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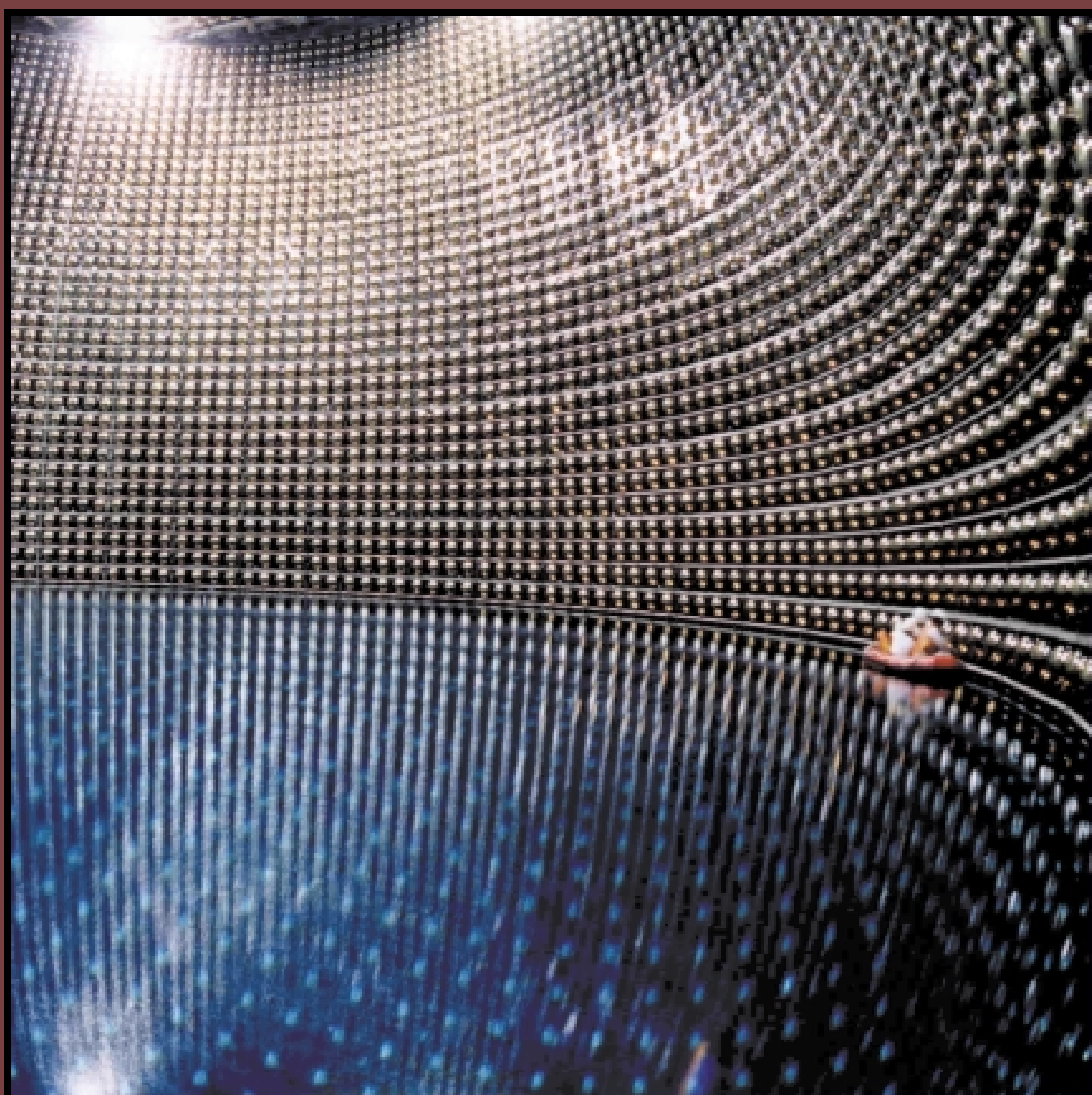

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

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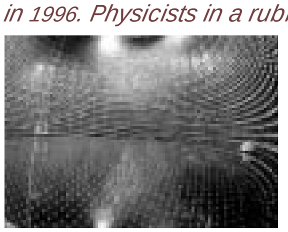

Cover: The Super-Kamiokande detector during filling in 1996. Physicists in a rubber raft are polishing the 20-inch photomultipliers as the water rises slowly. See John Learned's article on page 8. (Courtesy ICRR, University of Tokyo)

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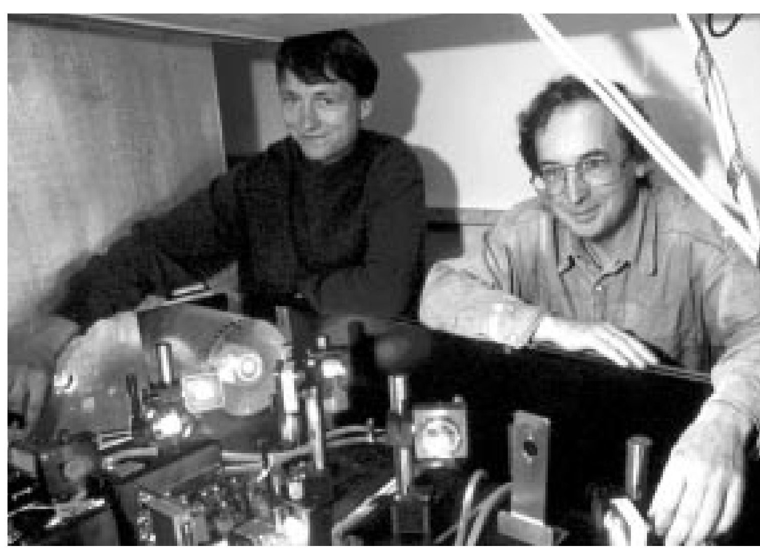

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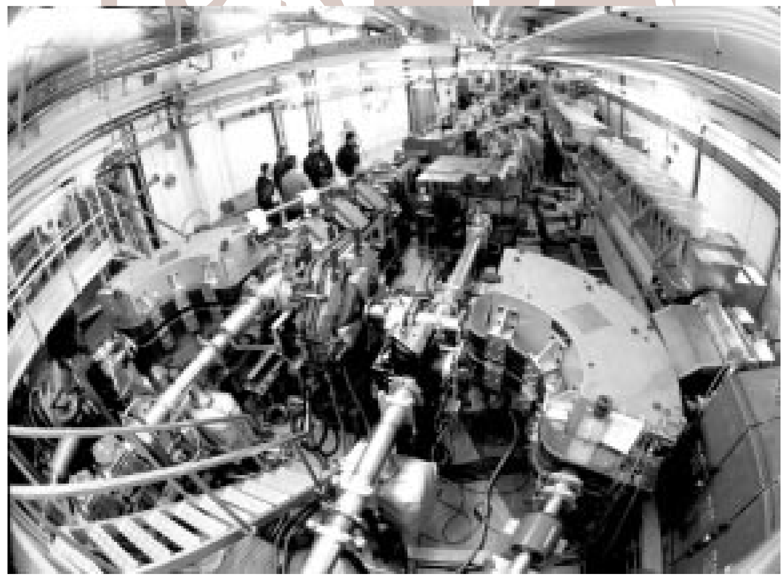

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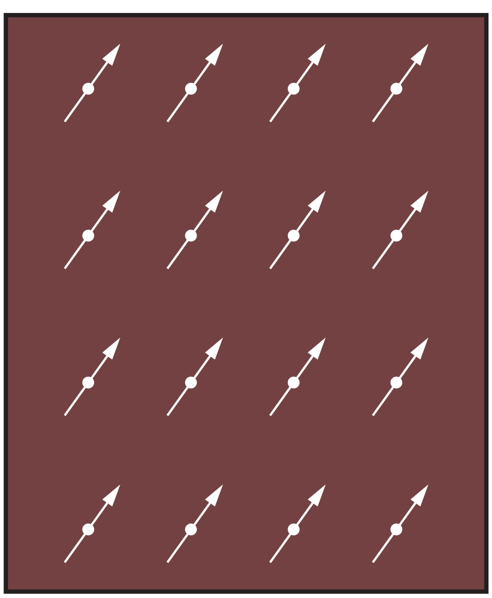
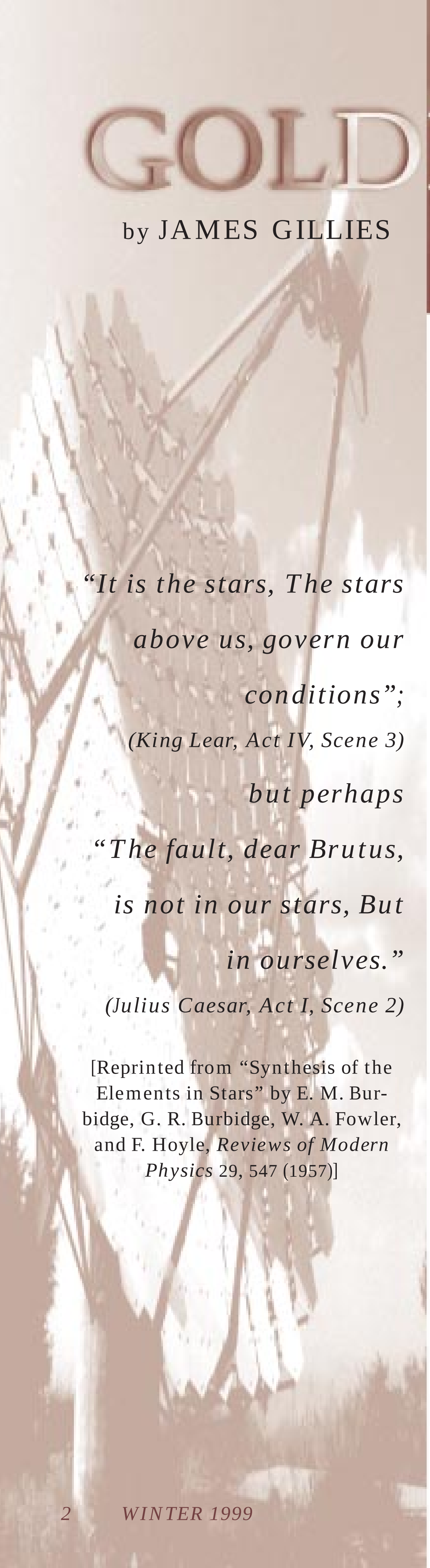




GOLDEN STARDUST

by JAMES GILLIES

"It is the stars, The stars above us, govern our conditions";

(King Lear, Act IV, Scene 3)

but perhaps "The fault, dear Brutus, is not in our stars, But in ourselves."

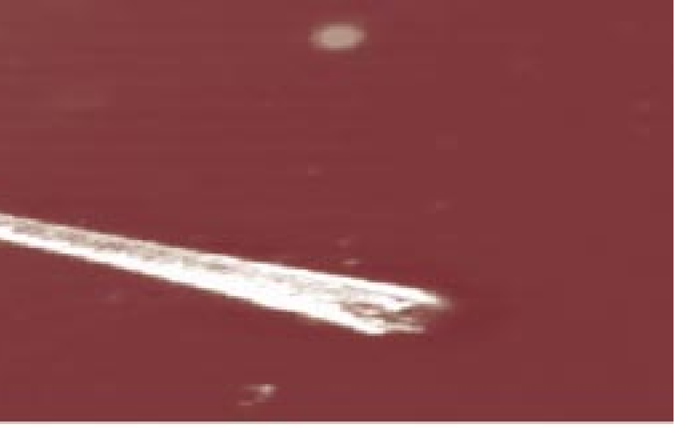
(Julius Caesar, Act I, Scene 2)

[Reprinted from "Synthesis of the Elements in Stars" by E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, *Reviews of Modern Physics* 29, 547 (1957)]

WHERE DO GOLD earrings come from? A simple answer is the local jewelry shop, but if you really want to know in depth, you'll have to dig a lot further. Gold is, quite literally, stardust. About half of it is forged in stars that burn normally, while the rest comes from large stars at the ends of their lives—in the cataclysmic explosions called supernovae. That much we know. But exactly how gold and all other elements heavier than iron are formed is still unclear. A new series of experiments at the ISOLDE facility at the European Laboratory for Particle Physics, CERN, in Geneva aims to find out.

The history of the elements is as old as the Universe itself. In the beginning, at the Big Bang, only the very lightest elements—hydrogen, helium, and a little lithium—were formed. Since then, so little heavier material has been created that even today hydrogen and helium make up over 99 percent of all the matter in the Universe. Everything else amounts to just a tiny fraction of 1 percent.

After the Big Bang, a billion years passed before any heavier elements appeared. They had to wait until the formation of stars, when gravity squeezed the light elements so tightly that they fused, igniting the stellar furnaces that forge heavier elements from lighter ones. In the normally burning part of their lives, these stars build elements as heavy as iron, producing energy from fusion as they do so. But then the process stops, because anything heavier than iron takes more energy to make than fusion gives out. That doesn't mean such elements can't be made in stars—the fusion process just uses some of the energy released by light-element fusion—



but the Universe simply hasn't been around long enough for all the heavy elements we observe to have been produced that way. Another process must be at work.

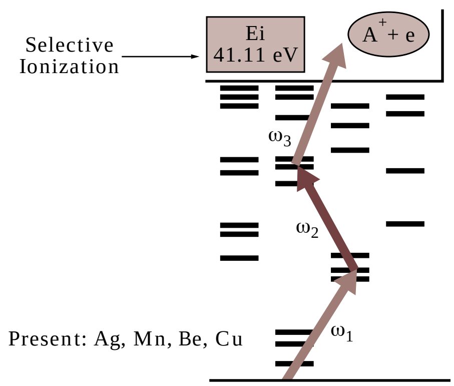
In 1957 the husband and wife team of Margaret and Geoffrey Burbidge working with Willy Fowler and the maverick British astronomer Fred Hoyle figured out what it could be. They published a paper which has since become legendary in the field of theoretical astrophysics and is known to aficionados simply as B2FH. In it, the Burbidges, Fowler, and Hoyle show how neutrons could provide the route to the heavier elements. B2FH describes the so-called s- and r-processes through which slow neutron absorption in stars could generate about half the present abundance of heavier-than-iron elements, with rapid neutron absorption, thought to occur in supernovae, making up the balance.

Left to right, Margaret and Geoffrey Burbidge, William Fowler, and Fred Hoyle, authors of the famous 1957 paper, "Synthesis of Elements in Stars." (Courtesy Astronomical Society of the Pacific)

The reason why neutrons can take over where fusion leaves off is that they are uncharged. There is no electrical repulsion resisting their entry into nuclei, and they can slip in more-or-less unnoticed. But only up to a point. When a nucleus becomes too neutron-rich it also becomes unstable and decays—nuclei tend to rearrange themselves into more energy-efficient configurations. Beta-decay turns a neutron into a proton, throwing out an electron in the process. The result is a nucleus with the same total number of constituent particles, but with one more proton and one fewer neutron.

In normally burning stars neutrons are released when helium nuclei fuse with other elements. There are relatively few of them around, and the probability that a nucleus will encounter one is consequently small. That's why B2FH named the neutron-capture process in stars the slow, or s-process: heavier-than-iron elements are built up slowly. What happens is that the neutron-capture chain marches steadily through the stable neutron-rich versions of an element until it reaches an unstable one. That nucleus then decays before it has a chance to absorb another neutron and the march towards heavier elements resumes in the element with one more proton.

Right, electrons orbit nuclei at well-defined energies which are unique to each element. The laser ion source (below) works by firing three laser pulses at a cloud of atoms in quick succession. The pulses are tuned so that the first lifts an electron from one orbit to another, the second lifts it again, and the third knocks it out completely. The combination of pulses is unique to the element required. Below, Michine Viatcheslav and Ulli Köster adjust the light bench for CERN's laser ion source.



The s-process is responsible for a lot of heavy elements, but it can't account for them all. There are many stable heavy elements which are highly neutron rich. To reach them involves passing through unstable isotopes on the way. That means that neutrons have to be so abundant that an unstable nucleus can absorb several before it gets a chance to decay, and that is where the rapid r-process comes in. R-process element generation happens in places where the neutron density is staggering—the sort of places, in fact, which are only found in certain stars when they reach the ends of their lives in the most violent explosions known in the Universe—supernovae.

Most stars finish their careers in unspectacular fashion, retiring peacefully from energy production before slowly fading away into darkness. Our own Sun is one of these. It has enough fuel to burn its way up to carbon, and in a few billion years from now it will end its days as a slowly cooling lump of ash. Heavier stars don't all go so quietly, and some of them, the James Deans of the cosmos, instead go out in spectacular style. A supernovae happens when a heavy star has completely burned up its insides. With its fuel source exhausted, there is nothing left to support it and the star collapses in on itself. Protons in the star resist the collapse because of the repulsive electric force between them, but the gravitational pull of all the matter in the dead star is stronger and the charge is literally squeezed out of the protons in the form of positive electrons (positrons), turning them into neutrons. The star's collapse generates a shock-wave traveling outwards which blows the outer layers of the star out into space in an explosion accompanied by copious neutrons. In this extremely neutron-rich environment, an unstable nucleus has a good chance of catching another neutron before it decays. Rapid neutron capture ensues, generating a wide range of unstable heavy isotopes. When this explosive burning is over, these unstable isotopes cascade through a chain of beta-decays ending up as stable neutron-rich isotopes. This all takes place in just a few seconds, and when it is over, the newly formed elements are sprayed out into the Universe where eventually gravity, that ultimate cosmic master of ceremonies, marshals them into new stars and planets.

IT HAS TAKEN 40 years for terrestrial experiments to catch up with B2FH. That's not too surprising, since stars and supernovae are not the easiest things to bring into the laboratory. Nevertheless, the paper's ability to predict the observed abundances of heavy elements has made it so widely accepted that it has become the stuff of textbook astrophysics. In 1997, new developments at CERN's veteran unstable-particle beam facility, ISOLDE, allowed physicists to put B2FH to the laboratory test for the first time. They began to measure the binding energies and half-lives of some of the unstable elements vital to the r-process.

ISOLDE can produce a wide range of unstable isotopes covering most of the elements. In 1997 it was complemented by a device, called the laser ion-source, which allows extremely pure beams to be created. The laser ion-source works like a key in a lock by selecting just the element of interest. At ISOLDE a beam of protons strikes a target. The impact causes a range of unstable atoms to be created. These are evaporated from the target and allowed to find their way into a small tube. Atoms are electrically neutral, and can not be transported to experiments using electric fields and magnets. First they must be ionized, losing an electron so they become electrically charged. This is where the laser ion source comes in. It works by firing three precisely tuned laser pulses into the tube in quick succession. The first pulse has just the right energy to lift an electron into a higher orbit around the nucleus; the second lifts it again; and the third knocks it out completely. The combination of laser energies is unique to the ion required—just as a key fits only one lock. Once ionized, an electric field pulls the atoms out of the tube, sending an ion beam on its way to a waiting experiment.

One of the first experiments to use the laser ion source in October 1997 was code named IS-333. It studied the properties of highly neutron-rich silver isotopes. For the first time, silver-129, an isotope with 22 more neutrons than the most common stable isotope of silver, was identified and its half-life measured. Silver-129 plays an important role in the r-process because it builds up in higher quantities than many other elements.

The half-life of silver-129 pins down one link in the supernova event-building chain, but it is nevertheless just one of myriad parameters in element generation calculations. Since that first experiment, IS-333 and successor experiments have

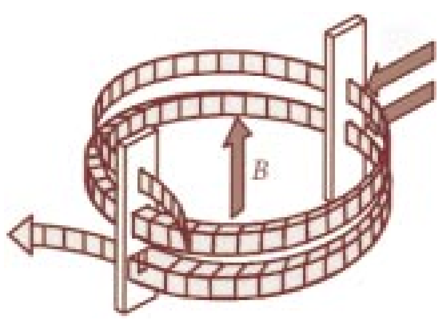
What Makes an Element an Element?

AN ATOM IS MADE UP of three kinds of particles: protons, neutrons, and electrons. Positively charged protons and electrically neutral neutrons compose the nucleus while negatively charged electrons orbit the outside and balance the charge of the protons in the nucleus.

The defining feature of an element is how many protons its nucleus contains. This is because the number of protons equals the number of electrons, and it is the electrons that determine an element's chemical properties.

Several versions of the same element can exist; these are called isotopes, and they differ in the number of neutrons in the nucleus. Similarly, different elements can have the same total number of protons and neutrons in the nucleus, but a different ratio. These are called isobars.

The nuclei important to element building in supernovae are unstable. They tend to decay rapidly by emitting electrons in a process known as beta decay. This is a random process and is characterized by a half-life—if you start off with a certain number of unstable nuclei, then after one half-life, there will be half as many left.



Top, David Lunney sets up the MISTRAL apparatus at the ISOLDE facility. Above, an isotope beam enters at the top and follows a spiraling path through the apparatus. Only isotopes of a particular mass escape through the exit slit at the bottom of the apparatus.

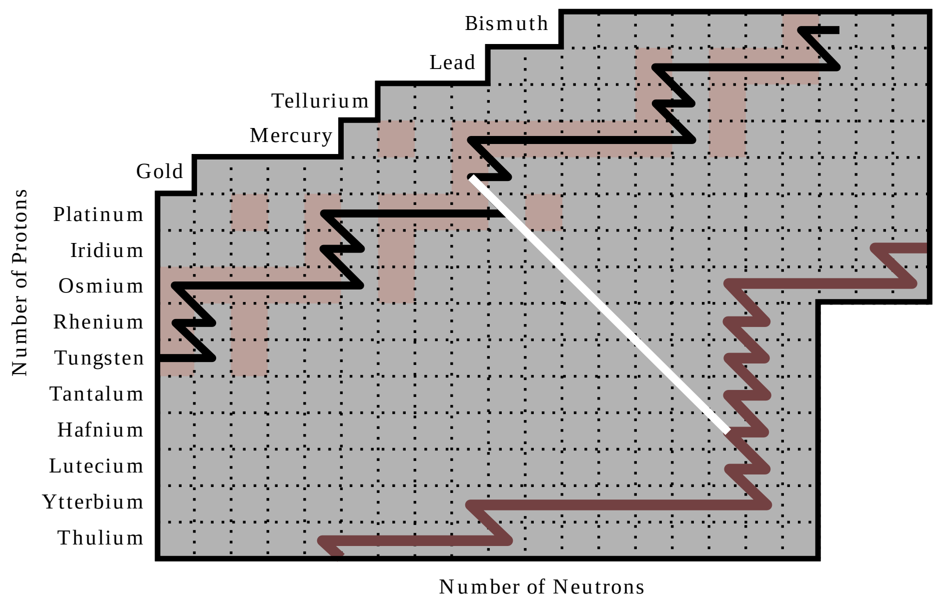
added a few more links in the form of the half lives of isotopes of cadmium, copper, and manganese which are also on the r-process path.

HALF-LIVES of unstable elements are just one important ingredient in understanding supernovae. They determine how long an atom will retain its identity, and so give an indication of how likely it is that the atom will absorb another neutron before it decays. But there's another vital ingredient too, and that is the subject of another ISOLDE experiment called MISTRAL. The goal of this experiment is to measure the masses of these unstable isotopes.

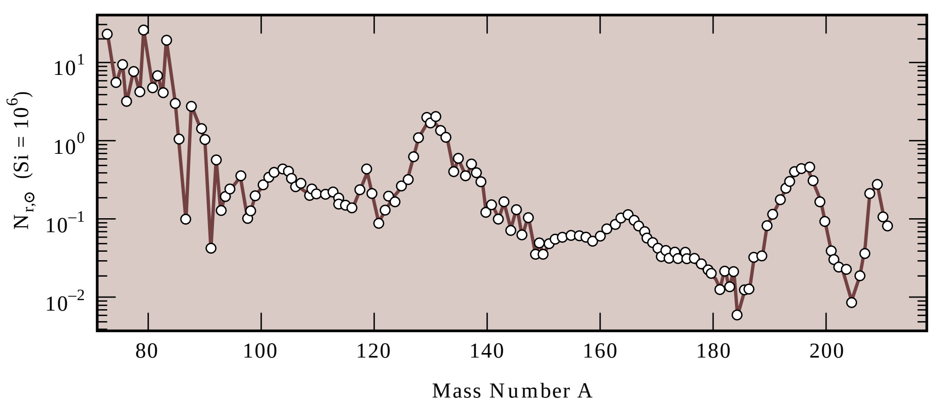
The mass of a nucleus is made up of two parts, the individual masses of the protons and neutrons within it, and the so-called binding energy which holds them all together. Iron has the highest binding energy per nucleon of any nucleus, which is what makes it so stable. In the highly neutron-rich nuclei important in supernova element-building chains, the energy binding the excess neutrons into the nucleus is small. And since it is this neutron binding energy which determines the energy needed to capture another neutron, it must be measured if scientists are to understand these processes fully. The MISTRAL apparatus has the unique capacity to measure the masses of the particularly short-lived isotopes involved in supernova element-building.

MISTRAL works by bending a beam of incoming ions in a spiraling path using a uniform magnetic field. This is done for stable ions of well known mass as well as for the unstable ions whose mass is to be measured. Then by comparing the time it takes for an unstable ion to complete an orbit with that of a known reference ion, the mass can be measured. Ions are injected into MISTRAL and vertically deflected so that they make two spiraling turns inside a magnetic field. An applied oscillating voltage modifies the trajectories of the ions such that only those with a particular mass escape from the apparatus through a narrow slit. By varying the applied voltage and counting the transmitted particles, precise mass measurements are made. The speed of this process enables the measurement of very short-lived isotopes, and the resolution of the apparatus is so good that it can cleanly separate the signals arising from isotopes of different elements having the same number of protons and neutrons but in different proportions. The tiny

On this plot of heavy elements, stable isotopes are marked by colored squares. The s-process path is shown by the black line and the r-process path by the dark brown line. On the s-process path, isotopes absorb neutrons slowly. When an unstable isotope is reached, it decays by emitting an electron, and the path takes a diagonal step up to the next element. On the r-process path which happens in supernovae, neutrons are rapidly consumed. When the process stops and the supernova blasts isotopes into space, unstable elements decay through a cascade of electron emission until they reach stability. One example is shown by the white diagonal line (the r-process path to gold).



The abundances of isotopes produced by the r-process. The mass number is just the total number of protons and neutrons in the nucleus. Some elements build up in greater numbers than others, like those in the bump around mass number 130. This is why studying unstable isotopes, such as silver-129, in the same mass range is particularly important.



difference in the mass of such isotopes, isobars as they are known, arises from binding energy determined by the configuration of the nucleus.

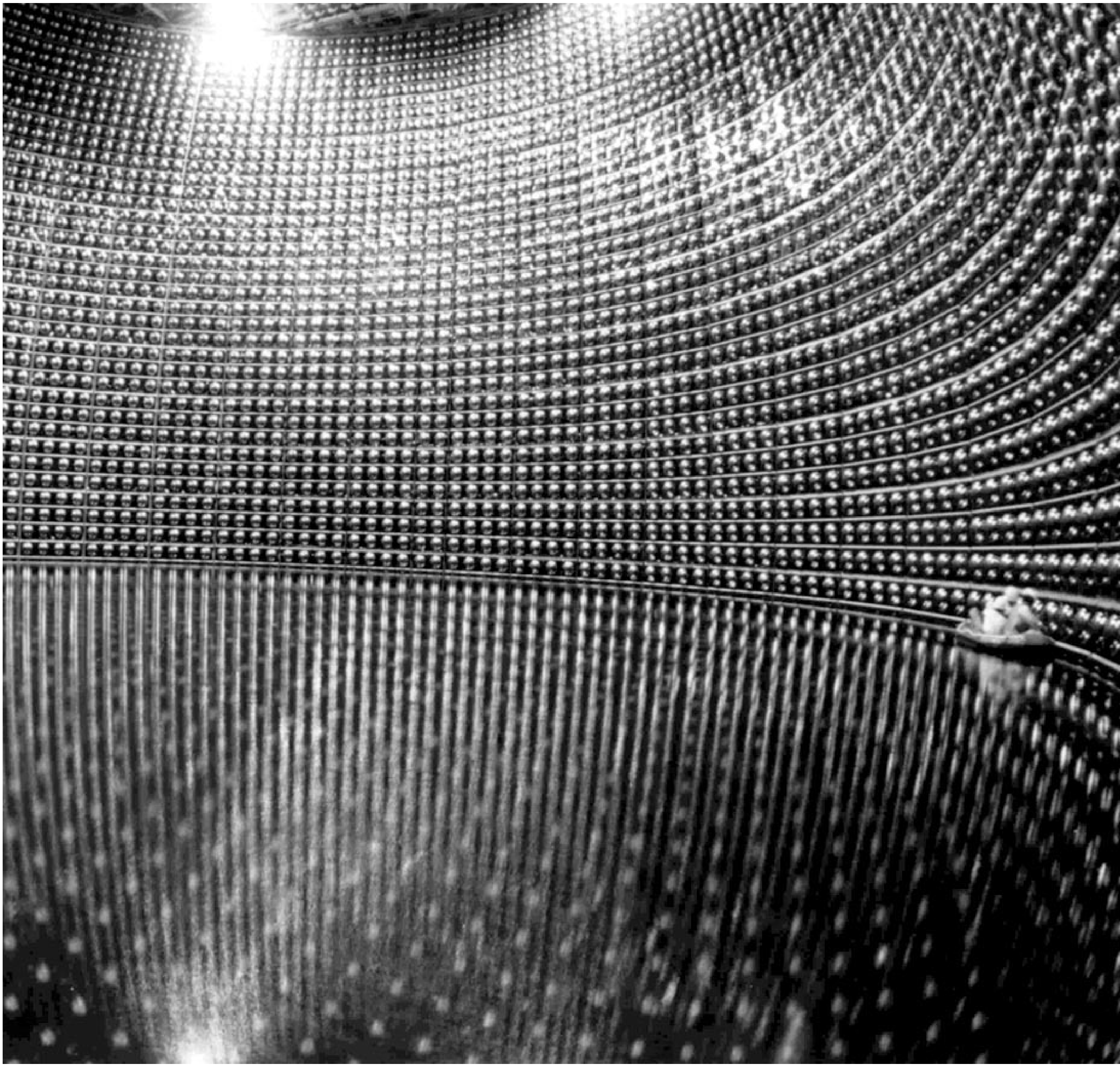
Once the mass has been measured, the binding energy can be calculated by remembering Einstein's lesson that $E = mc^2$, energy and mass are interchangeable. The combined mass of all the protons and neutrons in the nucleus can be added up and compared with the measured mass, the difference between the two is the binding energy.

MISTRAL's first measurements were made in November 1997 and continued through 1998. So far, several masses have been measured, some with extremely short half-lives. Further measurements which started in November 1998 will soon begin to feed into the recipes proposed in B2FH. So far, the Burbidges, Fowler, and Hoyle seem to have got it right.

The CERN results bear out their predictions and are starting to fill in the gaps between the forging of iron in stars, and the gold baubles to be found in the jeweler's shop around the corner.

Neutrinos Have Ma

by JOHN G. LEARNED



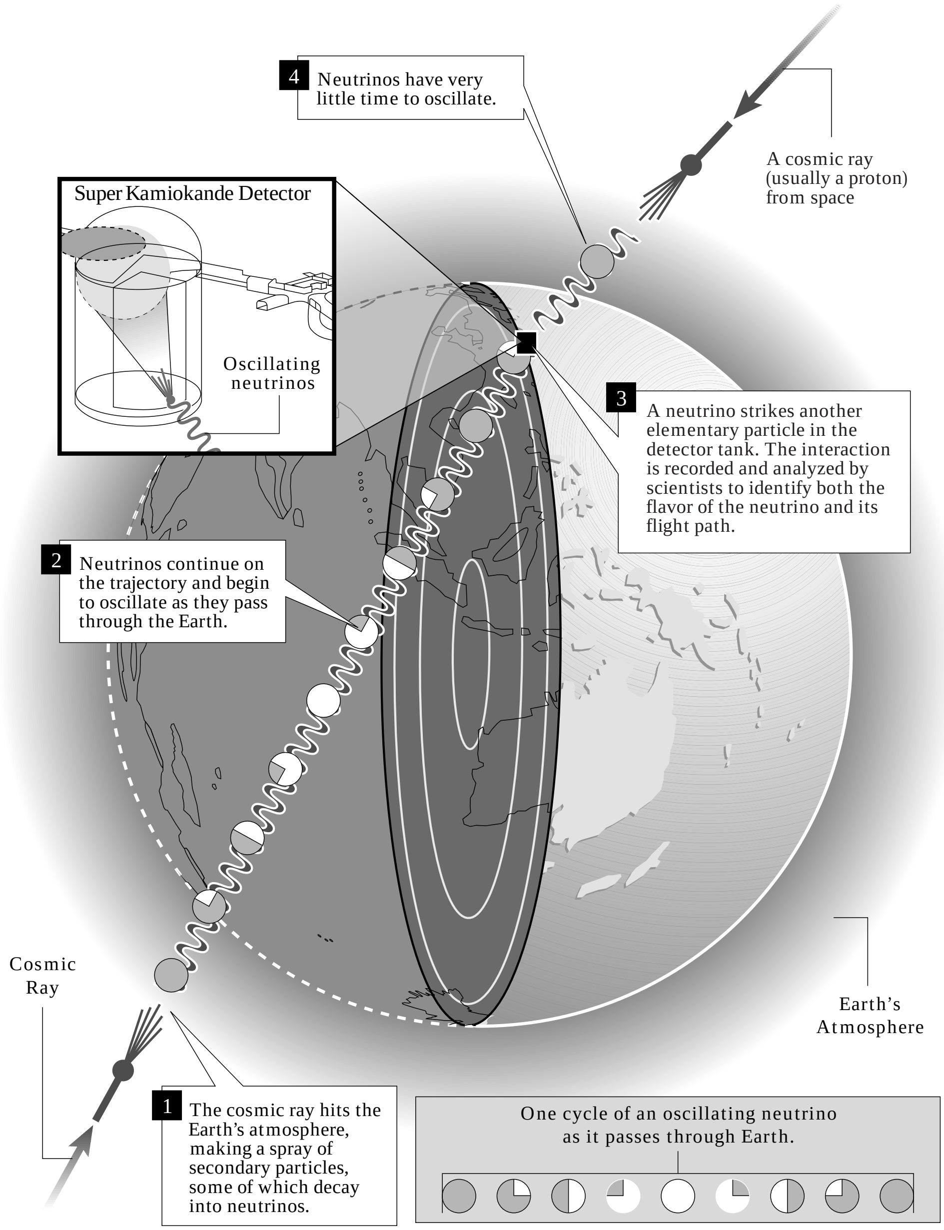
ss!

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?

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.



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.

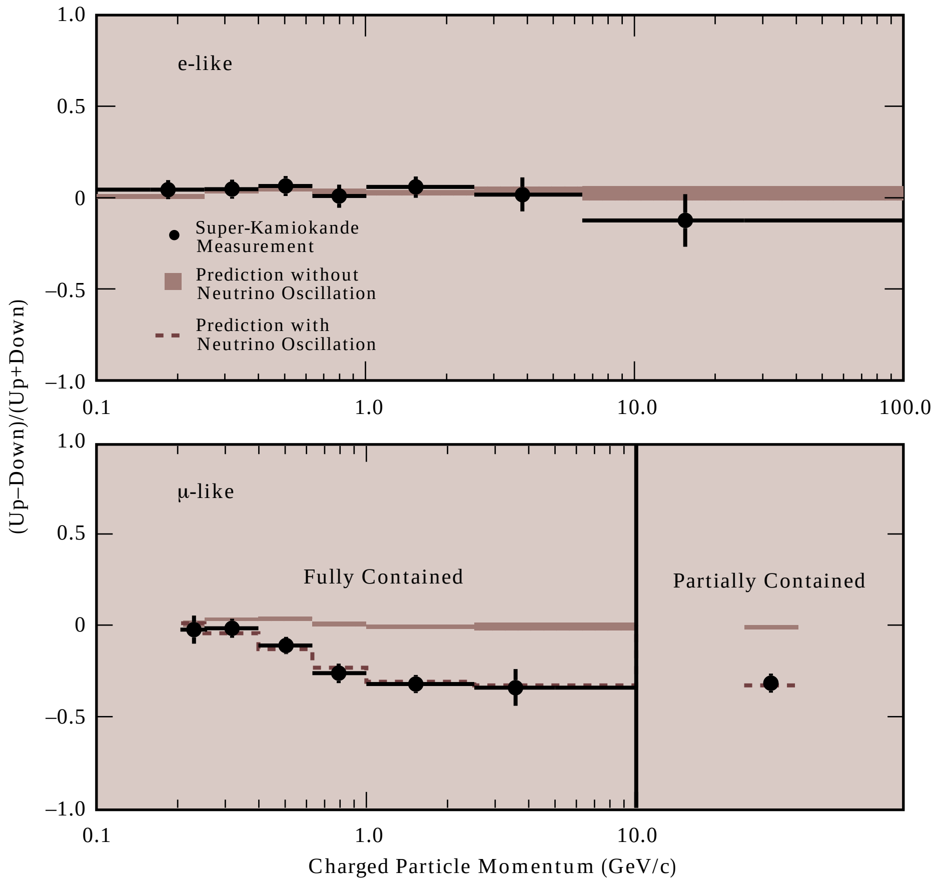
Not long thereafter the Kamioka collaboration came on line with its smaller but deeper and more sensitive detector, Kamiokande, located in Japan. The early work at Kamiokande produced results similar to those at IMB, and both groups then went on to develop more sophisticated techniques for distinguishing 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.

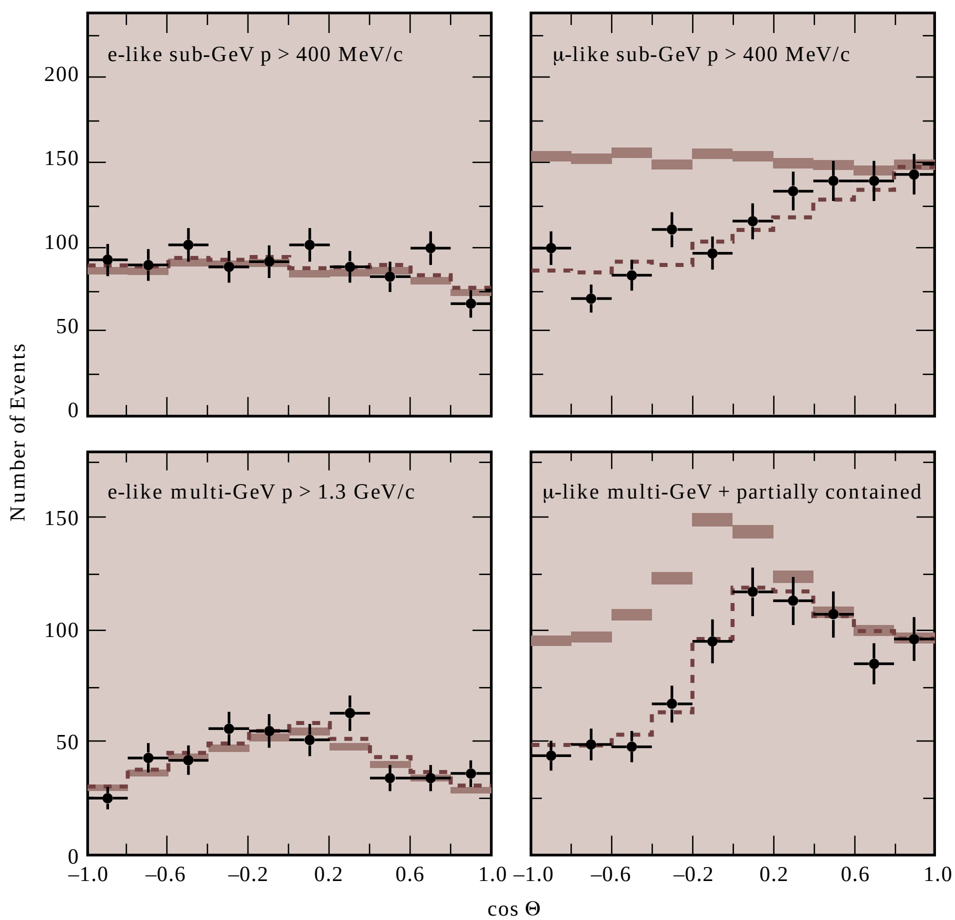
In early June 1998 we announced the results from analysis of the first two years of data accumulated in Super-K. The updated results as of



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.

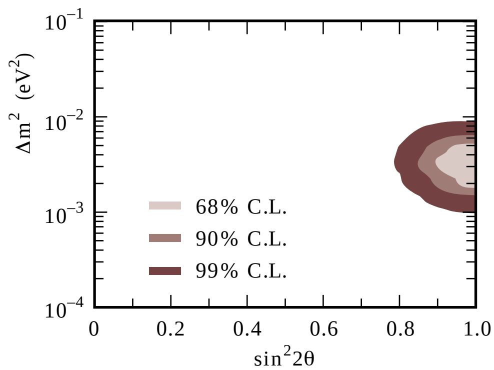
CORROBORATIVE EVIDENCE

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.

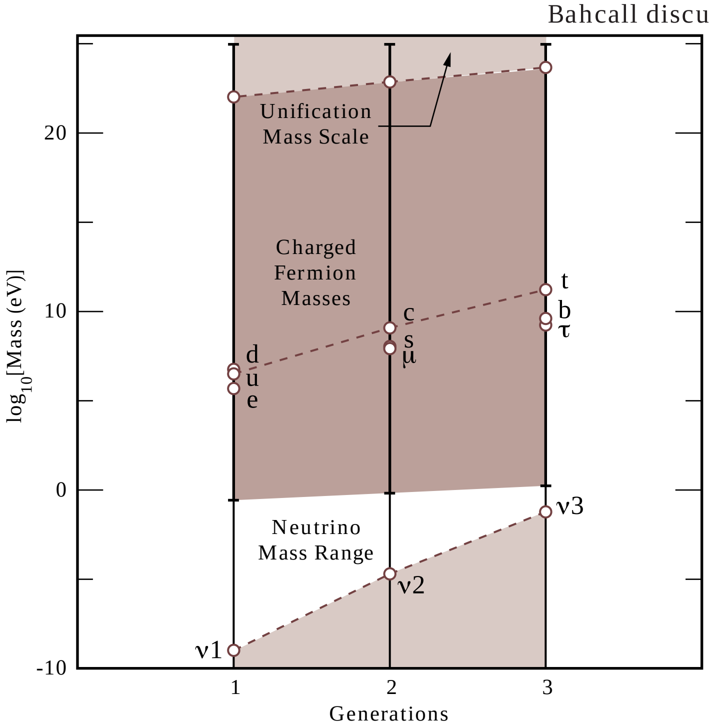
There is also supportive evidence for the Super-Kamiokande contained data from the through-going muons that originate from neutrinos of about 100 times higher energies; these events produce a useful consistency check even though they do not constrain the oscillation parameters as severely.

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

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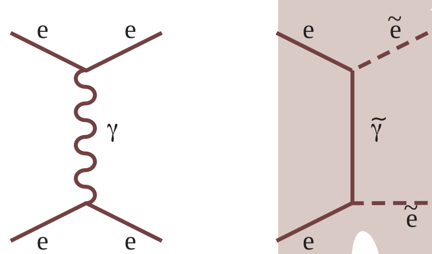
Particles that obey this rule are called fermions. There is another type of particle, a boson, that obeys the opposite rule, preferring to share the same quantum state. The most familiar boson is the photon, and lasers are devices in which many photons are in the same state. One of the early triumphs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

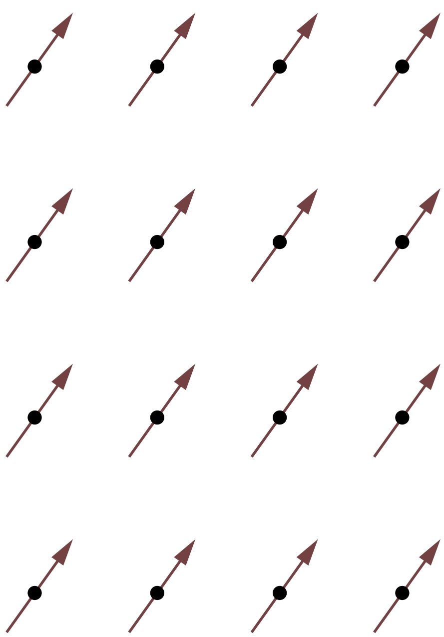
As an example of this new possible symmetry, one can write a generalization of, say, quantum electrodynamics (QED) which is supersymmetric. In the familiar version of QED, one has electrons, positrons, and photons. In a supersymmetric version, one would have, in addition to the electron and photon, a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

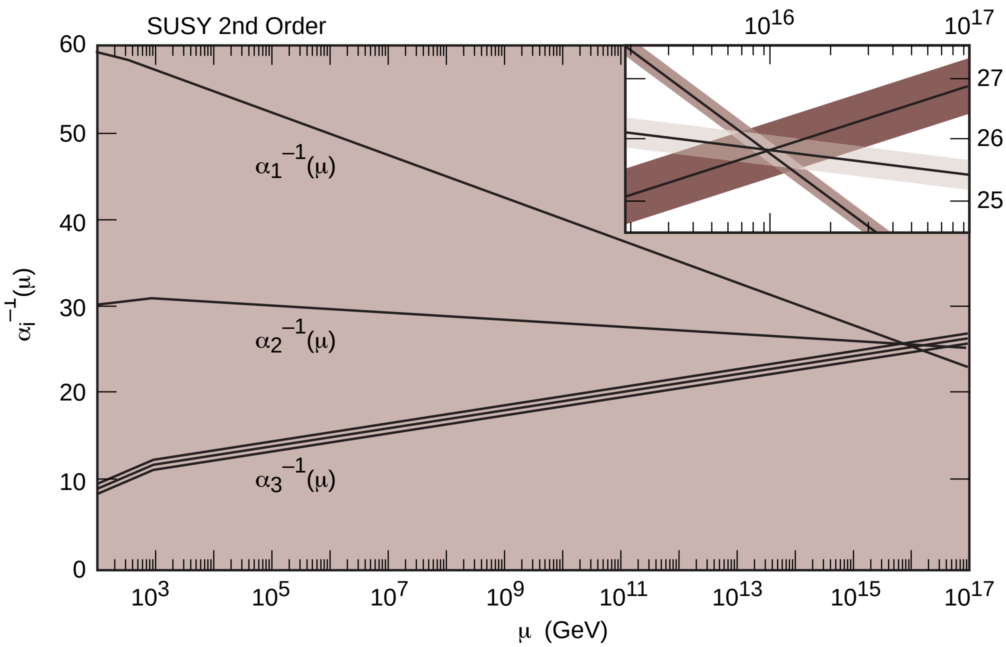
One argument is related to something known as the hierarchy problem. It was first posed by Paul Dirac as the more colorful—and meaningful—"problem of the large numbers." Because mass, in special relativity, is equivalent to energy, we can equally well speak of mass or energy scales. Max Planck, when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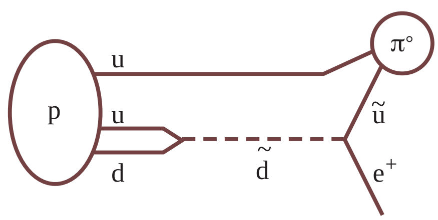
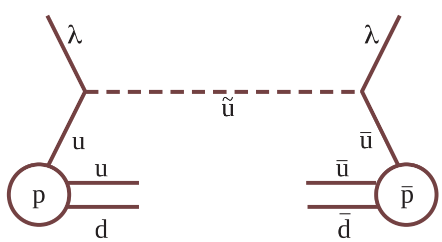


A proton decays to a π^0 and positron.



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.

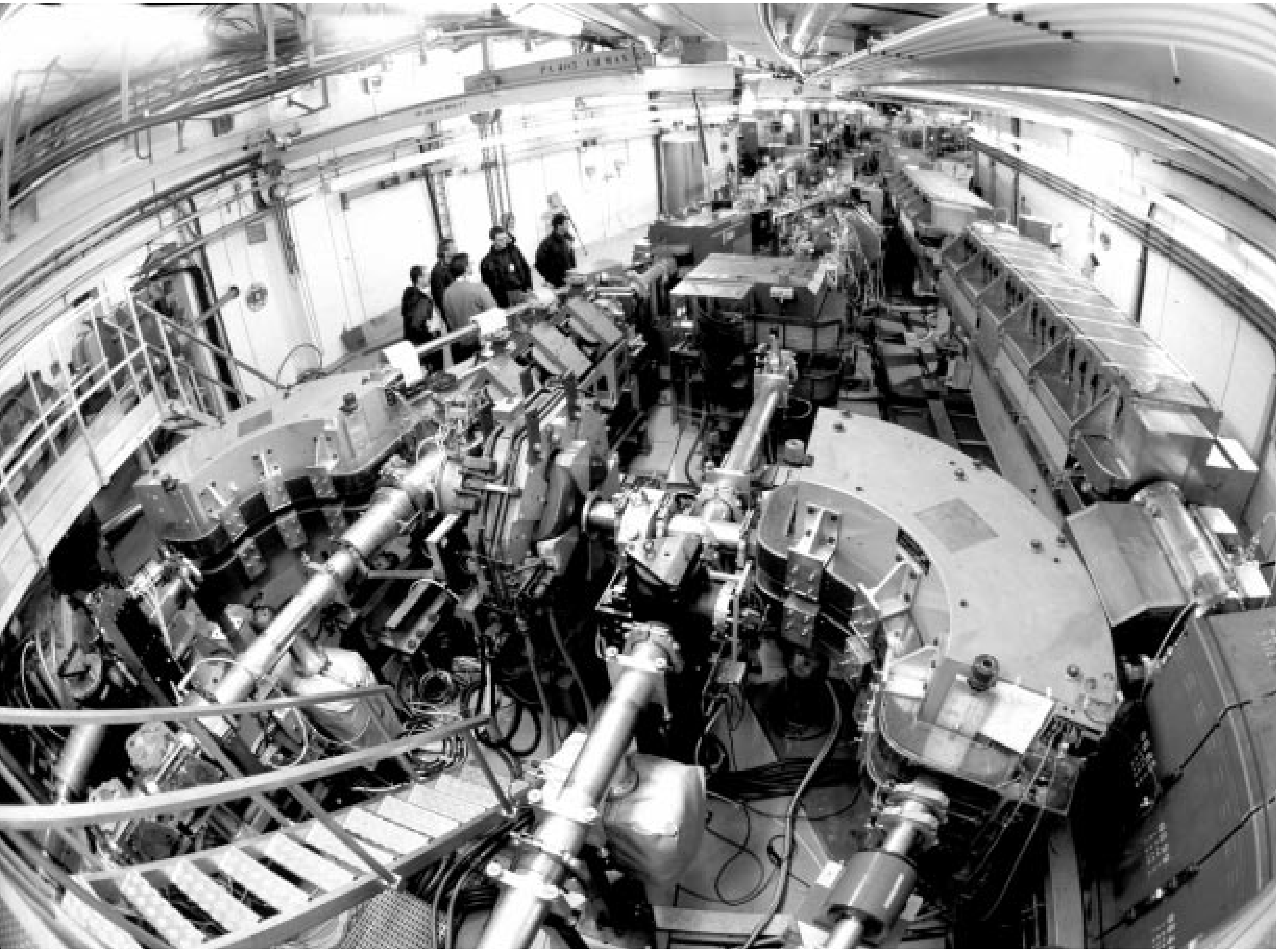
Suddenly we have entered a new era. In addition to the old problems of particle physics, such as measuring and understanding the quark mass parameters, we now have a whole new set of masses and mixings to understand—those of all of the new supersymmetric particles. Knowledge of some superparticle masses 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.

CERN's Low Energy Antiproton Ring

L·E·A·R

by GORDON FRASER



Beam transfer line ganglion at CERN. On the left are feeds from linacs towards the booster, and center, the antiproton ejection line from the PS proton synchrotron to LEAR. Across these is the bulky U-turn to steer linac particles directly towards LEAR. On the right is a section of the PS.

IN SHAKESPEARE'S TRAGEDY, King Lear falls victim to his own misjudgment and dies from grief after a series of Job-like misfortunes. Another LEAR, CERN's Low Energy Antiproton Ring, was also buffeted by the stormy waves of destiny. Coming in the wake of CERN's push for a high energy proton-antiproton collider, LEAR, a machine physicists' concert platform, eventually fell victim to an even larger scheme—the Large Hadron Collider.

Andy Warhol said that anyone can be famous for fifteen minutes. For LEAR, this fame came in January 1996, when newspapers and media all over the world carried the news that an experiment had synthesized the first atoms of chemical antimatter. But LEAR will also go down in science history as a stage which saw remarkable machine physics performances.

In the mid-1970s, antiprotons were just another item on a long menu of secondary beams. But the idea was taking root that new techniques using antiprotons could open up another route to physics. The demonstration of electron cooling, by Gersh Budker's team at Novosibirsk, and the invention of stochastic cooling, by Simon van der Meer at CERN, promised that high fluxes of antiprotons could be produced. In addition, the antiparticles would be free of contamination by other particles, and extremely "cold"—well collimated in momentum and energy. At the time, the first electron-positron colliders were making their mark on the world physics stage. Budker suggested doing annihilation physics with protons and antiprotons. But antiprotons are more difficult to produce than positrons, and to feed them into a collider needed additional control via cooling. With the demonstration of cooling, the door to proton-antiproton collider physics was unlocked. The key was turned by Carlo Rubbia, and at CERN a working group was established to look into the possibility of using the new SPS proton synchrotron as a proton-antiproton storage ring.

Still untouched by these collider ideas, Kurt Kilian, then at Heidelberg, was doing experiments using secondary beams of antiprotons from CERN's 11 GeV PS proton synchrotron. A mere five antiprotons per PS cycle were available at low momentum, but the special conditions of particle-antiparticle annihilation are always a fruitful source of physics. Kilian was impressed when his machine physics colleague Dieter Möhl at the PS told him that in principle the new cooling techniques could open up the antiproton sluice gates and provide a million antiprotons per second.

Rubbia and his colleagues were looking at how to produce antiprotons and accelerate them to high energies. For this, one initial idea was to use a small ring to decelerate the antiprotons so that electron cooling could be applied. This scheme was subsequently abandoned in favor of stochastic cooling at higher energies, but the possibility of decelerating antiprotons had been discussed.

Looking at the dynamics of antiproton production, Kilian soon realized that if secondary antiprotons produced by the PS could be decelerated, several orders of magnitude more antiparticles could be made available than via a standard secondary beam.

The 1977 International Accelerator Conference at Serpukhov heard a paper by Kilian, Möhl, and Ugo Gastaldi of CERN for the deceleration of antiprotons for physics experiments at a low energy antiproton factory. From the outset, the idea was very much overshadowed by the imaginative schemes pushed by Rubbia for high energy proton-antiproton reactions. Rubbia's aim was to use the proton-antiproton route to obtain sufficient energy to synthesize the long-sought *W* and *Z* carriers.

In contrast, the objective of the low energy scheme was to explore in depth the annihilation process, where many kinds of particles could be created. This would greatly extend the exploration of hadron spectroscopy. In addition, low energy antiprotons on tap would open up the study of antiprotonic atoms and even the possibility of synthesizing chemical antimatter, atoms containing nuclear antiprotons and orbital positrons.

While the big push at CERN continued for a high energy proton-antiproton collider, the low energy splinter group was joined by Pierro Dalpiaz, then at Ferrara, and many other enthusiastic antiproton physicists. The machine side was joined by Pierre Lefevre (later to become project and eventually group leader) and Werner Hardt of CERN.

To extract particles slowly from a circulating beam, the classic method is to excite a beam resonance and use a magnet to remove a thick layer of beam. With expensive antiprotons, such brutal treatment would be wasteful. However a new technique of ultra slow extraction developed at CERN enabled particles to be delicately scraped off the surface of the stored antiproton beam. This made it feasible to propose an additional ring, grafted onto the low energy side of the new CERN antiproton complex.

This ring was initially called by the unimaginative name of APR (Anti-Proton Ring), before Helmut Poth of Karlsruhe suggested the LEAR low energy antiproton ring acronym. The scheme had the strong backing of CERN's PS Division under Gordon Munday and Gunther Plass, and the enthusiastic support of a wide physics community.

The project was finally approved in June 1980, two years after CERN's major high energy proton-antiproton scheme had been given the green light. By this time a substantial low energy antiproton physics program had begun to crystallize, leading to 16 experiments involving 240 physicists from 44 research centers.

CERN, however, was justifiably very protective of its high energy proton-antiproton scheme. LEAR was only approved subject to the conditions that it should not interfere with the PS commitment to the high energy antiproton scheme, that it could use only six percent of CERN's antiproton production, and that it should have overall "low priority."

It was a deprived childhood, but nevertheless introduced a completely new way of life for the low energy antiproton physics community. Very nice results emerged—meson spectroscopy, antiprotonic atoms, low energy annihilation, reaction mechanisms on protons and nuclei, and strangeness production.

It was also a lengthy childhood, extended by the drama of the last experiment at CERN's Intersecting Storage Rings (ISR) before this machine was closed in 1984. This study, which used a gas jet target, clamored for a stored beam of antiprotons in just one of the two ISR rings.

AT THE RINGSIDE

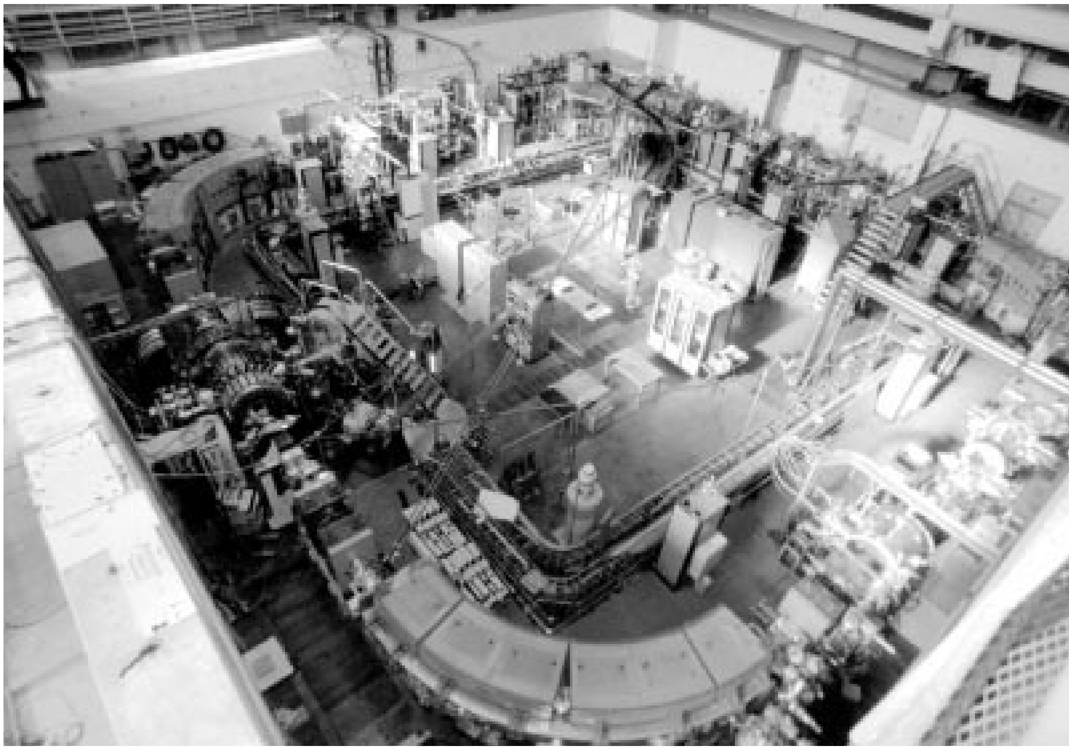
Before injection, LEAR's meager ration (typically 10^9 antiprotons) would be skimmed off from the Antiproton Accumulator once every 15 minutes or longer, and first be decelerated in the parent PS from 3.5 GeV/c to 600 MeV/c to benefit from phase space optimization. For this, the PS had to learn some new tricks, in addition to the repertoire needed to handle all CERN's different beams on complicated "supercycles."

Although LEAR's *R* stands for ring, it is in fact four 10-meter straight sections joined by 90 degree bends. It was built inside the existing South Hall of the PS in just 16 months.

Although a modest machine, LEAR had some interesting technical curiosities. Strong focusing proton rings have to face up to the problem of transition. When accelerated particles attain a certain energy, relativity effects come into play, and the radiofrequency accelerating field has to be adjusted to maintain the vital phase stability of the circulating particle bunches.

With conventional magnetic optics, LEAR's transition energy would have occurred right in the middle of its physics range. However, the design ensured that high momentum particles follow a shorter orbit rather than the larger one normally encountered. Transition was thereby totally sidestepped, a feature which has been adopted in the design of the proposed Japanese Hadron Facility.

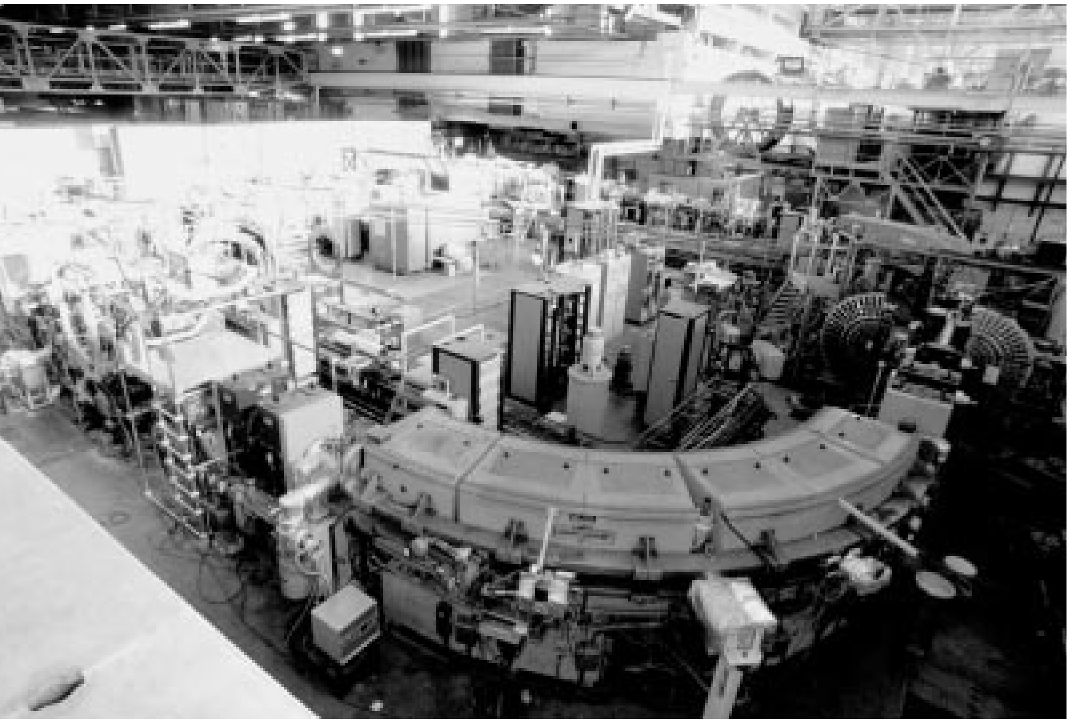
Having to contend for the crumbs of CERN's antiproton supply had a major influence on LEAR's design and operation. But there was not only bad news. With the PS warranting a new linac injector, LEAR inherited the old one and was thus able to extend its range of beams. LEAR was tested and later routinely set up for physics using expendable test particles (protons and negative hydrogen ions) and in principle could even store antiprotons and other particles at the same time, using colliding or overlapped co-rotating beams. However the linac was pointing the wrong way and this unexpected legacy required construction of a violent 210 degree U-turn to steer the linac particles towards LEAR.



CERN's LEAR low energy antiproton ring, the site of remarkable accelerator physics.

To shape LEAR's beams at injection and at higher energy required stochastic cooling. Assuring synchronization of the cooling signals over a range of energies called for special solutions, and this variable energy stochastic cooling became another LEAR trademark. Once cooled, the low energy beam was "frozen" by electron cooling. Taking the beam down to 100 MeV/c required just one minute, with intermediate cooling at 600 (stochastic), 300 and 200 MeV/c (electron cooling). LEAR was the first machine to use electron cooling as an integral part of its operations, using the electron cooler inherited from CERN's Initial Cooling Experiment and refurbished in collaboration with a group headed by Helmut Poth from KfK Karlsruhe.

LEAR was foreseen from the outset as providing antiprotons for a wide range of experiments. As well as the possibilities with co-rotating beams, the straight sections were designed to accommodate internal targets. The bending magnets at the corners of the ring were C-shaped so that electrically neutral states formed in experiments using internal targets in the straight sections would not be



LEAR was the first machine to use electron cooling as an integral part of its operation.

obstructed and could fly out. This was vital for the antihydrogen finale in 1995.

The machine design paid a lot of attention to internal targets; however, a large part of the experimental program used extracted beam with a network of beam lines and splitter magnets serving time-shared South Hall experiments.

After initial tests with protons in 1982, LEAR began providing antiproton beams to experiments in July 1983. However elsewhere in CERN's antiproton complex the UA1 and UA2 experiments studying high energy proton-antiproton annihilation were seeing their first *Z* particles and LEAR's experimental debut went relatively unnoticed.

MACHINE ACCOMPLISHMENTS

Having to live on a subsistence diet of antiprotons meant that LEAR had to learn how to make the most of its precious antiparticles. LEAR's resourceful machine specialists perfected a system of ultra slow extraction in which antiprotons were peeled off the rotating stack over several minutes. Just a single antiproton per turn could be shaved off, giving an extracted beam that resembled a slender antiproton chain stretching from the Earth to the Sun with a single antiparticle every 100 meters! The record was providing 30,000 antiprotons per second at 310 MeV/c to two separate experiments for 14 hours.

Ultra slow extraction required the development and perfection of resonance extraction with radiofrequency noise (really carefully orchestrated music) which drives particles very gently towards the resonance. Traditionally, extraction magnets chisel particles from a stored beam. However when the beam has to be ejected over a very long spill (several minutes), unavoidable ripple in the power supplies leads to an erratic extracted flux, with big spikes alternating with no particles at all, which is unacceptable for the experiments

With the objective of assuring quality beams, the scheme developed at LEAR instead carefully "diffuses" the beam against the resonance while the particles are still being accelerated. This gives a regular profile of the extracted flux over hours rather than seconds. Similar techniques are now proving invaluable for new machines to provide precision beams, such as those for cancer therapy.

NEW PHASE

In 1987, CERN's antiproton supply was augmented by the new Antiproton Collector ring and LEAR began a new phase of experiments with considerably boosted performance.

By this time, CERN's high energy proton-antiproton collider physics was nearing the end of its career, and LEAR was no longer the poor relation. In 1988, the first full year of operations using the new scheme, LEAR had six times more antiprotons than before. The antiproton supply gradually increased over the machine's lifetime, providing a total of 1.3×10^{14} antiprotons (0.2 nanograms).

In cost-conscious times, even masterpieces of physics have to be sacrificed on the altar of economy. At CERN, the Intersecting Storage Rings, the world's first proton-proton collider, had to be axed in 1984 to release money and resources for CERN's LEP electron-positron collider, then under construction. Twelve years later, LEAR in turn was a victim to CERN's next major project, the LHC proton collider. As if to underline the irony of its premature demise, the condemned LEAR was enjoying ten times more antiprotons than it had a decade earlier.

LEAR is not totally dead however. The LHC is designed to handle heavy ions as well as protons, and CERN's existing ion source and booster cannot deliver the ion beam intensity required for the LHC. LEAR (rechristened LEIR for Low Energy Ion Ring) joins the LHC injector chain. This time the emphasis is on injection and accumulation of ions from the linac rather than ejection to experiments, but the idea is similar. LEIR will keep pace with particle energy in the linac as it is increased, accepting particles over many LEIR turns rather than a single turn. Trials showed that doing this at the same time as applying electron cooling was initially difficult as ions recombined with the cooling electrons, but subsequent work showed how this could be overcome and big gains in intensity via stacking become possible.

The destiny of Shakespeare's King Lear was largely shaped by his three daughters. Apart from its physics discoveries and machine physics achievements, LEAR too was the father of a progeny of daughter rings which all use beam cooling techniques—ASTRID (Aarhus), CELSIUS (Uppsala), COSY (Jülich), CRYRING (Stockholm), ERS/SIS (Darmstadt), IUCF cooler (Bloomington, Indiana), TARN (Tokyo), and TSR (Heidelberg).

At CERN, the recently completed antiproton decelerator, a simpler machine than LEAR, will continue CERN's antiproton traditions.

Astrophysics Faces the

by VIRGINIA TRIMBLE

Time has no divisions to mark its passage; there is never a thunderstorm or blare of trumpets to announce the beginning of a new month or year. Even when a new century begins, it is only we mortals who ring bells and fire off pistols [and review articles].

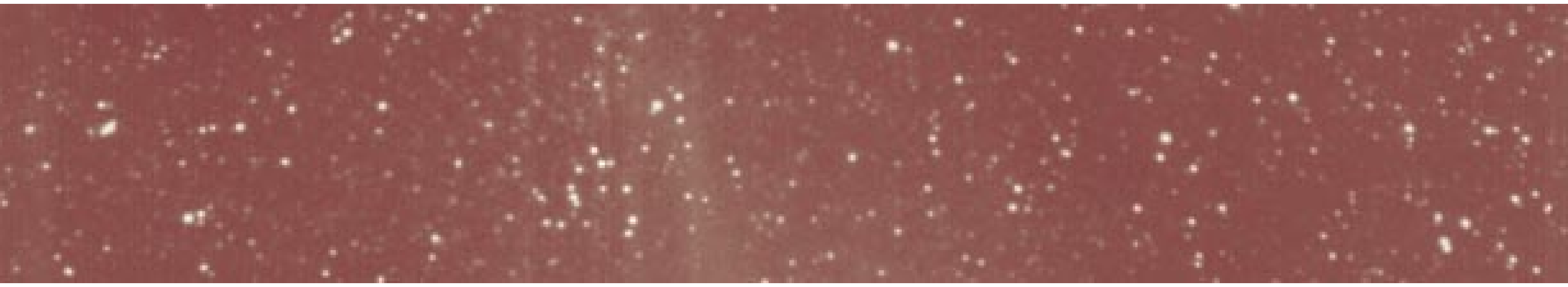
—Thomas Mann, The Magic Mountain, Ch. 2.

ONE WRITES ABOUT THE MILLENNIUM, I suppose, for the same reason that one climbs a mountain: because it is there. And because, unlike the mountain (cf. Mohammed c. 622), it will soon be here, or at least now. Whether "soon" for you means midnight, 31 December 1999 or 31 December 2000 is a small perturbation on these time scales, though personally I will drink champagne on both occasions.

In the meantime, the next few installments of "The Universe at Large" will examine some of what astronomy has accomplished, and how, beginning with the events that falsified many of the accepted principles of Aristotelian and medieval science. Not everything will be perfectly chronological, because I plan to follow some of the themes up to the press release era, theme by theme. The starting point is the synthesis of Greek philosophy and Catholic church teachings that largely shaped European thinking for some centuries ending between 1543 and 1642. The duration of complete agreement was in fact quite brief. The details were still being worked out in some centers of scholarship while the foundations were being undermined in others. The name most closely associated with the synthesis is that of Thomas Aquinas (1225–74).

THE IMMUTABILITY OF THE HEAVENS

"Secular" has as its root meaning "of or pertaining to time," that is, changing in a non-cyclic way. While the phases of the moon, the seasons, and the tribal festivals synchronized with them come back again and again in identical form, the affairs



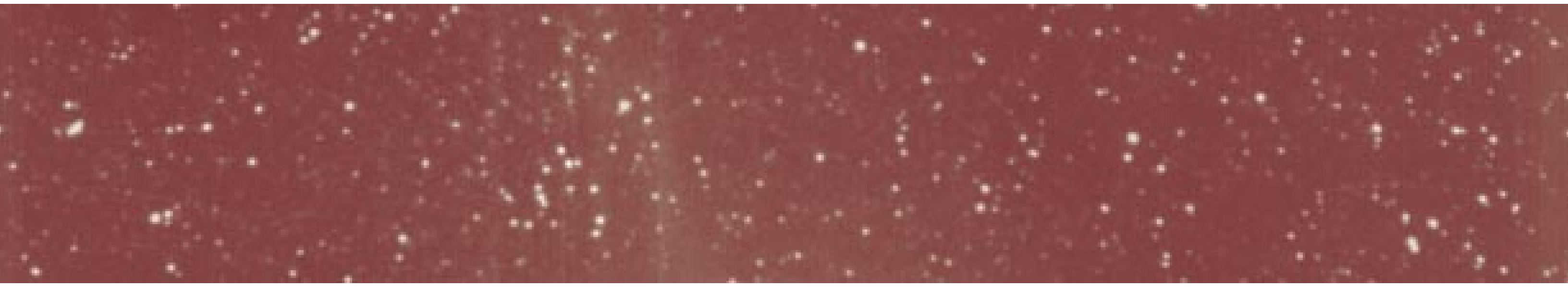
A somewhat idealized portrait of St. Thomas Aquinas, who was, however, described by several contemporaries as being quite stout physically as well as mentally. (Courtesy The Dominican School of Philosophy and Theology Website http://www.dspt.edu)

of man might take off on any old tangent and never recover. Hence the now-commoner meaning of secular is, roughly, the opposite of religious.

That secular changes (in both senses!) occur on Earth was never doubted, but the spheres of the heavens and the angels were supposed to be exempt. Thus aurorae, lightning, meteors, and comets were all attributed to atmospheric processes. Well, three out of four isn't bad. Other cultures had other preconceptions and priorities. One way or another, this difference must have contributed to the Chinese records of "broom stars" (comets) and "guest stars" (novae and supernovae) being much more complete than European ones.

Naked eye comets come around at a rate of 86 per century, and naked eye novae every ten years or so. Nevertheless, it seems retrospectively to have been extraordinarily good luck that a bright one of each, the comet of 1577 and Tycho Brahe's nova stella of 1572 (now recognized as a supernova) appeared when the right person was ready both to observe them with care and to explain what his observations meant. They were, in fact, null observations. That is, Tycho was unable to detect any geocentric parallax for either, placing them out beyond the sphere of the moon. After the publication of Tycho's 1588 "comet" book, no scholar could continue to doubt that the heavens are at least occasionally mutable.

Variability of astronomical objects has, obviously, been a major topic of astronomical research ever since. A crude



summary of the results is that everything changes on every time scale allowed by special relativity (and a few that seemingly are not) if you look hard enough. The sun, for instance, is brightening over billions of years, cycling on several time scales of 10–1000 years, oscillating in minutes to hours, and flaring up (especially in radio and X rays) with sub-second spikes.

Some false alarms have been historically interesting. Pre-photographic observers often reported that the relative brightnesses of features in nebulae (for example, Orion, according to Herschel) were changing in years. Photographic images largely disproved these claims, but, in turn, led to Adriaan van Maanen thinking that he had seen the spirals rotate, thereby placing them, if not quite inside the Earth's atmosphere like pre-Tychonic comets, at least inside our galaxy.

Rapid changes in the radio structure of quasars were dubbed "superluminal" even as we all recognized that they were demonstrating special relativity (and projection effects) not disproving it. One local newspaper, however, headlined the first reports "Einstein is Dead." This had actually happened some time before.

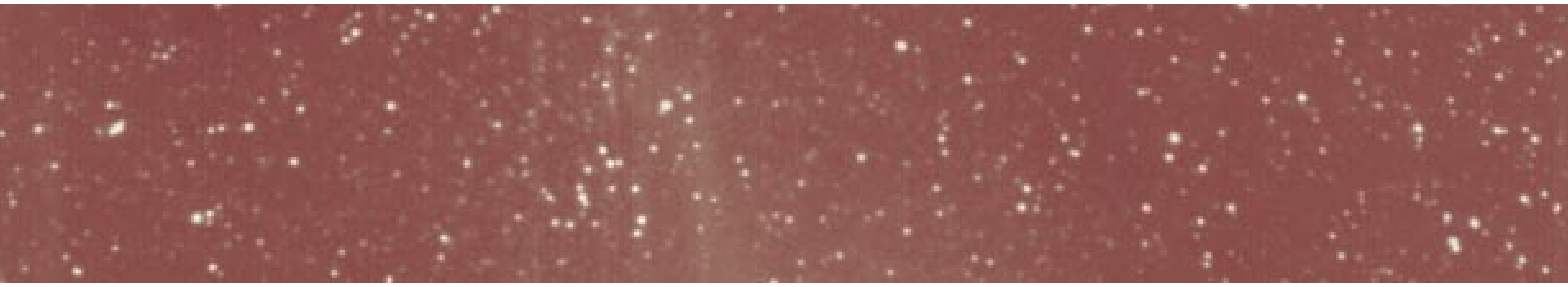
The last couple of years have seen a certain amount of excitement over what is sometimes called "real time stellar evolution," that is, noticeable changes in brightness, color, or surrounding gas structures in months to decades, more subtle than mere novae and supernovae. Some happen among very young stars (with instabilities in accretion probably responsible), others among stars near the ends of (non-explosive) lives. A new planetary nebula turns on every year somewhere in the Milky Way, on average. One of the ten belonging to the 1990s has been caught in the act. And, in the immediately preceding evolutionary phase, we find the galloping giant, WZ Sagittae, whose surface temperature dropped from about 20,000 K to 6,000 K and whose visual brightness increased more than a factor 10 in the current century. A similar seventeenth century example has been found among musty old journals; one from the 1920s (with an actual spectrogram long hidden away in Stockholm); and the most recent is called Sakurai's object, for the Japanese amateur astronomer who reported the beginning of its brightening a few years ago. This is the complete known inventory, and all four appear to have experienced one last flash of nuclear burning (helium to carbon) before they begin to shed their envelopes and become planetary nebulae.

THE FINITE SPEED OF LIGHT

Sound travels rather slowly, as must have been noticed by any thoughtful ancient observer of thunder and lightning (and certainly, if only briefly, by the first renaissance soldier to be killed by a cannon ball before he had heard the sound of the explosion). Instantaneous propagation of light was, however, a firm pillar of natural philosophy from Euclid and Ptolemy down to Descartes (1596–1650) and his followers, intimately bound up with a particular theory of vision and of how we perceive external reality. It was supported by an assortment of logical arguments and absence of observed effects that you would expect if propagation were not instantaneous (like misalignment of sun and moon during total eclipse).

Galileo may or may not have been the first person to carry out a relevant experiment, but he was the first to record it. In *Dialog Concerning Two New Sciences* (published in 1638), he suggests that a PI and a co-investigator, each holding a covered lantern, stand some distance apart. The PI uncovers his lantern. As soon as the Co-I sees the flash of light, he uncovers his lantern, and the PI records the total elapsed time from his uncovering to the return flash. Using distances up to a mile, Galileo concluded that the return flash was, if not instantaneous, extraordinarily rapid. For what it is worth, Albert Abraham Michelson's measurement of the speed of light, using rotating slot collimators atop Mts. Wilson and San Gorgonio, is the logical equivalent of Galileo's method.

The first successful determination of *c* also owed much to Galileo, though he had been long dead, because the speedometer was Io, one of the Jovian moons he had discovered in 1610. Both Gian Cassini (of the Cassini division in Saturn's rings) and Ole Roemer (inventor of the



Ole Roemer
(Courtesy Yerkes Observatory and the Astronomical Society of the Pacific)

Fahrenheit thermometer) noticed in the 1670s that eclipses by Jupiter of his satellites seemed to occur earlier and earlier as the Earth approached Jupiter and later and later as we moved away. Only Roemer had faith in his interpretation of the data, making a definite prediction before the Paris Academy of Sciences that the eclipse of Io on 9 November 1676 would be 10 minutes late. It happened as he had said, and in due course Roemer returned to his native Denmark and a successful career as astronomer royal, mayor of Copenhagen, and so forth. Distances in the solar system were not then very well known, but the implied velocity was, anyhow, of the right order of magnitude.

Acceptance of the result was not instantaneous (nor even extraordinarily rapid). Roemer (1644–1710) had, in turn, been dead nearly 20 years when James Bradley found independent confirmation of the finite speed of light. Bradley was attempting to measure stellar parallaxes, the small apparent changes in position of stars that result from our being on opposite sides of the sun at six month intervals. Instead, he discovered aberration of starlight, the small apparent changes in positions of stars that result from our moving in opposite directions at six month intervals. How could he tell which he had found? Well, parallax is smaller for more distant stars, while aberration is the same for all (this is probably obvious). And the shifts are in different directions for the two. For a star that is directly overhead at midnight on 21 March (for instance), parallax will be most conspicuous on 21 June and 21 December, while aberration will be largest on 21 March and 21 September (no, of course you can't see the star through the entire year, but you can see enough to construct the ellipses of parallax and aberration).

Incidentally, most discussions of this topic mention what a strange name is aberration of starlight. It comes from a rare word, *aberr*, meaning to stray or deviate from a straight or expected path. Thus it seems to me to be a perfectly sensible name for the phenomenon.

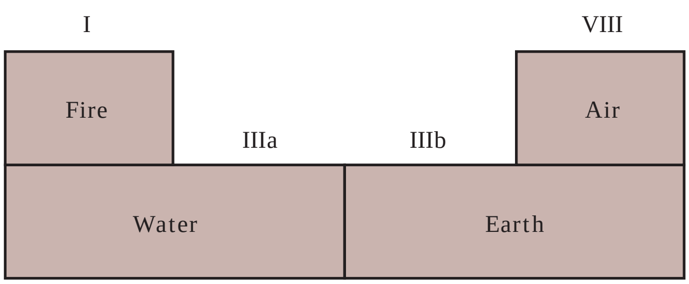
Bradley's speed of light was within about 10 percent of the modern value. Laboratory methods replaced astronomical ones in the nineteenth century with the work of Fizeau and Foucault, and *c* is now known so precisely that you are not allowed to measure it anymore. It has become part of the definition of the meter.

Cartesian opposition largely disappeared with this confirmation, and astronomers recognized that their telescopes were time machines. The idea has a certain charm, if you care to think that the light we now see coming from the Hyades left when George Washington was president, or thereabouts. Over larger distances, the "look back" time has advantages and disadvantages. On the one hand, by studying galaxies with redshifts of one and larger, we can study galaxy formation and evolution more or less directly. On the other hand, the fact that distant galaxies are guaranteed to be different from those here and now is a barrier to using them as probes for other purposes.

You are used to seeing *c* in one context where it doesn't really mean the speed of light. The standard expressions for solar system tests of general relativity, like deflection of light and advance of the perihelion of Mercury, have *c*'s in them. But that *c* is the speed of propagation of gravitational information. Of course we get the right answer using the familiar *c*, indicating that the two speeds are the same to within five percent or so. The implied limit on the mass of the graviton is not an interesting one.

THE FALL AND RISE OF QUINTESSENCE

You have, of course, a modern periodic table of the elements in your office.* The one below is an earlier version, shared by the Greek philosophers and the medieval



Early Periodic Table

church. In retrospect, it is probably precisely because air and water were so long regarded as fundamental substances that their decomposition into other things was such an important step forward in chemistry, beginning with Joseph Priestly's 1774 recognition of "respirable air" as a discrete substance and Henry Cavendish's 1783 break-up of water into "inflammable" and "respirable" air. The latter was dubbed oxygen by Lavoisier, who is the traditional culture hero of this subject, having established the modern notion of elements, with the inventory subject to change. The title of his 1789 (French)–1790 (English) book, *The Elements of Chemistry*, was presumably a live pun at the time.

Meanwhile, back at Alexandria, it had also been agreed that celestial bodies must be made of a different, fifth, element, that is, quintessence. Prevailing opinion changed quite slowly, as the heavenly bodies gradually came to seem more and more Earth-like, beginning with mountains on the moon, spots on the sun, and Jupiter as a center of attraction and motion for its satellites. These were among the discoveries made with the first astronomical telescopes beginning in 1610, with primary credit to Galileo, though others were involved. The trend continued with the acceptance of Newton's universal gravitation. Still, well into the nineteenth century, it seemed perfectly reasonable that we might never be sure of the composition of the planets and stars.

In 1858–59, however, Robert Bunsen (of the burner) and Gustav Kirchhof (of the laws) put spectroscopes into beams of sunlight and recognized in absorption the familiar colors produced in emission by laboratory gases of sodium and iron. That all stars and nebulae are made of "people stuff" soon came to seem obvious, especially after 1869, when William Huggins found emission lines of familiar substances in the light of some of the bright nebulae, thereby demonstrating that they were truly diffuse gas masses and not unresolved clusters of stars.

The notion that the Earth tells us the composition of everything else lasted well into the twentieth century, with most astronomers expecting that careful analysis of the light from stars would reveal them to consist primarily of oxygen, silicon, iron, magnesium, and other terrestrially abundant elements. Even the modest correction of "same elements but different proportions" (dominated by hydrogen and helium) was firmly resisted when first put forward in 1925 by Cecilia Payne [a story that has been told elsewhere in these pages (see *Beam Line*, Spring 1994, Vol. 24, No. 1, pp. 35–40)]. The amended

**By copying it on to tinted paper and suspending it suitably, you can provide a proper scientist's answer to the ancient riddle, "What's yellow and hangs on the wall?" The traditional answer.is, "A herring."*

Fritz Zwicky
(Courtesy Astronomical Society of the Pacific)

version, in which everything in the Universe was mostly hydrogen and helium, with a percent or two of heavier elements survived unchallenged for another half century.

Thus when Fritz Zwicky discovered, in 1933. that a particular cluster of galaxies had a total mass something like 100 times that implied by the light coming from it, he stated, without feeling any need for proof, that the deficit must be made up by faint galaxies and diffuse gas between them. The advent of radio and X-ray astronomy led to the gradual demonstration that such diffuse stuff contributed more to the cluster masses than do the individual bright galaxies, but not much more.

Zwicky's "dunkle materie" became dark matter in English. Attempts to identify it with people stuff in small. cold clumps or other cloaks of invisibility failed so slowly that "ran up against" anything is an inappropriate figure of speech. Instead, while the ubiquity of dark matter was widely conceded by about 1975, and non-zero-rest-mass neutrinos and weakly interacting massive particles were already available in the cosmic recipe books at the same time, general acceptance of "non-baryonic" dark matter crept slowly upon us. Better calculations and measurements of the mix of light nuclides coming from the early Universe and repeated failures to find lots of missing baryons in any conceivable form were both factors. David Schramm was the first person I heard say uniquivocally that "there are dark baryons and there are dark non-baryons." Most astronomers (and virtually all the particle-physics-and-cosmology types) would by now concur.

And still the word "quintessence" remained the possession of historians and aesthetes, to whom it had meanwhile come to mean something like "the purest and most exalted part of something," probably only to be properly appreciated by the cultured writer or speaker and not by the philistinian reader or listener. Until 1998. And suddenly, there was with the baryons a new quintessence, now meaning a particular sort of non-baryonic stuff with pressure proportional to density, but with a negative constant of proportionality.

Quintessence shares with ordinary matter a positive mass density. Anything that doesn't was chased at ever increasing acceleration down the positive X-axis and out of the Universe long ago. But even rather strange things like neutrinos and axions exert positive pressure. If you blow them into a balloon, the balloon expands, and if you let them out, it contracts. Quintessence (sometimes also called x-matter) does the opposite. More important for the cosmological case, if your balloon (or Universe) is just nicely balanced between positive and negative pressure stuff, and you expand it a bit, then the decreasing density of the substance with negative pressure causes the expansion to continue and to accelerate exponentially.

Quintessence, in other words, acts rather like a cosmological constant, but with the additional freedom of being able to gather together in lumps, at least on large scales, and so participate in the formation of galaxies, clusters, and voids.

PREDICTABILITY: FROM "IT IS YELLOW AND FAVORABLE TO THE EMPEROR" TO "IT IS BEST TO USE A FULL APERTURE SOLAR FILTER"

You probably noticed that the September 1999 earthquake in Turkey followed by only a few weeks an eclipse of the sun visible from more or less the same place. Equally probably, you did not think the connection was a causal one or that the inhabitants of Guernsey were at equal risk of an earthquake shortly after the eclipse path crossed their territory. Our ancestors would have thought quite differently and, as a result, felt quite differently both about the events and about the national leadership that permitted them to occur.

To us, eclipses are events whose causes are fully understood and whose occurrences, down to the nearest minute and mile, are completely predictable. Earthquakes are at least partly so. I own a house in the San Fernando Valley, and earthquakes strong enough to crack the plaster have occurred at roughly 20-year intervals there at least since 1933 (Long Beach) through 1994 (Northridge). I will be very surprised if we make it to 2018 without another. Meanwhile, the Chevy Chase house is at frequent risk only of hurricane edges and the neighbors' overgrown trees.

Additional predictable events now include (1) periodic comets like Halley; (2) some impacts; for instance that of comet Shoemaker-Levy 9 on Jupiter was foreseen a whole orbit in advance, at least by us, if not by the Jovians; (3) the fadings (eclipses) of Algol, the demon star that is the eye of Medusa in the constellation Perseus; (4) relatively inconspicuous, rare events like the transit of Mercury across the sun (15 November 1999); and (5) meteor showers, though just how spectacular the Leonids will be in any year remains less certain; you will know whether 1999 (November 17–18) was a vintage year before this appears. For all these, the physics is fully understood, though occasionally difficult to calculate. The same physics (mostly Newtonian gravity), led to prediscovery predictions of Neptune and the white dwarf companions of Sirius and Procyon.

The flareups of novae, supernovae, violently variable quasars, and gamma-ray bursters are, at the moment, only statistically predictable, like earthquakes. You know what sorts of underlying objects are potential victims and roughly how often a given sort of event will take place, based on at least partial understanding of what is going on. For instance, the quasar OJ 287 flares up about every 12 years (and this may well be the orbit period of a binary black hole at its core).

Within the Milky Way, we expect about 10 novae, 0.01 supernovae, and 10^{-7} gamma-ray bursters per year. One can think of ways of doing better. A sufficiently sensitive and directional neutrino telescope would give hours to days advance warning of supernovae. Ditto for gamma-ray bursters, given an appropriate detector for gravitational radiation. And no, we do not currently know how to make them sufficiently sensitive and directive.

The trek from omens to solar filters has been a long and arduous one, which includes folk tales like the Chinese court astrologer who was executed for failing to predict a "guest star" (nova or supernova. probably) and battles supposedly won or lost because only one side had known an eclipse was coming and used the threat of it as a weapon. Items that I believe are at least approximately true include these:

- Lunar eclipses are much easier to predict well than solar ones, because they are seen over half the earth. The late Babylonians, Greeks, Chinese, and (probably) Maya had good enough records of the motions of the sun and moon relative to the stars to forecast most of them.
- Solar eclipses fall within 18 year, 11-1/3 day intervals, called Saros (the word is supposedly Chaldean), which improve the chances of a pre-Copernican astronomer knowing that one was on the way. But to be sure that an eclipse would be total (rather than merely partial or annular and so less spectacular) and just where it would be visible requires proper Keplerian orbits and some perturbation theory.
- Modern scholars have employed medieval Chinese tables of motions in the traditional way and find that they do indeed catch most of the eclipses that would have been seen from somewhere near the capital, but that the degree of totality and just where you should go for the best view were much less reliable.

Path of Halley's predicted 1715 eclipse across England. (Courtesy Houghton Library, Harvard University, from an article by Jay M. Pasachoff, Williams College)

• The first person to do a really good job of mapping an eclipse path in advance was Edmond Halley, for the event of 1715, which passed over roughly the same part of Europe as did 1999 August 11. He is, of course, also the Halley of Halley's comet, because he recognized that the events of 1531, 1607, and 1682 had very similar orbits, so that there would probably also be a comet of 1758. Indeed there was, though Halley himself did not see it from any terrestrial observatory.

• Many earlier apparitions of Halley are, in retrospect, to be found in Chinese, and sometimes Babylonian, Roman, and other records. This includes every return back to 87 BCE, caught by the Chinese. No where, however, does there seem to be any sense of periodicity. A whole human lifetime is apparently just too long between drinks. Indeed, young people are already asking what the number in the American Association for the Advancement of Science Project 2061 means.

• Comets ("broom stars" to the Chinese), eclipses, and guest stars or new stars apparently had very different meanings to different cultures at different times. A Chinese scholar has noted recently that the total number of portentous events and the ratio of evil to favorable ones rose on several occasions just before a change of government, presumably reflecting general discontent with the old regime.

• Very recently, a coven of American astronomers has suggested that the supernova of 1054 really was seen all over Europe, both before and after it passed behind the sun in June, but that the failure of a conference meant to hold together the eastern and western churches the same year made it seem like an unlucky portent, not to be remembered. The 1054 event was the one described as "yellow and favorable for the Emperor," and its place in the sky is now occupied by the Crab Nebula.

• A May eclipse, occurring just before an eighth century church conclave apparently had the same feel about it. The clerics were attempting to reconcile different versions of the algorithm for determining the date of Easter,* and the eclipse made it clear that the visiting Englishmen had celebrated on the wrong day, while the host Irish had it right. Incidentally, the conclave voted on non-astronomical grounds, and calendar and reality continued to slip further apart until the time of Pope Gregory.

- The supernova of 1604, the one studied by Kepler, was not, of course, predicted. But it did occur within a predictable, and predicted, triple conjunction of Mars, Jupiter, and Saturn, thereby frightening the brychans off a large fraction of the populace and much influencing Kepler's views on the nature of the Star of Bethlehem. (Don't worry; I am not going to try to tell you what that was; at least not today).
- As recently as 1833, Lincoln's landlord, a deacon of the local Cumberland Presbyterian church, tried to tell him that the (truly spectacular) Leonid shower was the beginning of the end. Lincoln was not persuaded.
- If you put your full aperture solar filter on a telescope for the 11 August solar eclipse, it would also have worked for observing the 15 November transit of Mercury across the sun. Unfortunately, the predictions are now good enough that I can say in advance that there isn't any place on Earth from which both were visible.

WHERE DID ALL THIS COME FROM?

The story of Lincoln, Landlord, and Leonids is in the November 1999 *Sky & Telescope*. The 1604 supernova remark appears in Michael Molnar's *The Star of Bethlehem* (Rutgers University Press 1999). Comet Halley is in D. K. Yeomans' *Comets* (Wiley 1991). Eclipse Halley comes from Jay Pasachoff's article in the April issue of *Astronomy and Geophysics* (newsletter of the Royal Astronomical Society). European sightings of SN 1054 and their suppression are suggested by G. W. Collins et al. in *Publications of the Astronomical Society of the Pacific* (111, 871, 1999). Michael Hoskin's *The Cambridge Concise History of Astronomy* (Cambridge University Press, 1999) contains many items relevant to the breakdown of the medieval synthesis. Many of the modern astronomical items have appeared in my annual round-ups, Astrophysics in 1991 to 1998, in *Publications of the Astronomical Society of the Pacific*. The details of the eighth century conclave in Ireland have appeared both someplace respectable (*Journal of the History of Astronomy*) and in a murder mystery (case solved by a nun attending the conclave). Brychans were used by Ellis Peters' Brother Cadfael. And beyond this we rapidly reach the circumstances of a delightful piece of synagogue music, described by its composer (the late Chazzan Philip Moddel) as "from a song I heard."

**Just in case you don't carry it around with you, my Mother's version of the rule was "the first Sunday after the first full moon after the Vernal equinox." Part of the problem arises from the fact that the Vernal equinox and full moon happen at the same time for all observers, but Sunday depends on where you are. In addition, by then, solar and calendric Vernal equinox were already out of step about six days, owing to the observance of erroneous Leap Days in the years that eventually became 100, 200, 300, 500, 600, and 700. If you also insist that Passover has to end first, then you have enough to keep eastern and western churches apart for another thousand years.*

FROM THE EDITORS' DESK

Herman Winick

David Burke

George Smoot

WITH THIS ISSUE of the *Beam Line* we welcome three new Editorial Advisory Board members to our team: George Smoot from LBNL, and David Burke and Herman Winick (for a second term) from SLAC. They replace Robert Siemann, George Brown, and Joel Primack who have had long and productive terms on the Board. The new members join Patricia Burchat and Lance Dixon from SLAC, George Trilling from LBNL, and Karl van Bibber from LLNL. Contributing editors Gordon Fraser from CERN, Judy Jackson from Fermilab, Akihiro Maki from KEK, Michael Riordan from SLAC, and Pedro Waloschek from DESY compose the remainder of the editorial team.

Members of the Editorial Advisory Board are responsible for guiding the *Beam Line* and recommending to us topics of interest and potential authors, so if you are interested in contributing an article, or have a suggestion for one, you can convey your ideas to either a member of the Board, a contributing editor, or to us directly. The Board meets once or twice a year to discuss issue planning and policy concerns. One area in which the Board has been extremely helpful is in suggesting and planning for the special "Quantum Century" issue scheduled for publication later this year. For such special issues work generally begins two years ahead of the publication date.

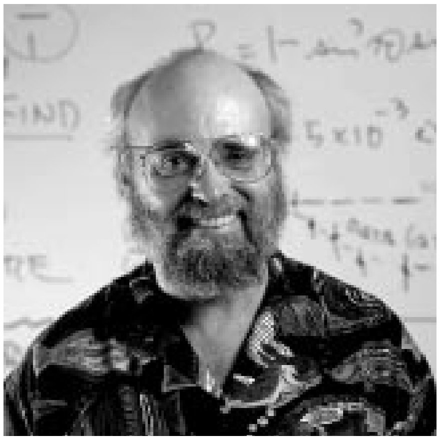
As editors we think of the Board as our "collective wisdom" who we can turn to for guidance and reality checks. Without them, there would be no *Beam Line*.

Rene Donaldson

Bill Kirk

CONTRIBUTORS

JAMES GILLIES began his physics career as a graduate student at Oxford University working with the European Muon Collaboration at CERN in the mid-1980s. Moving on to the Rutherford Appleton Laboratory, he became interested in communicating science, working for a summer with the BBC World Service Science Unit setting up a regular local radio science spot. In 1993, he left research to become Head of Science with the British Council in Paris. After managing the Council's program of scientific visits, exchanges, and cultural events for two years, he returned to CERN in 1995 as a science writer and is currently the CERN *Courier's* News Editor. He is co-authoring a history of the World Wide Web to be published next year by Oxford University Press under the title of *How the Web was Born*.



JOHN LEARNED, a repeat *Beam Line* author, has been a Physics Professor at the University of Hawaii, Manoa campus, for the last 20 years. He went there to get the DUMAND project started and thought he would leave in several years. He has done elementary particle physics at accelerators and in cosmic ray experiments; in addition, he has been a leader in neutrino studies and neutrino astronomy.

He was a co-founder of the IMB nucleon decay experiment and had his greatest scientific thrill participating in the discovery of the neutrino burst from supernova 1987A.

Learned and others from IMB joined with the Kamioka group in creating Super-K, with most construction funds from Mombusho in Japan plus some from the Department of Energy. He acknowledges the entire collaboration under the leadership of Yoji Totsuka from the University of Tokyo for the work reported herein.

MICHAEL DINE is interested primarily in elementary particle theory. Much of his work has been devoted to resolving puzzles left unanswered by the Standard Model of particle physics. He received his Ph.D. from Yale University in 1978 and held a postdoctoral position at SLAC from 1978–80. Subsequently, he was a long term member at the Institute for Advanced Study and taught at City College of New York. Since 1990, he has been a professor at the University of California, Santa Cruz, and a regular visitor to SLAC and Stanford University. For some time, Dine has worked actively at the interface between particle physics and cosmology; he has studied the possibility that the weak interaction might be responsible for generating the asymmetry between matter and antimatter in the early Universe.

GORDON FRASER has been Editor of the CERN *Courier* for a long time. While a research student at London's Imperial College in the mid-1960s, he wrote short-story fiction as a respite from theoretical calculations and became side-tracked into journalism. He returned to physics as a science writer, eventually transferring to CERN. He is co-author, with Egil Lillestøl and Inge Sellevåg, of *The Search for Infinity* (New York, Facts on File, 1995) which has been translated into ten other languages; author of *The Quark Machines* (Bristol, Institute of Physics Publishing, 1997); and Editor of *Particle Century* (Bristol, Institute of Physics Publishing, 1998). His new book, *Antimatter—The Ultimate Mirror*, is published by Cambridge University Press this spring.

VIRGINIA TRIMBLE currently chairs the Historical Astronomy Division of the American Astronomical Society. She is shown here presenting the certificate and check that represent the 1999 Leroy Doggett Prize of the Division to the winner and lecturer Owen Gingerich of the Smithsonian Institution and Center for Astrophysics (Harvard), during the January 2000 AAS meeting. His lecture was on "The Copernican Revolution Revisited," and if Trimble has not yet plagiarized from it for the *Beam Line*, she surely will in the future. A discerning reader can be forgiven for deducing from the picture (which was taken by HAD secretary Thomas Hockey) that the combined age of the chair and the lecturer is very close to a millennium. The stylized mirth was caused by the chair's (very unoriginal) remark that, "Our secretary gave me a check just before this session started. Unfortunately, it's made out to Owen."

DATES TO REMEMBER

Apr 2–8	3rd Latin American Symposium on High Energy Physics (SILAFAE III), Cartagena de Indias, Colombia (silafae-III@fisica.udea.edu.co; http://jhep.sissa.it/silafae-III)
Apr 5–7	ESA-CERN Workshop on Fundamental Physics in Space and Related Topics, Geneva, Switzerland (M. Jacob, TH Division, CERN, 1211 Geneva 23, Switzerland; http://www.cern.ch/Physics/Events/Conferences/2000/0405CERNESA/)
Apr 5–9	5th International Workshop on Heavy Quark Physics, Dubna, Russia (hqp2000@thsun1.jinr.ru); http://thsun1.jinr.ru/~hqp2000/)
Apr 17–19	PHENO 2000: Symposium on Phenomenology for the Nu Century, Madison, Wisconsin (Linda Dolan, Physics Department, University of Wisconsin, 1150 University Ave., Madison, WI 53706; or ldolan@pheno.physics.wisc.edu; http://pheno.physics.wisc.edu/pheno00/)
Apr 25–30	8th International Workshop on Deep Inelastic Scattering and QCD (DIS 2000), Liverpool, England (DIS 2000, Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Oxford Street, Liverpool L69 7ZE, Great Britain or dis2000@hep.ph.liv.ac.uk; http://hep.ph.liv.ac.uk:80/DIS2000/)
Apr 25–May 12	Theoretical Institute on SUSY and Higgs 2000, Argonne, Illinois (HEP Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439 or berger@anl.gov or chalmers@pc19.hep.anl.gov; http://gate.hep.anl.gov/tait/anlsusy2k/#us)
Apr 29–May 2	APS April Meeting 2000, Long Beach, California (American Physical Society, One Physics Ellipse, College Park, MD 20740; http://www.aps.org/meet/APR00/)
May 8–16	CERN Accelerator School Course on RF Engineering, Seeheim, Germany (Suzanne von Wartburg, CERN Accelerator School, AC Division, 1211 Geneva 23, Switzerland or Suzanne.von.Wartburg@cern.ch; http://www.cern.ch/Schools/CAS/)
May 12–14	4th Workshop on Continuous Advances in QCD, Minneapolis, Minnesota (QCD@tpi.umn.edu; http://www.tpi.umn.edu/QCD00.html)
May 14–19	Conference on Precision Electromagnetic Measurements (CPEM 2000), Sydney, Australia (CPEM 2000 Conference Secretariat, Box 128, Sydney NSW 2001, Australia or cpem2000@tourhosts.com.au; http://www.tourhosts.com.au/cpem2000)
May 19–23	Meson 2000 Workshop, Cracow, Poland (MESON 2000 Workshop, Institute of Physics, Jagellonian University, Cracow, Poland or meson2k@jetta.if.uj.edu.pl; http://zfj-www.if.uj.edu.pl/meson2000)

May 21–27	8th Pisa Meeting on Advanced Detectors: Frontier Detectors for Frontier Physics, La Biodola, Isola d'Elba, Italy (A. Scribano, INFN - Sezione di Pisa, Via Livornese 1291, I-56010 S. Piero A Grado, Pisa, Italy, or pisameet@pi.infn.it; http://www.pi.infn.it/pm/20000)
May 22–28	7th Conference on Intersections Between Particle and Nuclear Physics (CIPANP 2000), Quebec City, Canada (B. MacInnis, MIT-Bates, Box 846, Middleton, MA 01949 or macinnis@mit.edu; http://CIPANP.mit.edu)
May 29–Jun 2	44th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN 2000), Palm Springs, California (Lloyd R. Harriott, Bell Labs-Lucent Technologies, 600 Mountain Avenue, Murray Hill, NJ 07933 or eipbn@physics.bell-labs.com; http://www.eecs.umich.edu/~pang/)
May 29–Jun 3	Bologna 2000: Structure of the Nucleus at the Dawn of the Century, Bologna, Italy (Alberto Ventura at nucth2000@bo.infn.it; http://nucth2000.bo.infn.it/index.html)
May 30–Jun 16	15th Annual HUGS at CEBAF (HUGS 2000), Newport News, Virginia (Sue Ewing, Jefferson Lab, MS 12H2, 12000 Jefferson Avenue, Newport News, VA 23606)
Jun 4–7	Annual Congress of the Canadian Association of Physicists (CAP 2000), Toronto, Ontario, Canada (CAP@physics.uottawa.ca; http://www.cap.ca/)
Jun 4–30	Theoretical Advanced Study Institute in Elementary Particle Physics (TASI-2000): Flavor Physics for the Millennium, Boulder, Colorado (Kathy Oliver, Physics Department, Campus Box 390, University of Colorado, Boulder, CO 80309 or TASI@spot.colorado.edu)
Jun 5–8	Pixel 2000, Genova, Italy (Laura Opisso, INFN Sezione di Genova, Via Dodecanes 33: I-16146 Genova, Italy or opisso@ge.infn.it; http://www.ge.infn.it/Pix2000/Pixel2000.html)
Jun 5–16	US Particle Accelerator School, Stony Brook, New York (US Particle Accelerator School, Fermilab, MS 125, Box 500, Batavia, IL 60510 or uspas@fnal.gov; http://www.indiana.edu/~uspas/programs/sunysb.html)
Jun 16–18	Beyond 10^{34} e^+e^- Workshop: Physics at a Second Generation B Factory, Sleeping Bear Dunes, Michigan (I. Shipsey, Physics Department, Purdue University, 1396 Physics Bldg., West Lafayette, IN 47907-1396 or shipsey@physics.purdue.edu; http://www.physics.purdue.edu/10E34/)
Jun 16–21	19th International Conference on Neutrino Physics and Astrophysics - Neutrino 2000, Sudbury, Ontario, Canada (Neutrino 2000 Conference Secretariat, National Research Council Canada, Bldg. M-19, Montreal Road, Ottawa, ON K1A 0R6 Canada or nu2000@nrc.ca; http://www.nrc.ca/confserv/nu2000/)