Is Supersymmet Layer of Structu

by MICHAEL DINE

SYMMETRY IS A FAMILIAR CONCEPT in art and design. In daily conversation, it usually refers to transformations in space, such as rotations of an object about an axis. In science, the word has a more general meaning and a profound significance, because its role in understanding the laws of Nature has been one of the dominant themes in physics. It figured heavily, for example, in much of Albert Einstein's work. He realized that the laws of electricity and magnetism, the great triumph of nineteenth century physics, had a puzzling symmetry. Postulating that it was common to *all* of the laws of Nature led him to special relativity, in which space and time are not absolute and fixed. Reconciling Newton's laws of gravity with this symmetry principle led him to develop the theory of general relativity.

Symmetries were also crucial to the post-war development of particle physics. By the mid-1960s, huge numbers of particles had been discovered with accelerators. Murray Gell-Mann and Yuval Ne'eman brought order to this chaos by searching for symmetries and discovering that they provided a periodic table for the elementary particles which then led to the idea of quarks. Symmetries also can determine the basic laws themselves. Electricity and magnetism can be understood as a consequence of a symmetry called gauge invariance. In 1954, Chen Ning Yang and Robert Mills generalized the symmetry of electromagnetism to larger symmetries. While their discovery was originally purely theoretical, within 25 years such symmetries were experimentally established as the basis for the Standard Model, the reigning theory of subatomic particles and their interactions.

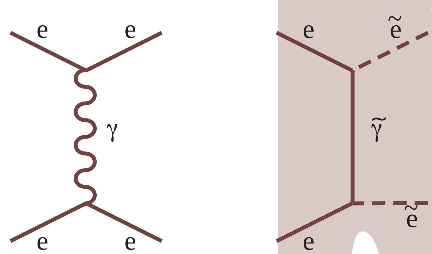
In the early 1970s a new type of hypothetical symmetry, "supersymmetry," was discovered. To understand it, one needs to recall a rule learned in chemistry. In building the Periodic Table, no two electrons can occupy the same state.

ry the Next
re?

Particles that obey this rule are called fermions. There is another type of particle, a boson, that obeys the opposite rule, preferring to share the same quantum state. The most familiar boson is the photon, and lasers are devices in which many photons are in the same state. One of the early triumphs of particle physics was the prediction of the spin-statistics connection, where particles of half-integer spin (the electron, muon, quarks, neutrinos) are fermions and obey the exclusion principle. Particles of integer spin (the photon, gluon, *W* and *Z* bosons) are bosons. Supersymmetry is a symmetry that relates fermions to bosons.

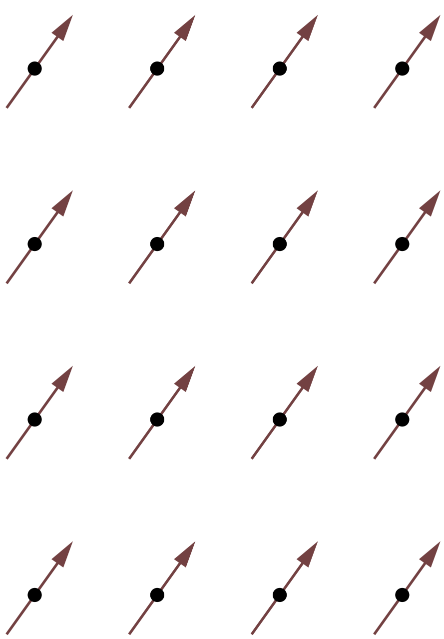
As an example of this new possible symmetry, one can write a generalization of, say, quantum electrodynamics (QED) which is supersymmetric. In the familiar version of QED, one has electrons, positrons, and photons. In a supersymmetric version, one would have, in addition to the electron and photon, a scalar electron ("selectron") and a spin-1/2 partner of the photon ("photino"). Just as two electrons can interact with a photon, an electron and selectron could interact with a photino (see figure on the right). The strength of these two interactions would be the same. One could extend this to the full Standard Model and even add gravity to the story. In addition to the graviton predicted by general relativity, there would be a "gravitino" of spin 3/2.

These turn out to be beautiful theories. But as originally proposed, they make a prediction which is obviously false. If the symmetry is present, then the *masses of the different particles and their superpartners must be the same*. But there is obviously no scalar partner of the electron with the same mass, nor is there a massless photino.



Left, electrons interact through the exchange of a photon. Right, electrons exchange a photino and produce a pair of scalar electrons.

In a ferromagnet, the lowest energy state has spin aligned in some direction—which direction is not important.



BROKEN SYMMETRY

It is possible for a symmetry of Nature's laws to be hidden, or "broken." This idea may seem paradoxical; however, such symmetries are common. An example is provided by an ordinary magnet. Atoms often act as little magnets, but in most materials, there is no net magnetism since the atoms point in random directions. Magnets are special: in the state of lowest energy, the magnetism of each of the individual atoms (their spins) point in some direction. Because the underlying laws don't change if the system is rotated, this magnetism may point in any direction, but it must point in some direction, that is, it must "spontaneously" break the symmetry (see figure on the left).

Particle physics provides other examples of this phenomenon. The pions are much lighter than the other hadrons as a consequence of the breaking of a symmetry called chiral symmetry. The gauge symmetry of the weak interactions is also a broken symmetry. The yet to-be-discovered Higgs boson is the agent of this breaking. It is the breaking of the symmetries that permits the *W* and *Z* bosons to have mass. Even the electron would be massless without the symmetry breakdown.

If supersymmetry is a symmetry of Nature, it must be a broken symmetry in a similar sense. Just as the electron and the neutrino do not have the same mass in the Standard Model, so the electron and the selectron need not have the same mass if the symmetry is broken. There should presumably be some particles which play a role in symmetry breakdown, analogs of the Higgs boson. If Nature turns out to be supersymmetric, understanding this symmetry breakdown will be one of the most important questions for experiment and theory.

IF IT'S BROKEN, WHY SHOULD WE HOPE TO SEE IT?

So it is possible that there is a new symmetry of Nature, which is spontaneously broken. The missing states, the partners of the ordinary quarks and leptons, photons and gluons, should be massive. But why should their masses happen to be such that we could find them at Fermilab's Tevatron or CERN's Large Electron Positron accelerator (LEP II) and the Large Hadron Collider (LHC)?

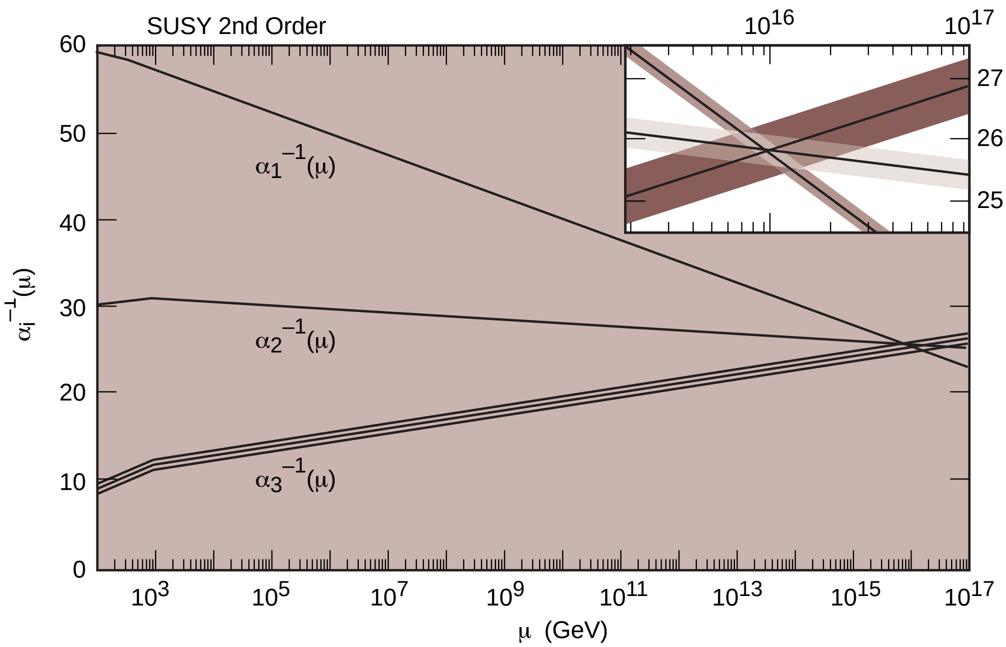
One argument is related to something known as the hierarchy problem. It was first posed by Paul Dirac as the more colorful—and meaningful—"problem of the large numbers." Because mass, in special relativity, is equivalent to energy, we can equally well speak of mass or energy scales. Max Planck, when he first discovered his famous constant, noted that one can construct from Newton's constant another energy scale, now known as the Planck scale, M_p. This scale is enormous, 10^{17} times larger than the masses of the *W* and *Z* bosons. Dirac's question was: where does this huge number come from? Within the Standard Model it is hard to understand why the *W* and *Z* masses aren't so large.

To look for a way out of this dilemma, we can examine another small mass—that of the electron. In the Standard Model, it has long been understood why this number should be so small—the theory becomes more *symmetric* as the mass of the electron becomes small. The electron mass is a small symmetry-breaking effect. This symmetry was first noticed in QED, and it is related to the fact that in addition to the electron, QED contains another particle, the positron, and is related to the fact that QED predicted the existence of antimatter. Similar remarks hold for the other quarks and leptons.

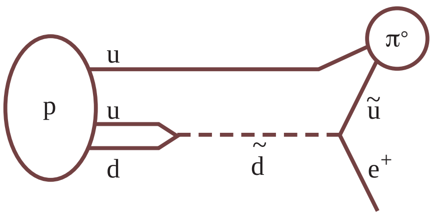
In the Standard Model, all of the particle masses are related to the mass of the Higgs particle, and the problem is that the Standard Model does not become more symmetric as the Higgs mass tends to zero. If the Standard Model is enlarged so as to be supersymmetric, however, scalar masses *can* naturally be small, just like the electron mass. If the symmetry is broken, scalar masses are on the order of the scale at which the symmetry is broken. Turning this argument on its head, if supersymmetry is relevant to Nature, the natural scale of supersymmetry breaking is on the order of the *Z* mass, perhaps 100's of GeV to a TeV or so. So these particles might be seen at LEP II or the Tevatron, and certainly the LHC. The price of this extra symmetry is similar to that in QED—the number of particles must be doubled.

The hypothesis that supersymmetry is broken at about 1 TeV leads to a striking experimental prediction, which has already been confirmed—the "unification of couplings." The strength of each of the interactions of the Standard Model is characterized by a number, called a "coupling constant." For the electromagnetic interactions, this is the famous fine structure constant, α. There are similar constants for the weak and strong interactions. These couplings all depend on the energy. In the study of atoms, α is 1/137, but for the much more energetic *Z* boson, it is about 1/129. If one plots the Standard Model couplings as a function of energy, assuming that Nature is supersymmetric, one finds that they meet, to a high level of precision, when the energy is very large, about 10^{16} GeV (see the figure above), provided that all of the new particles have masses not too much larger than the *Z* mass. This suggests that Nature is indeed supersymmetric, and at some very high energy scale, not too terribly different from the Planck scale, the interactions are unified into a larger theory. This meeting might be a coincidence, but it is striking how well the simple hypothesis does.

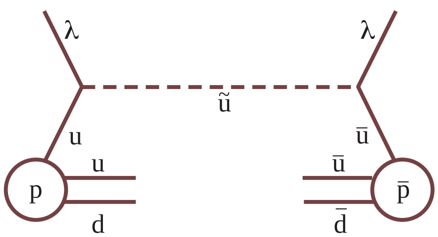
The hypothesis of supersymmetry at a TeV also makes a spectacular prediction in cosmology. While



Reprinted from Physics Letters B260, 447 (1991), "Comparison of Grand Unified Theories with Electroweak and Strong Coupling Constants Measured at LEP," by Ugo Amaldi, Wim de Boer, and Hermann Fürstenau, with permission from Elsevier Science.



A proton decays to a π^0 and positron.



A quark from a proton and an antiquark from an antiproton collide, exchanging a squark and producing a gluino pair.

most supersymmetric particles should have very short half lives, the lightest supersymmetric particle, or LSP, is quite possibly stable. One can predict how many of these LSP's were produced in the Big Bang. This number turns out to be in the right range to account for the missing mass of the Universe, and searches for this dark matter are currently underway (see the previous article by John Learned).

There is another theoretical argument that supersymmetry may be present in Nature, and that it might be broken at energy scales accessible to experiment. General relativity has been quite successful in describing phenomena on very large scales, such as the solar system. But when one attempts to ask how the theory works at extremely short distances, one finds paradoxes and inconsistencies. The situation is much like that of the theory of weak interactions prior to the Standard Model which makes almost exactly the same predictions as this older theory for low energy phenomena, but looks very different at high energies. In the case of general relativity, it is widely believed that the puzzles are resolved by superstring theory. Much as the Standard Model is the inevitable generalization of the Fermi theory, so there is good (if not quite compelling) reason to believe that superstring theory is the unique answer to the puzzles of quantum gravity. String theory is a theory in which the basic entities are strings rather than point particles (see "Whatever Happened to the Theory of Everything," by Lance Dixon in the Summer 1994 *Beam Line*, Vol. 24, No. 2). For reasons that are not well understood, such a theory is automatically a theory of gravity *and* the gauge interactions of the Standard Model. It has quarks, leptons, *and supersymmetry*! Within our current, rather primitive understanding of this theory, supersymmetry at energies accessible to planned experiments is almost inevitable.

A SUPERSYMMETRIC STANDARD MODEL

What would a supersymmetric version of the Standard Model look like? It is easy to figure out what the basic building blocks of such a model would be. In addition to the quarks, there would be squarks. Each lepton would have a slepton partner. The *W* and *Z*'s would be accompanied by fermions (charginos and neutralinos) and the gluon would be partnered with a "gluino." From current experiments we know that all of these have masses larger than their partners, except possibly for the top quark and some of the charginos/neutralinos.

We cannot currently predict the precise masses of these particles. But it turns out we do know a great deal about their interactions, and as a result, we know how they would show up in various kinds of experiments. Once one knows the masses of the superpartners, the experimental consequences can be predicted in a straightforward fashion.

To completely work out the phenomenology, however, we need to face another problem. In the Standard Model—and in Nature—the proton is an extremely long-lived particle. If it is unstable (and most particle physicists believe that it is), its half life is longer than 10^{31} years. In the Standard Model, this stability is easy to understand. Because of the various symmetries, one simply can't write interactions of quarks and leptons which permit proton decay. When one introduces supersymmetry, however, this is no longer true. It is possible, for example, for two of the quarks in the proton to turn into a (virtual) antisquark, and for this antisquark to decay into an antiquark and an electron. This leads to proton decay through the process shown in the top figure on the left. One would expect this decay to be very rapid, the proton decaying in a small fraction of a second.

So if supersymmetry is to make sense, one must explain why this process can't occur. Theorists do this by proposing another symmetry, called "R parity," a rule that says that the number of superpartners can only change by an even number in any process. This rule would be violated by proton decay. In addition, if R-parity is a symmetry, the lightest of the new particles predicted by supersymmetry can't decay; it is the LSP which we argued is a candidate for the dark matter. If one produces a pair of supersymmetric particles in an accelerator, they will decay to normal particles plus one of these LSP's. So, for example, at the Tevatron, a pair of quarks can annihilate, as in the bottom figure on the left, producing a pair of gluinos. Because of R parity, their decay products will always include an LSP. The LSP's are typically neutralinos, partners of the Z, γ, and Higgs, and interact very weakly with ordinary matter. As a result, they escape without detection, and the signature of this process will be some number of leptons and/or jets, and missing energies. Experimenters are well aware of these signatures, and are vigorously searching for such events. To date, searches by CDF and D0 at Fermilab can set limits of order 200 GeV on squarks or gluinos. Similarly, LEP II is placing strong limits on slepton and chargino/neutralino masses.

Apart from direct searches, there are other constraints on the superparticle spectrum. Even with R parity, proton decay occurs too rapidly if certain of the superpartners are too light. Rare K decays and CP violation experiments also strongly constrain the superparticle spectrum.

There has been a great deal of progress in recent years in understanding the dynamics which can lead to supersymmetry breakdown. While there is not yet one compelling model of the masses of the superpartners, there are some attractive ideas that make definite predictions for the values of the masses of the squark, slepton, and ???.

2001—A FANTASY

Imagine, for a moment, it is the year 2001, not too long after the publication of this article. CDF and D0 have simultaneously announced the discovery of supersymmetry at the Tevatron. Two characteristic signatures have been observed at a statistically significant level, one corresponding to a gluino, one to a chargino. A rough estimate of the masses can be made.

Suddenly we have entered a new era. In addition to the old problems of particle physics, such as measuring and understanding the quark mass parameters, we now have a whole new set of masses and mixings to understand—those of all of the new supersymmetric particles. Knowledge of some superparticle masses lends new urgency to the accelerated construction of a TeV linear collider. Theorists frantically start building models of supersymmetry breaking to predict the masses of other states. (Papers with new models and proposals appear daily). The following year, discrepancies between the Standard Model prediction of CP violation and experiment are reported by BABAR at SLAC and BELLE at KEK. These don't fit naturally into any proposed scheme for supersymmetry breaking. Theorists are frantically proposing new models. String theorists have redoubled their efforts to understand supersymmetry breaking and have made some tentative predictions for the masses of undiscovered states.

Of course, supersymmetry might not in the end be relevant to low energy physics, and certainly the timetable for discovery might be different. Yet of all of the ideas for understanding the underlying physics of the Higgs phenomena, supersymmetry seems the most promising. Perhaps this fantasy is not so implausible after all.