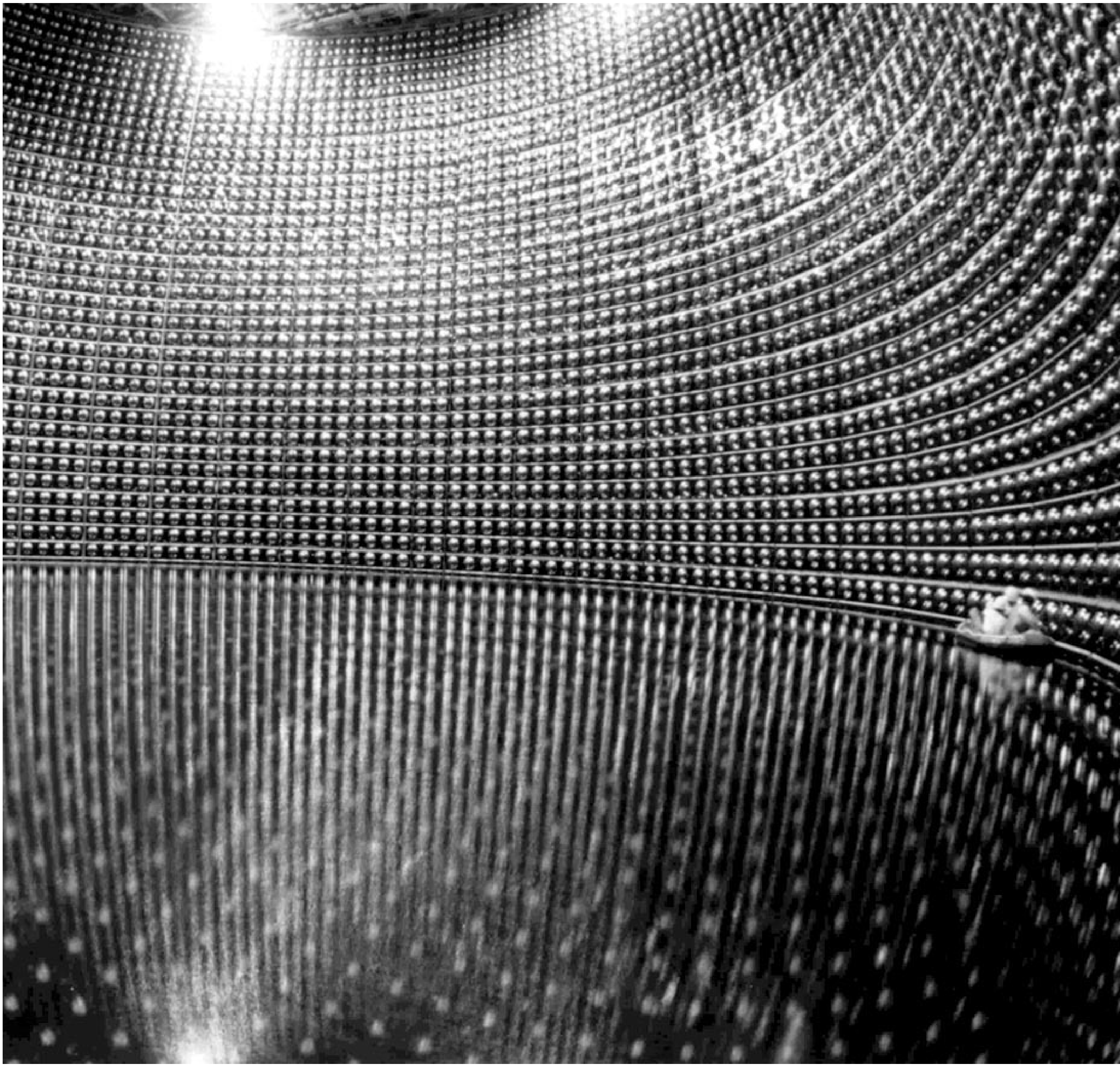
Neutrinos Have Ma

by JOHN G. LEARNED



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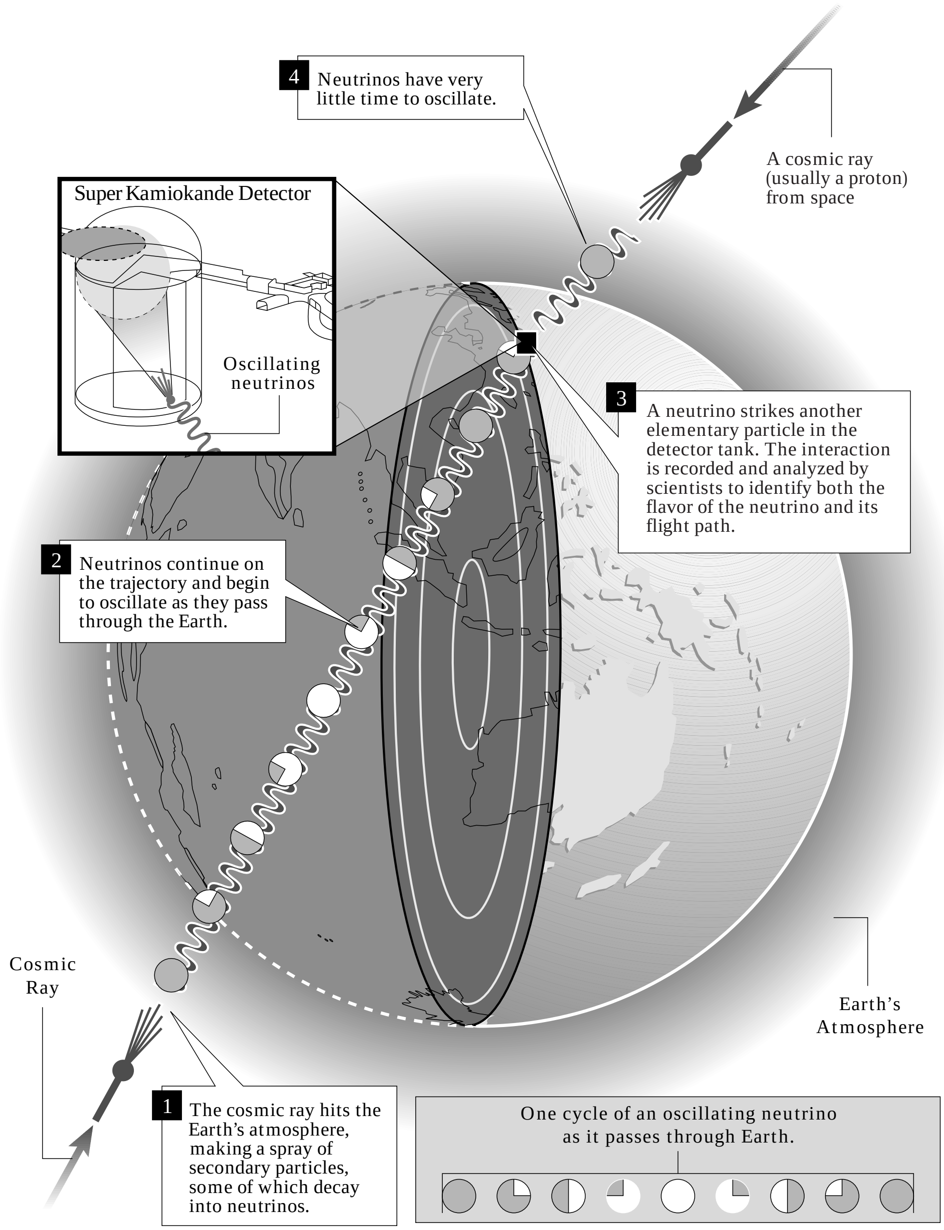
The Super-Kamiokande detector has found a deficit of one flavor of neutrino coming through the Earth, with the likely implication that neutrinos possess mass. One of the experimenters describes their results and what this could mean for particle physics.

OVER A YEAR AGO PHYSICISTS working on the Super-Kamiokande (Super-K) project in Japan announced strong evidence for neutrino mass and jolted the physics world by indicating that a rethinking of the Standard Model of particle physics—which assumes that neutrinos have no mass at all—would surely follow. It was not the first time that the elusive neutrino had been reported to have mass. But the evidence this time seemed irrefutable, coming as it did from the most sensitive instrument of its kind in the world: a 50,000-ton massive cylindrical detector filled with 12.5 million gallons of pure water and lined with 13,000 sensitive light detectors, located deep underground in the Japanese Alps (see photograph on opposite page). Particle physics is not the only field that will have to rethink things. Cosmology and astrophysics may also have their fair share of recalculating to do to accommodate neutrino mass. Examples include the effect of neutrino mass on the generation of an excess of matter over antimatter in the Big Bang, on accounting for the mass of the Universe, and on the generation of heavy elements in supernovae explosions.

Now, almost two years after the startling announcement that neutrinos appear to change identities—or oscillate—and thus to have mass (see "Searching for Neutrino Oscillations" by Maury Goodman in the Spring 1998 *Beam Line*, Vo1. 28, No. 1), more Super-K data have been collected. As their analysis is refined, the evidence for oscillation and thus neutrino mass becomes even stronger.

What does this work mean for particle physics? Does it bring us any closer to answering the grand questions about the Universe, such as its origin and future? What obstacles lie ahead in pursuing these answers?



A schematic illustrating the origin of neutrinos detected underground from high energy cosmic rays hitting the atmosphere and making secondary particles that decay, leaving neutrinos to penetrate the Earth and occasionally interact in detectors. The neutrinos coming from the far side of the world have much greater flight times during which to oscillate, as apparently do muon neutrinos but not electron neutrinos. (Courtesy University of Hawaii)

OSCILLATIONS IN THE AIR

As with most stories in the cosmic-ray business, there is a long history. The experimental tale begins with the first observations of natural neutrinos in 1967 in the world's deepest mines in South Africa and in the Kolar Gold Fields in India. At that time the instruments measured a rate of neutrino interactions a little lower than expected, but nobody made much of the discrepancy, and neutrino-flux calculations made by others soon agreed with the data.

The second round of experiments began in the late 1970s, using instruments that were designed primarily to search for the proton decay that had been predicted by certain grand unified theories. The first very large instrument in this class was the IMB detector, located in a salt mine near Cleveland, Ohio. The experimental technique was simple in the extreme: fill a large tank with ultra pure (and hence transparent) water, and surround it with light detectors looking inwards. When a neutrino interacts in the water, producing secondary particles, or when a charged particle enters the tank from the surrounding rock, most of these particles are sufficiently energetic that they travel at close to the speed of light. But the speed of light in water is significantly less than the speed of light in a vacuum, so the particles outstrip their disturbance of the medium (as does a jet plane making a sonic boom by exceeding the speed of sound in flight, or a boat leaving an expanding wake). As a result, the particles produce characteristic Cerenkov radiation, which projects onto the photodetector wall as a transient (nanosecond) ring of very blue light. The location, timing, and amplitude of the sensor signals allows one to reconstruct the track directions of the radiating particles. A further aid to particle identification is the fact that muons tend to produce a rather crisp ring of Cerenkov light, whereas the much lighter electrons scatter in the water, zigzag ahead, and produce a more diffuse, fuzzier ring of light.

The expected ratio of muon-neutrino to electron-neutrino events is a rather simple quantity to calculate and not susceptible to much uncertainty. When neutrinos interact in the deep-mine water tanks after traversing the Earth, we expect two muons to appear for every electron. The early results, however, were nearly an equal number.

Soon after beginning operations in 1982 the IMB (Irvine-Michigan-Brookhaven) group found that there were not as many muon decays following neutrino interactions as they had expected. This deficit caused much debate among the IMB physicists, including of course consideration of possible neutrino oscillations as the cause. But there were several other possible explanations at that time, both systematic and physics-based. Thus the collaboration chose to publish their results in a rather understated way in order to get it into the record, but not to stake out any grand claims that were not then supportable.

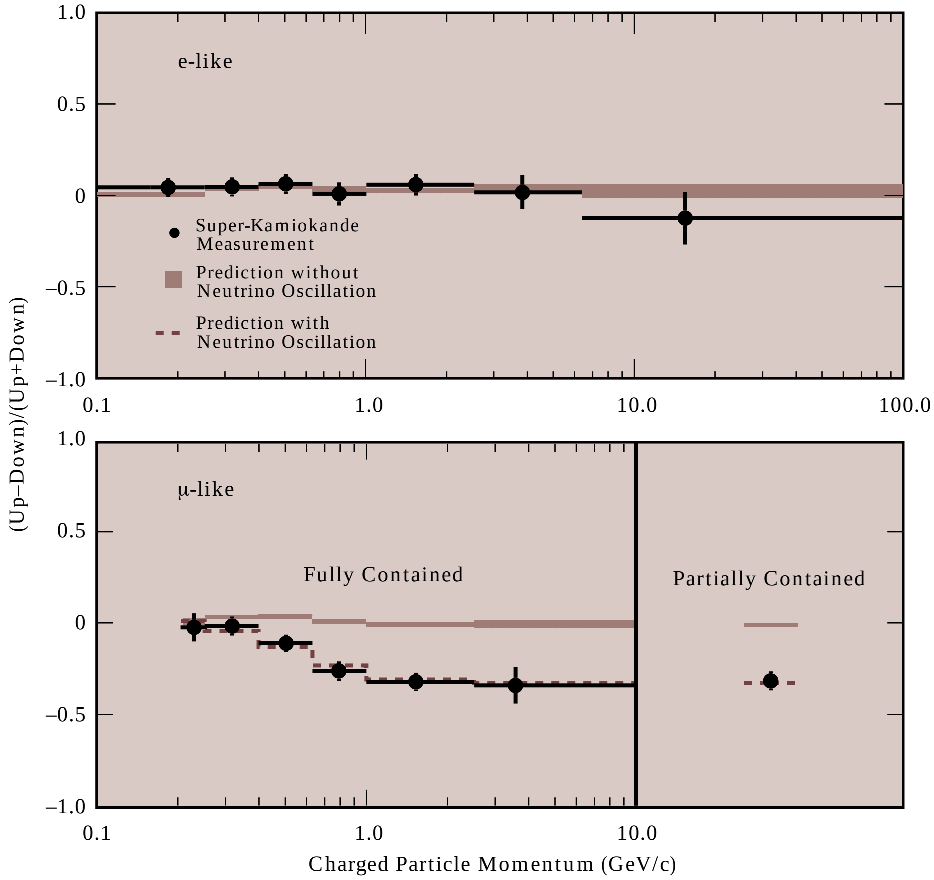
Not long thereafter the Kamioka collaboration came on line with its smaller but deeper and more sensitive detector, Kamiokande, located in Japan. The early work at Kamiokande produced results similar to those at IMB, and both groups then went on to develop more sophisticated techniques for distinguishing between muon and electron events. The situation began to change, however, towards the end of life of the old Kamiokande detector, after enough events had been accumulated and analyzed to publish an angular distribution of muon neutrino interactions in the detector (but where the muons leave the tank). This evidence was still rather weak, because the statistics were not good enough to rule out the possibility of zero angular variation, but it certainly appeared suggestive. Since acceptance of major new results clearly requires extraordinarily convincing evidence, it follows that any claim for neutrino oscillations, and hence neutrino mass, demands gold-plated evidence.

Acceptance of major new results clearly requires extraordinarily convincing evidence.

SUPER-K FINDS THE SMOKING GUN

The Super-Kamiokande detector is an awesome piece of technology, and in the photograph on page 8, physicists in a rubber raft polish the 20-inch photomultiplier tubes (PMTs) as the water slowly rises. The detector is a vast hall carved from hard rock in an old zinc mine near Mozumi, about 325 feet from the predecessor Kamiokande instrument (now being rejuvenated into the 1,000-ton liquid scintillator KamLAND). Super-K is housed in a huge stainless steel tank, welded in place, and containing a concentric structure which supports 11,000 20-inch PMTs looking inwards. There are also 1,800 eight-inch PMTs with wavelength-shifting light-collecting collars (recycled from the IMB experiment) looking outwards into the two meter thick veto region. The fiducial volume, taken as the region two meters inside the PMTs, contains 22,000 tons of water. This may be compared with the old Kamiokande at 600 tons, and IMB at 3,000 tons. It is indeed a big jump in collecting power, but perhaps the most important difference is in the ability to contain muon events. Muons travel a distance of about five meters in water per GeV of kinetic energy. The old Kamiokande instrument could only record muons up to about 1 GeV with any efficiency, while the Super-K instrument can record muon events up to several GeV, since it is nearly 50 meters across the long diagonal. As it happens, this improvement was crucial.

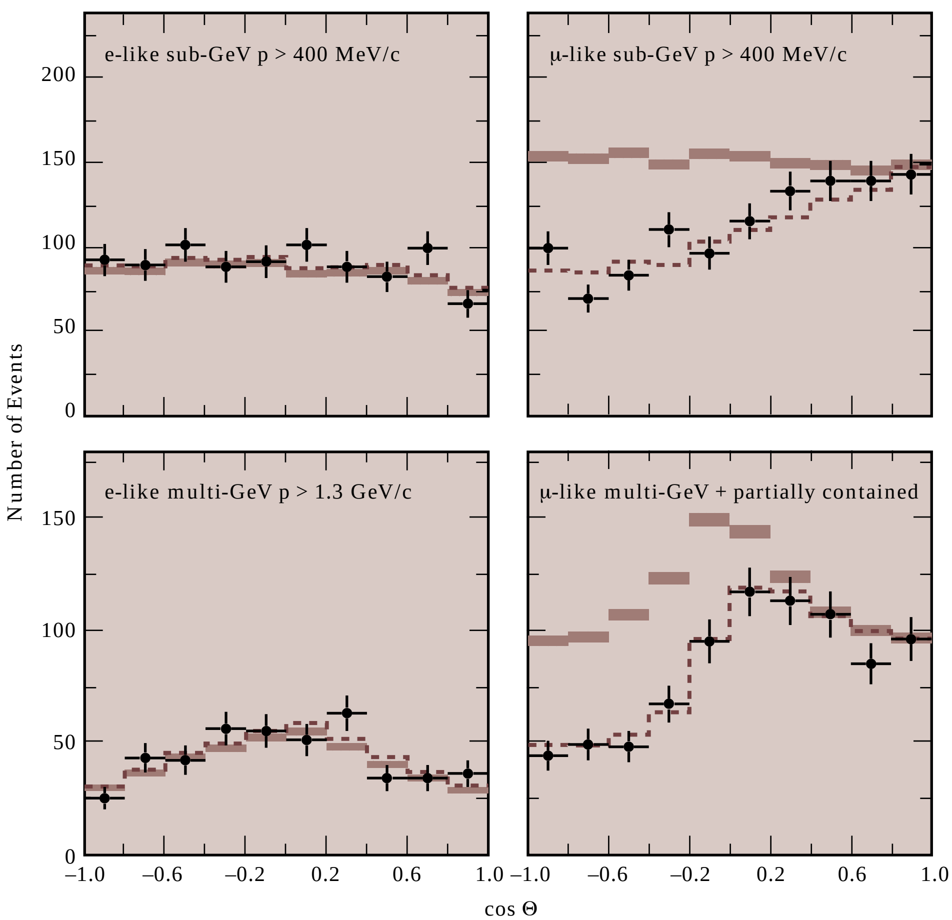
In early June 1998 we announced the results from analysis of the first two years of data accumulated in Super-K. The updated results as of



The up-down asymmetry for muon- and electron-type events in Super-K from 848 days of live time (analyzed June 1999), as a function of observed charged-particle momentum. The muon data include a point for the partially contained data having more than about 1 GeV kinetic energy.

summer 1999, with 848 days of live time analyzed, are shown on the left. The most compelling data consists of those events with single electrons or muons produced by neutrinos (2/3 of total), for which the secondary particles are completely contained within the fiducial volume. We record this type of event on average about once in every 10 hours of operation.

The figure at the upper left shows the asymmetry between upward-going and downward-going events, electrons and muons, and is particularly important because many systematic errors cancel out, and some results are interpretable without calculation. The electron events are up-down symmetric, as demanded by geometry in the absence of oscillations or other unexpected phenomena. For the muons, on the other hand, there exists a dramatic asymmetry which corresponds to a deficit of nearly one half for the upward-going muons, and which directly indicates that the oscillations must be (most surprisingly) nearly maximal. The shape of the asymmetry versus momentum curve is just what one would expect for oscillation: the dashed curve is a computer simulation. This plot alone rules out some hypotheses which could not be eliminated prior to Super-K. Of course, it still remains to explain the odd fact that the geometry of the Earth is so well matched to eliciting the maximal deviation from expectations. Are we being fooled somehow?



Cosine of zenith angle distributions of the contained preliminary event data from Super-K for two different energy ranges, and for electron and muon-like events. Cosine = 1 corresponds to downward-going events.

The figure at the bottom of page 12 shows the angular distributions of muon and electron events for two energy groupings. This may be the result that has been most convincing to the particle physics community, since it shows dramatic evidence that indeed the anomaly is with the muons, and that the onset of the deviation is smooth and not confined to the up-going muons. A fit to the hypothesis of oscillations is also shown, and again it clearly indicates the presence of maximal oscillations with a mass-squared difference of 0.0035 eV^2 and with an error of about a factor of two.

The allowed regions for the oscillation parameters between muon neutrinos and tau neutrinos are also shown in the illustration on the right. As the contour lines indicate, the mass-squared difference lies in the range of 0.002–0.007 eV^2, and the mixing is very nearly maximal.

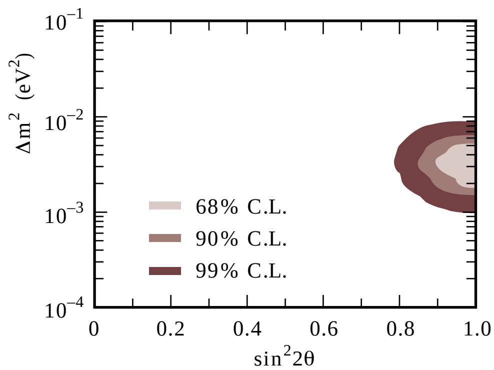
CORROBORATIVE EVIDENCE

Another detector in a mine, the Soudan II instrument in Minnesota (built to search for nucleon decay as were IMB and Kamiokande), has weighed in during the last few years with evidence for a low value for the ratio of muon-to-electron events, and is completely consistent with the old IMB and Kamiokande data. Unfortunately the statistics are not good enough to see the angular distribution, but at least the results dismiss the hypothesis that there is something uniquely peculiar about a water target. Also, the Soudan instrument has a veto shield lining the mine cavity, and this perhaps helps one to understand the reasons for the failure of the earlier and smaller European instruments to detect the anomaly.

There is also supportive evidence for the Super-Kamiokande contained data from the through-going muons that originate from neutrinos of about 100 times higher energies; these events produce a useful consistency check even though they do not constrain the oscillation parameters as severely.

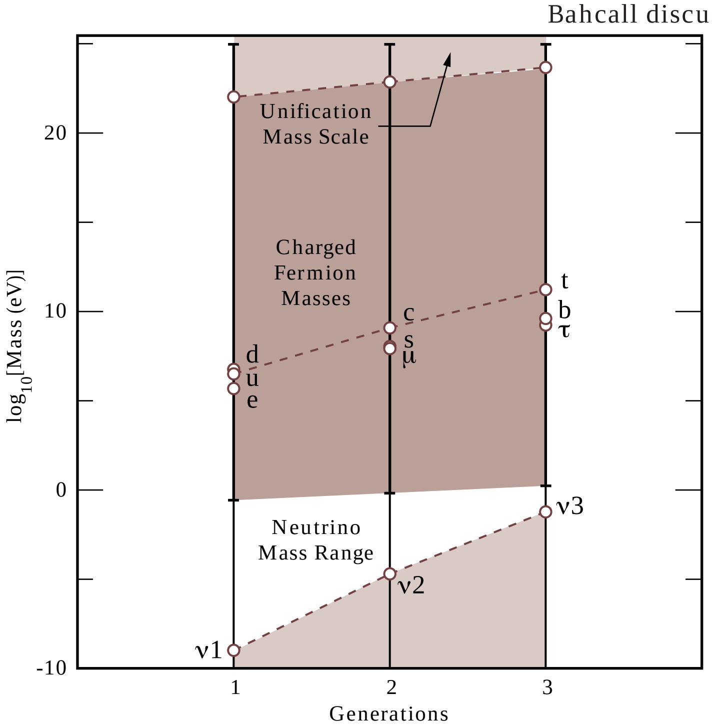
But is it really neutrino oscillations, one may well ask? As in much exploratory science, we must proceed here like Sherlock Holmes, eliminating all alternative hypotheses until we are left with only one. In fact we have done this, carefully examining such things as potential detector biases, cross sections, neutrino-flux ratio calculations, and even some rather wild physics possibilities. Nothing we have tried even comes close to fitting the evidence, except oscillations.

This does give one the flavor of how we are tightening the noose on the phenomenon we have encountered. We still worry, of course, that there might be some trick eluding us and that we have not got the interpretation quite right, or that something more bizarre is lurking in the data. Still, in the less than two years since we made the announcement at the Neutrino 98 conference, the data and analysis have only become more reassuring that we are on the right track. The new K2K (KEK to Kamioka) Long Baseline Neutrino Oscillation Experiment in Japan has taken its first steps toward verification of the discovery, with a few events already in hand but not yet enough to say anything definitive.



Preliminary data from Super-K showing the regions for various degrees of statistical acceptability (confidence level) in the plane of mixing angle and mass squared difference between muon and tau neutrinos.

The masses of the three generations of the fundamental fermions. The charged fermions (quarks and charged leptons) cluster in a central band. The neutrinos are well separated in a lower region of which we know only the general outline at this time. The unification mass scale is about as far above the charged fermions as the neutrinos are below on this logarithmic scale, pointing towards models that link neutrino masses with such phenomena as proton decay.



One central question has been whether the muon neutrino's oscillating partner is the tau neutrino, the electron neutrino, or both—or even worse, some new "sterile" neutrino. Our data indicate that the muon neutrino couples at most only weakly (less than a few percent) to the electron neutrino for the oscillations we see. A hypothetical sterile neutrino would not interact with ordinary matter at all; we are now finding evidence that the sterile neutrino hypothesis does not work very well for explaining our data. In contrast, every test we have made so far is completely consistent with the oscillating partner of the muon neutrino being the tau neutrino.

OTHER HINTS AT OSCILLATIONS

In his article in the *Beam Line* (Fall/Winter 1994, Vol. 24, No. 3), John Bahcall discusses the grandfather of all neutrino problems, the solar neutrino deficit. Oscillations seem the likely solution, but we need more solar data from Super-K, and most importantly data from the now operating Sudbury Neutrino Observatory in Canada, and two other detectors under construction, KamLAND and Borexino in Italy.

A most peculiar result came from the Liquid Scintillator Neutrino Detector (LSND) in New Mexico in 1990, in which a few events were detected that appeared to be attributable to muon neutrinos oscillating into electron neutrinos. These results were from a stopping proton beam, and thus at quite low energies (30 MeV) and small distances (30 m), and they involved only a tiny fraction of the through-going neutrino flux. Another experiment with somewhat overlapping regions of sensitivity, KARMEN in England, has not found any supporting evidence but has not ruled out the LSND results. If correct, the LSND result would have tremendous implications. No one has been able to make a simple model incorporating oscillations from atmospheric neutrinos, solar neutrinos, and the LSND results. If the LSND group is correct, we will need more neutrino types or some other dramatic physics.

WHERE DO WE GO FROM HERE?

Ever since Wolfgang Pauli's proposal for the neutrino's existence it has been known that neutrino masses cannot be very large. Direct attempts at measuring the masses have only given us an upper bound of about 3 eV for electron neutrinos (less than one hundred thousandth of the electron mass), and somewhat poorer limits on the others (which are even harder to measure). Cosmology reinforces this by telling us that since neutrinos in staggering numbers are left over from the Big Bang—about 2 billion for every proton—the sum of the masses of each of the six neutrino types (electron, muon and tau, neutrinos and anti-neutrinos) taken together cannot exceed about 12 eV or else the gravitational effect would be such that the Universe would already have collapsed back upon itself. On the other hand, since the number of neutrinos left over from the Big Bang must be about the same as the number of photons measured in the cosmic background radiation (as seen in the marvelous COBE results of a few years ago), and since we also know roughly how much matter there is in all the stars we can see, we can then calculate that the total mass of neutrinos in the Universe is approximately as much as or more than the total mass of all the stars one sees! Although it appears that neutrinos with mass cannot be the long-sought non-baryonic dark matter, they will certainly play an important role in such astrophysical questions as the origin of the excess of matter over antimatter and generation of the heavy elements in supernovae explosions.

Until recently there has been no widely accepted evidence to suggest that neutrinos have mass. As a result, the present Standard Model of elementary particle physics has assumed that the masses of its constituent neutrinos were precisely zero. But as we have described here, the atmospheric neutrino evidence of the last year suggests that at least one kind of neutrino has mass, of the order of 0.05–0.07 eV at minimum. If we further assume that neutrino oscillations are the probable solution to the solar neutrino problem as well, then this would demand that at least two kinds of neutrinos have mass. Probably all three kinds possess some mass. There is a huge theoretical difference between zero mass and some mass, even if it is very small. One of the central problems in particle physics is illustrated in the figure on the previous page, where one sees that the charged fermion masses all cluster at roughly the same distance (on a log plot) above the neutrino masses as they are below the anticipated scale for the unification of all the forces. The challenge to model builders is to try to account for this huge scale jump. A second problem is to account for why the neutrinos are so much more mixed than the quarks—certainly not the simplest expectation.

The future for neutrino studies seems bright, with new experiments building and more being proposed. One of the more interesting prospects is intense pure beams from muon factories. After clarification of the neutrino-mixing situation in the next few years, the medium range push seems to be clearly towards looking for CP violations with neutrinos. Cosmic experiments can explore in other directions and to the highest energies. Measuring absolute masses and directly observing the Big Bang relic neutrinos remain unsolved future challenges.

In summary, we now have evidence for a whole new sector of interesting particle behavior, with far-reaching implications for particle physics and cosmology. It seems fitting that the experimental results described here came from instruments that were originally intended to search for proton decay. While the physics may seem very different, there is a deep relationship here that may help to point the way toward a grand unified theory.

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.

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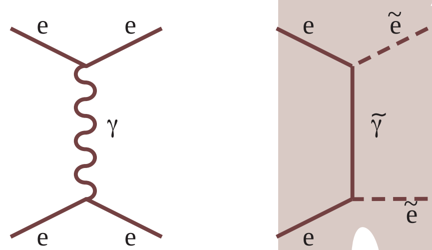
Particles that obey this rule are called fermions. There is another type of particle, a boson, that obeys the opposite rule, preferring to share the same quantum state. The most familiar boson is the photon, and lasers are devices in which many photons are in the same state. One of the early triumphs 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.

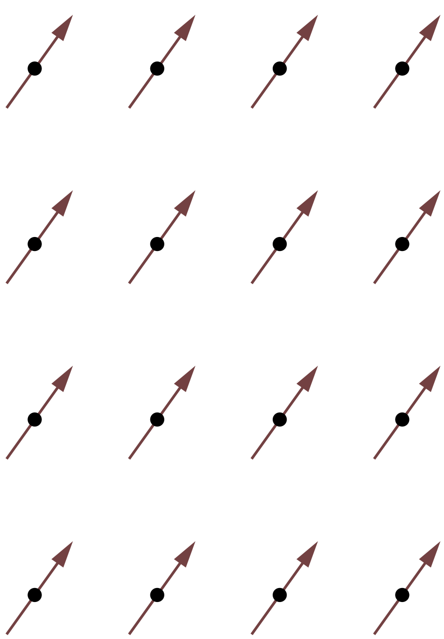
As an example of this new possible symmetry, one can write a generalization of, say, quantum electrodynamics (QED) which is supersymmetric. In the familiar version of QED, one has electrons, positrons, and photons. In a supersymmetric version, one would have, in addition to the electron and photon, a 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)?

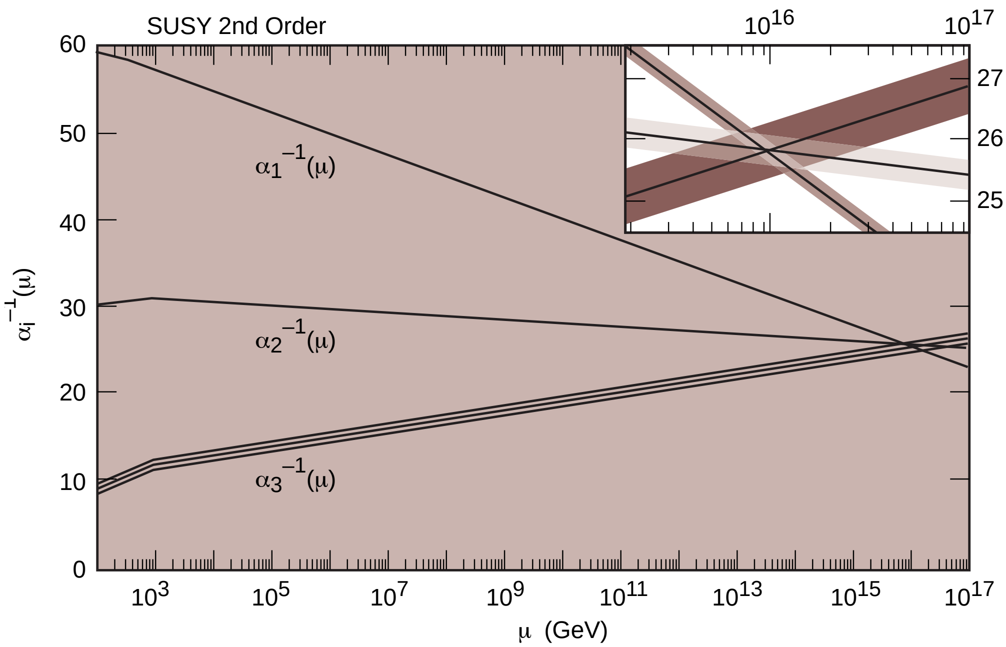
One argument is related to something known as the hierarchy problem. It was first posed by Paul Dirac as the more colorful—and meaningful—"problem of the large numbers." Because mass, in special relativity, is equivalent to energy, we can equally well speak of mass or energy scales. Max Planck, when 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



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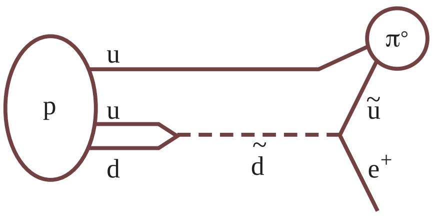
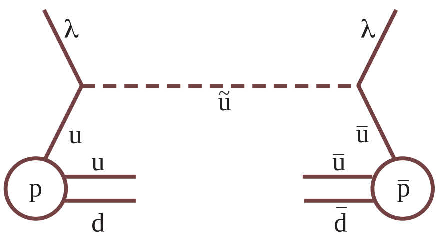


A proton decays to a π^0 and positron.



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.