of the unified theory symmetry. A number of theorists have worked on supersymmetry as applied to the hierarchy problem, including Pierre Fayet of the Ecole Normale Supérieure in Paris, Glennys Farrar of Rutgers University, Savas Dimopoulos of Harvard, Stuart Raby of the Los Alamos National Laboratory, Edward Witten of Princeton University, and Wilczek.

Recently, theorists have invoked cosmological arguments to put limits on the energy at which supersymmetry might break down. Heinz Pagels of Rockefeller University and Joel Primack of the University of California at Santa Cruz have used the upper bound on the cosmological mass density to arrive at a symmetry-breaking energy of 10^6 GeV or less. The conclusion follows from the argument that gravitinos (the supersymmetric partner to the quantum of the gravitational field, the graviton) cannot be too heavy or else the expansion of the universe would be slowing down faster than it is. Weinberg took the opposite tack and considered very massive gravitinos. If these particles were heavy enough, they would decay early in the history of the universe and not contribute to the present deceleration of the universe's expansion. He arrived at the conclusion that a breaking of supersymmetry at energies of at least 10^{11} to 10^{16} GeV is allowable, although this would not help with the solution of the hierarchy problem.

One other consequence of supersymmetry in grand unified theories occurs in proton decay. The principal decay mode in a grand unified theory with supersymmetry becomes a positively charged K meson and an antineutrino, according to calculations by Demetrios Nanopoulos and John Ellis of CERN and others.

In addition to grand unified theories and supersymmetric theories, elementary particle theorists have conjured up a host of other models. Many of these require some or all of quarks, leptons, bosons, and the Higgs to be composites of even more elementary entities. Another approach considered independently by Weinberg and by Wilczek and Anthony Zee of the University of Pennsylvania is not to postulate any particular theory at all. The idea is to look at what symmetries or conservation laws are exactly but accidentally obeyed in the standard model, but might not be followed in a more complete theory valid at higher energies. Examples would be nonconservation of the number of baryons or leptons in an elementary particle reaction. Experimental observation of violations of these conservation laws would then point the way to the construction of the larger theory. Weinberg calls this "debris physics" because the standard model is seen as the low-energy residue of the complete high-energy theory that is still hidden.

With no real clue as to which direction to go, theorists have no choice but to heed the advice of Fermilab director Leon Lederman (not a theorist). "As long as there are no answers, the reasonable thing is to pursue experiments at higher energies."

—ARTHUR L. ROBINSON

A Sanguine Future for Biomaterials

The increased flexibility and inherent selectivity for albumin of new polymers may finally make possible small blood vessel repair

The body is an extremely harsh and discriminating environment for implanting foreign material as prostheses. When such materials are implanted, says Allen S. Hoffman of the University of Washington, "the body generally has two responses: wall it off or destroy it." Those responses lead to many problems, such as the formation of clots or thrombi. What is needed, says Donald J. Lyman of the University of Utah, is a "polymer that is compatible with its environment, and we are now beginning to approach that situation."

One area where that approach is being made is in the repair of small blood vessels—those with a diameter of less than 6 millimeters. Thrombogenesis causes most potential small blood vessel replacements to be blocked or occluded, often in less than an hour. When small vessel repair is required now, the material of choice is a saphenous vein from the leg. But this procedure requires the trauma of two operations—removal of the vein from the leg and reimplantation elsewhere—and as many as 25 percent of prospective patients do not have a satisfactory saphenous vein. Lyman estimates that as many as 300,000 individuals could be helped each year if a synthetic small blood vessel replacement were available.

Such help may be on the way. Lyman announced at the recent Macromolecular Symposium of the International Union of Pure and Applied Chemistry that he has a synthetic vessel that will enter clinical trials in humans before the end of the year. Hoffman, at the same meeting, disclosed that he hopes soon to begin long-term trials of a small artificial blood vessel in baboons. Although neither will reveal the precise compositions of their potential prostheses until patent applications have been filed, the two materials are obviously quite different. The two products are characteristic of a dichotomy that pervades the entire field, and they illustrate many of the problems that are involved in the use of biomaterials.

A major problem is that the nature of the interaction between blood and polymer is still largely a mystery. The large synthetic vessels that were first implanted in the 1950's, says James M. Anderson of Case Western Reserve University, "were so successful that nobody looked to see why they worked." Only recently have scientists begun to investigate the interaction in detail, and their success has been limited. "If you really look at it," says Lyman, "none of us knows what we are talking about. We have our own hypotheses, we think thrombogenesis occurs in certain ways, and this helps us design our experiments. Another group may have their own hypotheses that are quite different, but that help them design their experiments. . . . These controversies add to the excitement because we are pioneering into a whole new level of understanding."

While the details of mechanism may remain a mystery, a more general overview is emerging. One key event, nearly everyone agrees, is the adhesion of platelets to the polymer surface. That event initiates a complex chain of reactions that results in formation of a thrombus. Platelet adhesion, however, is controlled by an earlier event, the deposition of a layer of protein on the surface of the polymer.

It has been recognized since the 1950's that a surface coating of albumin seems to reduce thrombogenicity, but the reason for this remains a mystery. Nonetheless, the goal of most investigators has been to find some way to coat the surface of the polymer with albumin.

There are two principal ways to produce a surface coating of albumin. Lyman has sought to synthesize new or altered polymers that have an intrinsic attraction for albumin. Hoffman and others, in contrast, have sought to modify the surface of existing polymers to increase compatibility while maintaining the mechanical and permeation characteristics of known materials.

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