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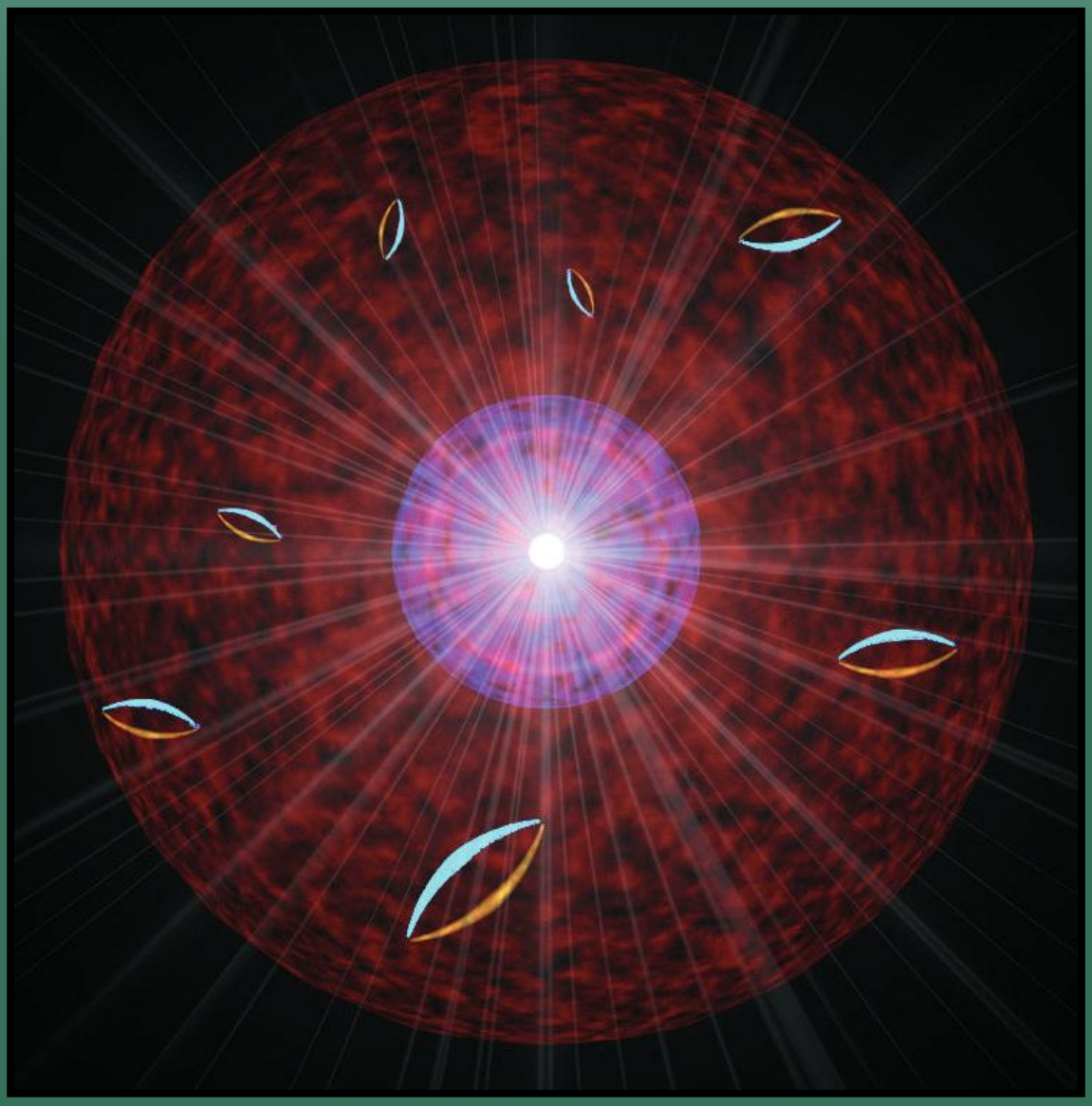

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

SUMMER 1997 VOL. 27, NUMBER 2

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Cover: According to recent measurements made by Purdue University physicists, an electron may not be a simple point charge, as previously thought. Instead, the particle may be thought of as being at the center of a fuzzy "cloud," as in this artist's conception, where the electromagnetic force increases toward a central core. The "cloud" consists of virtual particles, which wink in and out of existence in pairs—one particle positively charged (blue ellipses) and the other negatively charged (gold ellipses). The faint white lines radiating from the electron's core indicate its electric field, and the central reddish glow represents the area most strongly affected by its charge. (Graphic courtesy Dennis Harp, Purdue University Physics Department)

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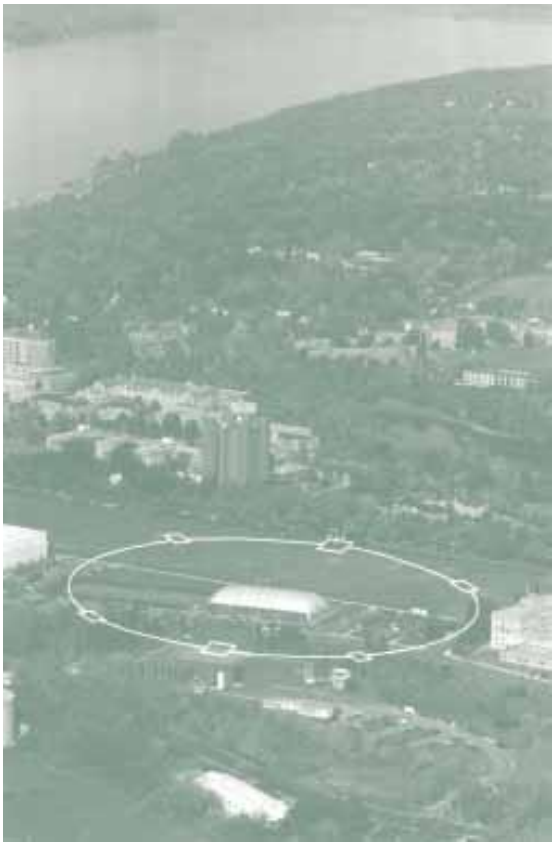

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HUNTING THE PR

by EMLYN HUGHES

SLAC and CERN have led the search for what carries the spin of the proton and neutron.

ONE OF THE GREAT CHALLENGES in high energy physics is to understand the proton. On the one hand, the proton is a very simple, basic object. It has a definite mass and spin. It has a lifetime measured to be older than the Universe. Protons are abundant and are one of the most basic building blocks of matter. On the other hand, the proton has an extremely complicated internal structure. To the particle physicist it is so complicated that it cannot be regarded as a fundamental particle. The proton consists of quarks with different flavors and gluons of different colors, all moving inside it with mysterious dynamics. Quarks are confined to be inside the proton for reasons still not understood. In fact, the "confinement" problem is one of the great unsolved mysteries. In an attempt to understand how the proton works, physicists aim to connect the simple, fundamental properties of the proton to its complex, internal structure.

Many high energy physicists in two subfields study what the proton is made of and how it works. The first uses an enormous circular accelerator to excite electrons and protons to high energies and then collide them with one another. By breaking the proton at the highest energies possible, one can extract information on what is inside. The colliding protons at HERA at the DESY laboratory in Hamburg, Germany, have energies of 800 billion electron volts (800 GeV) whereas the energy of the electrons is 30 billion electron volts (30 GeV). This exciting new project began only a few years ago and was reviewed by Franz Eisele and Günter Wolf in a *Beam Line* article, "Looking Deeper Inside the Proton," in Vol. 24, No. 3, 1994.

A second major endeavor using high energy particle accelerators is directed at studying the proton's substructure in order to extract what is responsible for its spin of 1/2. This particular effort has become extremely exciting

OTON'S SPIN

since 1988 when it was found that the quarks inside the proton do not account for its spin. Before diving into this topic, it is worthwhile to review the spin of elementary particles.

Spin has played a unique role historically. It was first postulated by George Uhlenbeck and Samuel Goudsmit in 1925 in order to explain the hyperfine splitting in the atomic spectra of hydrogen. The mystery at the time was why the number of energy levels was twice as many as expected. Wolfgang Pauli postulated that the electron might have an additional quantum number that accounted for the splitting, whereas Goudsmit and Uhlenbeck postulated that the new quantum number should have a value of 1/2, and they named it "spin." Soon afterwards the proton and neutron themselves were found to have spin of 1/2 along with other atomic nuclei. This realization added fuel to the quantum mechanics revolution and created a field of study on the spin dependence of elementary particles. Today the spin of all elementary particles is regarded as a fundamental quantum number which takes on discrete values that are some multiple of 1/2, namely 0, 1/2, −1/2, 1, −1, 3/2, −3/2,....

Among all elementary particles, nature is further divided into two classes depending on spin. One class is those with half-integral spin called fermions (1/2, 3/2, 5/2, . . .) and the other is those with integral spin called bosons (0, 1, 2, . . .). These two classes have fundamentally different behaviors. For example, fermions obey the Pauli exclusion principle, which states that no two identical fermion particles can be in the same state. Bosons do not obey this rule. They can, in fact, clump together and form superatoms that exhibit bizarre behavior. Atomic cooling techniques have recently, for example, created such superatoms at temperatures on the order of 10 nanokelvin. In the study of particles and their interactions, most elementary particles used in the high energy laboratories are fermions, whereas the force carrying the interaction between these particles come from bosons. For example, we

accelerate protons, electrons, or muons (all spin 1/2) to high energies, and we study their interactions to learn about the strong or electroweak interaction via the exchange of photons, *W* bosons, or *Z* bosons (all spin 1).

In the particular case covered in this article, the study of the proton's spin is taking place using high energy electrons and muons scattering off proton and neutron targets. The boson responsible for this interaction is the photon, the particle that gives us light. There are several basic questions relevant to the internal spin structure of the proton: What is carrying the spin of the proton? Does the present theory of strong interactions, named for the sake of simplicity "quantum chromodynamics," or QCD for short, account for the behavior of the proton? Can we understand what inside the proton gives it spin and why? This is where the proton spin story begins.

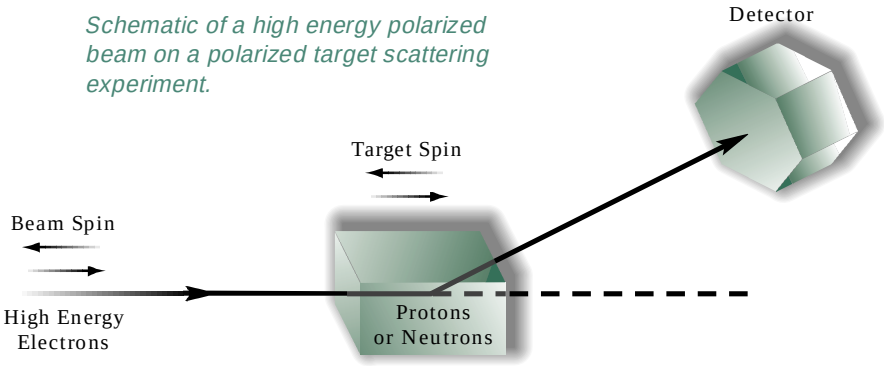
THE EMC SPIN EXPERIMENT

As a graduate student working at CERN, the European particle physics laboratory in Geneva, Switzerland, I spent a few nights rambling through the Old Town pubs. Joining me on the excursions was my friend and fellow graduate student, Vassili Papavassiliou. Vassili was a student at Yale working with my father, so our overlap had some humorous aspects. Although we discussed on a superficial level what he was doing, I confess that I did not absorb his enthusiasm for his thesis topic.

At the time I was performing one of the "hot" high energy fixed-target particle physics experiments. My thesis experiment used a high energy neutrino beam to measure the mixing between the weak and electromagnetic interactions. The measurement was performed immediately following the 1983 discovery at CERN of the *W* and *Z* bosons. The electroweak theory was established, soon to win CERN its first Nobel Prize in physics, and my experiment was going to be one of the first experimental tests of the radiative corrections to the electroweak theory. In retrospect, the result came out as expected—solid, but little excitement—not exactly a Nobel candidate.

In contrast, Vassili was pursuing the measurement of something called the proton spin structure function, using a high energy muon beam scattering off an enormous ultra-cold liquid ammonia target. Vassili was remeasuring some structure function that had first been extracted at the Stanford Linear Accelerator Center (SLAC) ten years earlier (E80,E130). To me, characterizing some complicated internal behavior of the proton and reconfirming its quark parton model predictions seemed on the dull side. I could not have been more wrong. The fallout from Vassili's thesis experiment, the measurement of the proton spin structure function, is still felt today, a decade later.

Schematic of a high energy polarized beam on a polarized target scattering experiment.



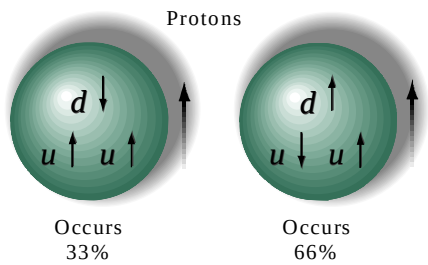
The EMC experiment (mentioned above) took a high energy muon beam produced by colliding high energy protons off a solid target at the CERN accelerator and selected the muon energies in such a way that the spin of the muon pointed along its momentum. There is some magic here. The muon spin will point in a particular direction when the muon originates from the decay of heavier particles called pions and kaons, and then a particular momentum of the muons is selected. The magic comes from the violation of parity in the weak interaction decay of the pions and kaons. But this is a story in itself—grounded in Nobel Prize winning work by T. D. Lee and C. N. Yang at Columbia in 1956.

The muon beam is directed onto a polarized ammonia target in which the protons in the ammonia have their own spins aligned either parallel or anti-parallel to the muon beam direction. In the experiment one records the outgoing scattered muons from the beam-target interaction. It is worth thinking of this as just a gigantic Rutherford scattering experiment, except one that is now keeping track of the relative spin directions of the beam and target (see diagram on the left). After one year of collecting data, the EMC experimentalists analyzed a few million events and extracted the proton spin structure function in a new kinematic region probing deeper inside the proton with this 200 billion electron volt (200 GeV) muon beam.

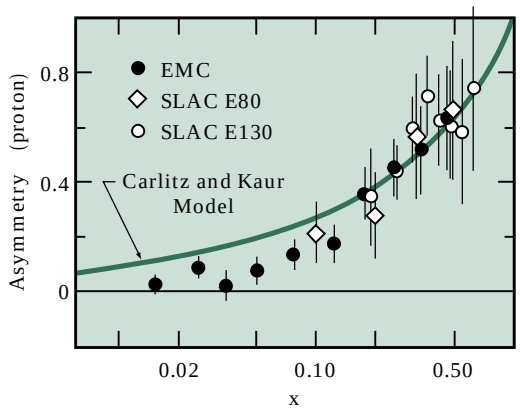
Why did the EMC result generate so much excitement? It was found at SLAC in the late 1970s and early 1980s that the number of scattered beam particles was larger when the beam and target spins are anti-parallel, compared to parallel. This was expected from the quark parton model and essentially followed the fact that the quarks inside the proton themselves line up in the direction of the proton's spin. A simplistic view of the proton is shown on the right. It was thought that when the muons interacted and transferred a large energy to the proton, the proton would break up and the fraction of spin carried by the broken pieces would be less than by the entire proton. So the spin dependence would get smaller at higher energies. What was surprising was that the EMC experiment found that the loss of spin dependence appeared to be happening faster than anticipated. The illustration on the right shows the asymmetries from the proton scattering experiment, comparing a standard quark parton model prediction with the EMC results. At low x (high energy transfer), the data fall consistently below the quark parton model prediction. This subtle effect had enormous consequences.

Armed with the experimental result from EMC, theorists were able to calculate the total spin content of the proton carried by the quarks. The result was close to zero! Quarks were not carrying the spin of the proton. What did? Was the measurement wrong? Was the theory of the strong interactions incomplete? Hundreds of theoretical papers were written. The field exploded and the famous "proton spin crisis" was born.

Here was a wonderful example relating the macroscopic property of the proton, its spin of 1/2, with its substructure, the quark content of the proton. But… it was not working!



Naive model of the quark spin direction inside the proton.



Early results on the proton spin asymmetry measurements compared to a quark parton model prediction. Notice that for small x the data fall below the prediction.

SLAC SPIN PHYSICS PROGRAM

The news of the CERN EMC experiment broke to the international community in the summer of 1987. SLAC reentered the business in 1989.

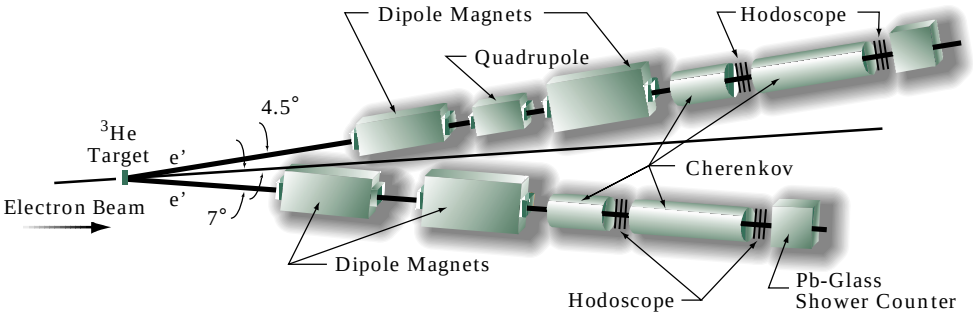
If the proton's internal structure was giving unexpected answers, then the next question was "what about the neutron?" Besides charge, the neutron is essentially the brother of the proton. In any quark model description, the proton consists of two "up" valence quarks (each with charge +2/3) and one "down" valence quark (with charge −1/3) plus sea quarks and gluons which give no total net charge. The total charge of the proton, naturally, works out to be +1. By a respected principle, called isospin invariance, the neutron is regarded as being identical to the proton except that one interchanges one up quark with one down quark to create a neutron. Therefore, the neutron has two down quarks and one up quark for a total neutron charge of zero.

To address the issue of the proton spin crisis, SLAC first sought to measure the neutron spin structure function. The experiment, E142, required reopening the fixed-target facility that had not operated at high energies since the early 1980s. E142 required a 23-GeV polarized electron beam using the entire accelerator to achieve the full energy. Luckily, the polarized beam facility already existed and worked reliably owing to the enormous effort invested in polarizing the electron beam for the Linear Collider project, the flagship at the time. The beam was directed into End Station A where it scattered off a polarized ^{3}He target. The scattered electrons were then detected in a spectrometer that determined the scattered electron's energy after the interaction (see diagram on the bottom left).

Why use polarized ^{3}He? It turns out that it is virtually impossible to create a neutron target. Free neutrons live only about ten minutes, and they are hard to contain. In fact, the highest density of neutrons to date comes from those contained in a bottle at ultra-cold temperatures next to a nuclear reactor. In addition, the density is tiny, not enough to perform a high energy physics scattering experiment. Since we cannot produce a free neutron target, we have to use nuclear targets and then infer the contribution coming from the neutrons inside.

The polarized ^{3}He nucleus is an elegant approximation to a polarized neutron. The nucleus of ^{3}He consists of two protons and one neutron. When one polarizes the ^{3}He nucleus, the neutron spin aligns itself in the same direction as the ^{3}He nuclear spin, whereas the two proton spins line up anti-parallel to one another according to the Pauli exclusion principle (see the top figure on the right). Therefore, scattering off a polarized ^{3}He nucleus is equivalent to scattering off a polarized neutron plus

Set-up of the SLAC E142 experiment.



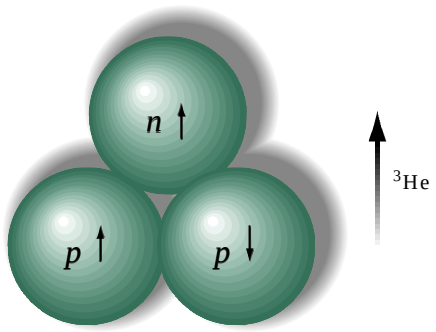
two unpolarized protons on average. Any effect in the experiment that depends on target spin will be largely a result of scattering from the polarized neutron in ^{3}He itself.

Armed with a high density polarized ^{3}He gas target, E142 measured for the first time with relatively high precision the neutron spin structure function. The results were interesting and at first somewhat controversial. The results on proton spin crisis implied that the neutron spin structure results should give large negative asymmetries. However, E142 found small negative results. The difference between expectation and experimental measurement generated controversy in the field. But in parallel, theoretical work on strong interaction corrections was being developed. With these new corrections, the proton and neutron results appeared to be reconciled. Here was a case where the interaction between new experimental results and advances in theoretical work pointed towards a coherent description of the proton and its spin.

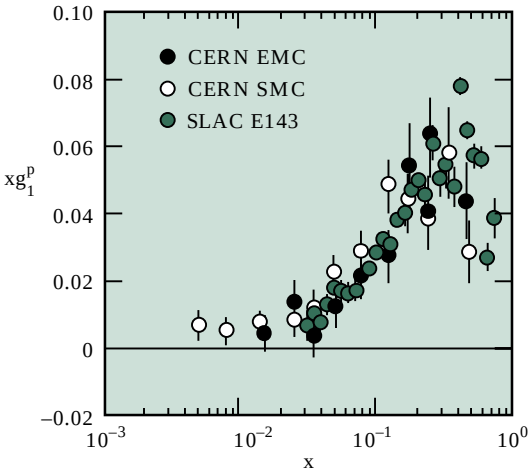
A year later in 1993, SLAC ran an incredibly high precision measurement of the proton and deuteron spin structure function in experiment E143 using the facility built for E142. The experiment confirmed both the 1988 EMC proton measurement and the E142 neutron result. The deuteron consists of one polarized proton and one polarized neutron. If one scatters electrons off the deuteron and subtracts the proton result, one gets an independent neutron result. The results from the E143 proton measurement are compared to the EMC result in the bottom right illustration.

The statistically precise data set from SLAC provided by the E142 and E143 experiments represented a major advance in the field. Theoretical corrections became an important ingredient for interpreting the results and developing a consistent picture of the quark contribution to the proton's spin. In parallel with the SLAC program, CERN continued collecting data with an upgraded version of the EMC experiment called SMC (Spin Muon Collaboration). The CERN experiments had a deeper view into the nucleon coming from the 200-GeV beam, but the SLAC experiments had the higher statistical precision. Today the world data sample with modern theoretical corrections appear to give a 30 percent contribution to the proton's spin coming from the quarks. The psychology of the community has evolved since 1988. With an initial result of a quark contribution between 0 and 20 percent, a change to a 30 percent result appears to be viewed as more palatable. Still, where is the rest of the proton's spin?

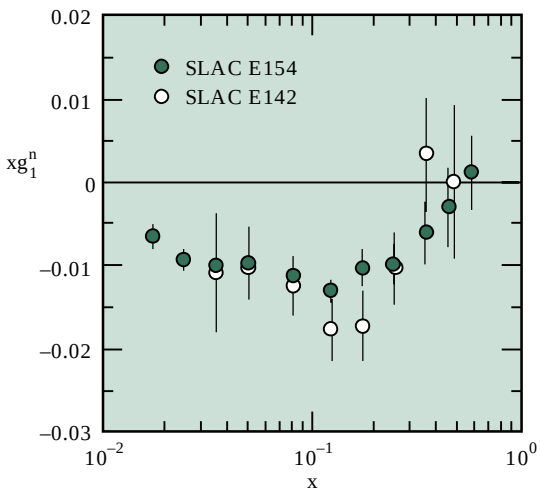
But the quark story was not over. The experiments at SLAC in 1992 and 1993 suffered from one significant weakness. They were performed at relatively low energies—20 to 30 GeV. Remeasuring the spin structure functions with the high precision and a higher energy beam would help solidify the results and check their interpretations. Theoretical corrections are very energy dependent and become large at low energies. Testing that one gets the same answer with smaller theoretical corrections at high energies was well motivated. In response, SLAC upgraded the beam energy for the fixed-target program to 50 GeV. Although this energy is



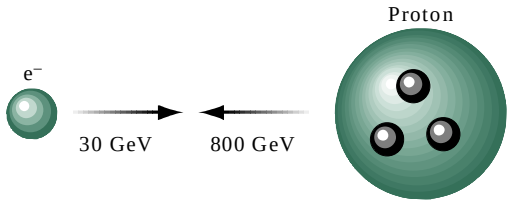
Spin directions of the protons and neutron in polarized ^{3}He.



World data on the proton spin structure function versus x.



Neutron spin structure function data versus x from SLAC Experiment 142 (1992) and Experiment 154 (1995).



Center of Mass Energy

$S \approx 300$ GeV

Fixed Target Equivalent Energy

$E_e \approx 50$ TeV

Energies of the electron-proton collider program at DESY in Germany.

only twice that of the previous experiments and still a factor of four lower than the CERN muon beam, the corrections get smaller rapidly as the energy increases—in particular changing from 20 GeV to 50 GeV.

In the fall of 1995 SLAC ran the first 50-GeV fixed-target experiment. The experiment, E154, collected about 100 million electron scattering events in a two-month running period with an 80 percent polarized beam scattering off a new thin-windowed high density ^{3}He target with up to 50 percent polarization for the ^{3}He nuclei. The experiment was a roller-coaster ride, since numerous target cells exploded in the beam. Without giving exact numbers, enough targets vented that there were, indeed, some interesting meetings between the SLAC directorate and the experimentalists during the experiment. Target replacements were especially painful, since it took a full day to repolarize the new target up to reasonable polarization values. But by the end, the story was a success. Enough high quality data were eventually logged to tape—especially in the last week—that the proposal specifications were actually met. The high statistical precision of E154 experiment set a new standard for measurements of the neutron spin structure function. The top left figure shows a comparison of the result from E154 with those from the 1992 experiment E142.

Presently E155, the twin of E143, is collecting data. The experiment is remeasuring the proton and deuteron spin structure functions with high precision using the new 50-GeV beam facility. The final set of data over the five year period from the End Station A fixed-target program represents a powerful compilation of spin structure function results for the proton and neutron. It is difficult to envision any future experiments outdoing the precision of these SLAC experiments in this energy range.

THE FUTURE

Where is the field heading? Are we done? Are the last measurements just clean-up? The quarks carry about 30 percent of the spin, today's best guess. Now what? What is left?

There is a missing 70 percent to our puzzle. There is high expectation that much of this contribution is coming from the gluons in the nucleon. The gluons have spin 1 and they can conspire to add up and give a contribution to the proton's spin. But there is little experimental evidence for the existence of the gluon's influence on the proton's spin. The future of the field is to hunt down the gluons.

There are presently two methods to go out and to trap the gluon's spin. One is to continue running mercilessly the deep inelastic scattering spin experiments and to exploit them at ever increasing energies. A natural, ambitious continuation is to take the HERA collider program discussed in the beginning of this article and polarize the electron and proton beams. The electron beam at HERA is actually already polarized for a fixed-target program called HERMES. Polarizing the proton beam would allow for a truly high energy measurement of the proton spin structure function (bottom figure on the left). As one accesses higher and higher energies in proton or neutron

scattering, one sees the structure functions at lower and lower x. Gluon effects are expected to show up at low x. So studying the shape of the spin structure functions at high energies may be one of the best windows on the gluons and their impact on the proton spin. Another idea in such a program would be to inject polarized ^{3}He into the HERA proton ring. This would, of course, allow for a high energy measurement of the neutron spin structure function to match the proton measurement.

A second endeavor to learn about the gluons—perhaps more directly—is to study jet production from proton collisions at high energies. When some probe interacts with the proton (either an electron, a muon, or another proton), one can break up the proton and identify the final-state particles. Some of these particles have a production that depends heavily on the existence of gluons. By studying these particles and their spin dependence, one can infer the gluon effects. There is a program approved to collect data at CERN called COMPASS that will use an upgraded muon beam line in a new fixed-target program to try to identify these final state effects. Possibly the most promising program in the near future, however, will come from high energy polarized proton-proton collisions produced at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. Observing a clear gluon spin signature is rapidly becoming the target for the field.

I am often asked why it is interesting to continue studying the proton's spin and characterizing what contributes to the spin. The question has different answers depending on the physics problems being addressed.

To the atomic physicist, the proton is a fundamental piece of the hydrogen atom. The interaction of the proton with an electron represents more-or-less the birth of atomic physics. Effects due to spin-dependent interactions are known to affect high precision atomic spectroscopy. The splitting of the hyperfine interaction in hydrogen, for example, actually has a term that depends on the proton spin structure function.

To the nuclear physicist, confinement and how a proton is bound to a neutron (in the deuteron) is probably the most fundamental question in the field. Since the proton and neutron are complicated, understanding this complexity is critical to understanding binding between each other and within nuclei, in general. No longer can one think of the proton and neutron as individual particles. One needs to understand what is inside to understand why they are bound together and how the strong interaction works.

To the particle physicist, the proton is the most promising tool for studying high energy interactions and searching for new forces. The largest high energy accelerator project in the world, called the Large Hadron Collider, now being constructed at CERN, will search for new particles coming from the interaction between two colliding high energy (7 trillion electron-volts) protons. Backgrounds from proton-proton collisions coming from the internal structure must be understood in order to detect new interactions. The backgrounds depend on understanding the proton structure. The discovery of the top quark (see "The Discovery of the Top Quark," by Bill Carithers and Paul Grannis, in the Fall 1995 *Beam Line*, Vol. 25, No. 3) was a detailed study of extracting a signal above large strong interaction backgrounds.

All three fields of physics mentioned above are needed to run the spin structure function experiments successfully.

Finally, there is spin as a quantum number and its importance to physics in general. The most studied, but unconfirmed, theory today is called supersymmetry (refer to "Whatever Happened to the Theory of Everything?" by Lance Dixon in the Summer 1994 *Beam Line*, Vol. 24, No. 2). Supersymmetry is mathematically elegant. It gives mass to the various particles that we observe. It is a strong basis for the most popular unified theoretical studies today (superstrings). And it unifies the fermions and bosons. Spin is critical to the theory as it is to quantum mechanics. The present article discusses spin as it applies to the proton's structure. This is only one facet of spin's effect on fundamental particles and nuclei. We still do not understand the origin of spin. Lurking in the background of all spin studies is this global question. And although there is no well-defined program that directly attacks the mystery of the origin of spin, it is an unavoidable player in much of modern-day physics. If one were to look back from the twenty-first century and judge the greatest physics advances in the previous century, it would be delightful to claim to have cracked the mystery of the origin of mass and spin in our Universe.

Pumping Out the

by SIDNEY PERKOWITZ

Research is thriving at Brookhaven's National Synchrotron Light Source.

LIGHT SOURCES FOR RESEARCH, which generate photons at high intensities, at unusual wavelengths, or under exquisite control, span a huge range in size. The smallest, those that produce a single photon, are essential if we are ever to understood the dual nature of light. The largest include lasers for thermonuclear fusion, such as the 500-foot National Ignition Facility recently proposed for Livermore; it would create conditions something like the early Big Bang inside a pellet of deuterium and tritium.

Equally impressive in its sheer massiveness, but designed for a different purpose, is a light source that has reached maturity during the last decade, the synchrotron. Its radiant power is not sufficient to emulate the early universe, but it is still enormous compared to other sources. And it comes with a bonus: unlike a laser, its power is emitted over much of the electromagnetic spectrum. Synchrotons offer a unique combination of high intensity and versatility; that is why those who use light as a research tool—from X rays to the far infrared—are flocking to these new sources.

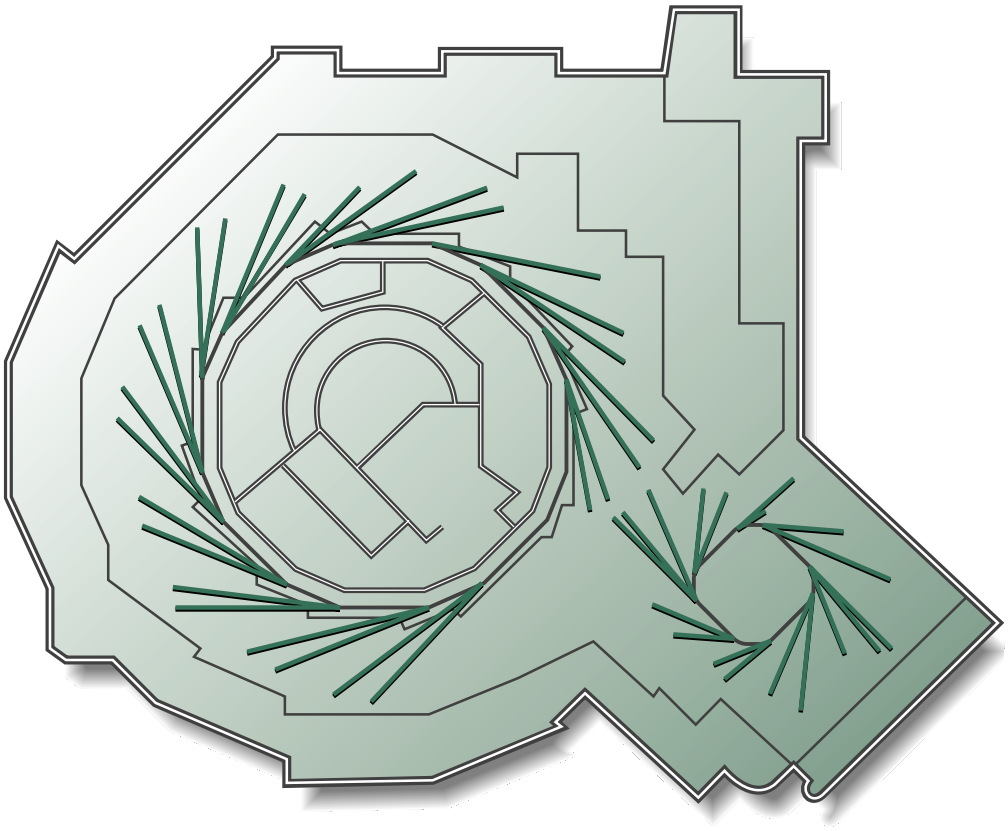
The synchrotron is descended from the cyclotron that Ernest O. Lawrence developed at Berkeley in the 1930s to study atomic nuclei and elementary particles, beginning a line of machinery that has dominated these fields of research ever since. In a synchrotron light source, electrons enter a tunnel formed into a horizontal ring up to thousands of feet in circumference. They are held in orbit around the ring by strategically placed magnets, while they receive bursts of energy that bring them near the speed of light. As the energetic charged particles swing around the circle, they deform the electromagnetic lines of force that bind them to the rest of the Universe. That makes a cascade of radiation millions of times stronger than any

Photons

conventional source emits, covering wavelengths from the X-ray region to the infrared. This light emerges in an extremely narrow beam, so its full power can be delivered to a small area. And the light pulses on and off as each group of electrons circles the ring, like a great photographic flash unit blinking on a time scale of trillionths of a second.

This mighty source of photons illuminates the properties of solid matter, and of biological systems from molecules to organisms. Unlike elementary particle physics and space science, research in these areas has traditionally flourished at the small-scale, table-top level. Now individual researchers rely on these centralized light sources, a new kind of big science that enriches the meaning of a synchrotron facility. I have visited several, but know best the one where I ran experiments, the National Synchrotron Light Source (NSLS) at the Brookhaven National Laboratory, located on Long Island some 50 miles east of Manhattan.

When I returned there not long ago, I drove; but even from the air it is easy to pick out the synchrotron because its form so clearly follows its function. Its circular building echoes the huge ring around which electrons race to make X rays. Linked to that ring is a smaller but still large doughnut for ultraviolet and infrared light, where I ran my experiment. Its hangar-like enclosure has an industrial look—exposed girders, a crane to lift massive machinery, pitiless heavy-duty lighting. Mounds of research equipment fill the area around the ring with obscure shapes in stainless steel, festoons of electrical cabling, and flashing digital displays that embody data on the fly. This confusion is typical of a working laboratory, but the essential design of the synchrotron imposes an underlying order. The apparatus is arranged in clusters, each sitting at the end of a pipe—a beamline—from which photons



Layout of the beam lines at the National Synchrotron Light Source. Two electron storage rings feed X rays or vacuum ultraviolet radiation (VUV) to nearly 100 experimental stations.

emerge, like a farm field watered by an irrigation channel. Each beamline feeds experiments sponsored by a given institution or consortium. The result is one of the world's denser concentrations of scientific effort, with nearly a hundred research stations at the X-ray and ultraviolet rings.

In this surreal environment, it is comforting to see that each experiment is based in a human-scale lair fashioned from desks, chairs, computers, and racks of electronic gear. These dens surround the synchrotron like huts around a campfire, but the inhabitants are rarely visible among the thickets of equipment. Only traces appear—empty soft-drink cans, a chess board and pieces atop one cabinet, a toy pink flamingo peering down from another, a sign that pleads "Please don't feed the scientists." Any scientist sighted through the hanging electrical vines is likely to be a younger member of the species. Graduate students, and research associates just past their doctorate, do much of the day-to-day taking of data.

The synchrotron runs hard except when it must be closed for maintenance or modification, steadily pumping out photons to drive down their unit cost. Data may come at any hour of day or night, and it is never easy to get all the delicate equipment on a given beamline operating well at the same time. Motivation is strong to keep taking data as long as everything works. This accounts for the all-night atmosphere of crumpled soda cans and empty coffee cups that I could see especially well when I carried out research at NSLS, because my experimental station was located above the ring.

Apart from the demanding hours, the research floor is a difficult place to work, with its harsh lighting and ceaseless background noise. It is not that photons pop out of orbiting electrons with cracks of sound, like tiny lightning bolts with minute thunder. Photons are noiseless, even as they are created; lightning makes thunder only as it affects the air through which it flashes. But the synchrotron and the beamlines are evacuated, to keep air molecules from deflecting electrons and photons. The large mechanical pumps that maintain this emptiness produce the unpleasant noise. And always there is the knowledge that uncontrolled synchrotron radiation can be dangerous. Horns blare and lights flash every few hours when new electrons are about to be pumped into the ring, because that carries a danger of escaping radiation. Everyone leaves the research floor before any such "fill."

A view of the experimental floor at the NSLS VUV ring. (Courtesy Gwyn Williams, NSLS)

THE SYNCHROTRON is also a wonderful place to work. Its demanding aspects lend urgency and mystique to this huge enterprise of light, where research is at the cutting edge. The cheek-by-jowl conditions bring a remarkable cross-fertilization among scientists whose only common interest may be what light can do. When I ran my experiment there, I continually encountered friends and colleagues doing a variety of research within a few steps of my own station. Such interaction is a fruitful aspect of this particular brand of big science. To some extent, it eases older images of science as a lonely enterprise.

Among the hundred-odd beamlines, uses across scientific fields come thick and fast. Much of the work is fundamental, such as the effort in which I was involved—a study of one of the fascinating materials called superconductors. These have a seemingly magical property: when cooled to a certain temperature, they lose all electrical resistance, carrying current without losing any of its energy as heat. This happens in certain solids whose quantum rules permit cold electrons to march in lockstep like trained troops, rather than in chaotic motion like a fleeing crowd. The effect has been known since 1911, but its perfect efficiency never had a dream of commercial application because the necessary temperatures were impractically low, near absolute zero. In 1987, however, the physicists Johann George Bednorz and Karl Alex Müller, of the IBM Research Laboratory in Zurich, made an astonishing discovery that won them a Nobel Prize. They found a new class of "high-temperature" superconductors that lost resistance at much higher temperatures, still far below ordinary cold, but that could be easily reached by refrigeration. The discovery set off a worldwide scientific frenzy to understand and use these materials.

Our measurement was made to see if one of these complicated compounds, yttrium barium copper oxide (or YBCO, for short), obeyed the prevalent theory. This theory predicts that a superconductor has a gap in its energy levels somewhat like the band gap of a semiconductor. If the gap existed in YBCO, it would reveal its presence by absorbing certain infrared photons, as each type of semiconducting material absorbs characteristic wavelengths of visible or infrared light. But there was a problem; our sample was a thick slab of material that transmitted little light. Only the synchrotron provided enough infrared power to penetrate the sample, which enabled us to carry out the first such measurement ever made. Our data indeed

The NSLS VUV ring with its radiation shielding removed. (Courtesy Gwyn Williams, NSLS)

seemed to show the predicted light absorption, but with unexpected complications that make its interpretation uncertain. Despite this and many other efforts, the high-temperature superconductors remain puzzling. Infrared data, however, give important clues, and our results could not have been obtained without the high power of the synchrotron.

THE FACT that synchrotron radiation emerges in a narrow beam makes possible other unique research, such as the X-ray analysis carried out on a minute strand of the element bismuth, less than a hundredth the thickness of a human hair. Bismuth is interesting in its own right, for it is akin to both a semiconductor and a metal; but the value of this measurement was in establishing that the tiny filament was of crystalline form, making it probably the smallest crystal ever observed. Novel man-made materials, especially biological ones, are often made first in extremely small lots, which can be examined only by the fine beam of synchrotron light.

Other work at NSLS involves surface science, the study of how atoms and electrons behave at interfaces, such as that between the semiconductor silicon, and air or vacuum. The behavior deep inside a crystal is understood through its unrelentingly repetitive atomic geometry, but the regular array of atoms stops abruptly at the surface. This boundary region is difficult to describe, raising fundamental questions about surface behavior. The answers are significant for the semiconductor industry, where silicon chips must be made with pure surfaces before they can be turned into devices—and for industrial processes based on chemical reactions, such as the refining of oil and the manufacture of plastics. These depend on catalysts, compounds that accelerate chemical reactions without themselves changing. Many catalytic reactions occur best at interfaces; for instance, the catalytic converters used in automobiles contain platinum or palladium arranged with maximum surface area to clean polluting chemicals from the exhaust.

These industrial needs benefit from fundamental studies of surfaces. Whenever atoms of one type attach themselves to a surface of a different sort—say oxygen on silicon—they oscillate at specific frequencies that can be analyzed to determine their arrangement and linkages. The oscillations can be examined by infrared light—but at wavelengths, as it happens, where adequate sources have been in short supply until infrared synchrotron light became available. Other synchrotron studies use ultraviolet photons in a kind of photoelectric effect that drives electrons out of atoms at the surface to determine the electronic energies.

The cheek-by-jowl conditions bring a remarkable cross-fertilization among scientists whose only common interest may be what light can do.

And X rays from the synchrotron provide short wavelengths to resolve the geometric arrangement of surface atoms, just as they give structural details for solids.

Other efforts at NSLS are explicitly devoted to industrial technology. One is X-ray lithography, a means to pack silicon chips more densely with the intricate conduits that make up electronic circuits. The smaller these channels, the more devices can be crammed onto a piece of silicon. That march to smaller features has steadily increased the capacity of random-access memory chips for computers. But it is limited by the wave nature of light, which enters through photolithography, the technique that puts the pattern of channels onto the silicon. A wafer of silicon is coated with a light-sensitive chemical called photoresist. Light shines through a stencil or "mask" of the desired pattern, casting its image on the wafer. The exposed photoresist (for some types, the unexposed material) is easily removed, and the remaining chemical defines the pattern for further processing.

No matter how narrow the features in the mask, the width projected onto the silicon surface is affected by the illuminating wavelength. When light passes through an opening, it diffracts—that is, spreads out beyond the limits of the opening. The smaller the wavelength, the more photon-like the light, and the less the diffractive effect. With visible light, the features on a chip cannot be made smaller than half a micrometer across. That is only a tiny fraction of the width of a human hair, but as has been demonstrated at NSLS, short-wavelength X rays reduce the scale tenfold. This can translate into hundredfold gains in the density of electronic devices, and there are plans to standardize X-ray lithography for the semiconductor industry.

THE PATTERNS cut into silicon are complex, but biological patterns are even more so. Synchrotron light explores them in novel ways. Molecular biologists seek to understand the structural characteristics of molecules such as proteins, which determine their biological functions. X-ray and ultraviolet analysis can determine the positions of the atoms and how they are linked, but the data are not easy to come by for these large, intricate molecules. In pre-synchrotron times, X-ray data could not completely explain the structure of DNA, although they were the main clue that in 1953 led James Watson and Francis Crick to the double helix. Even later, in 1965, thousands of conventional X-ray images had to be assembled to give the first fully determined structure of an enzyme, one of the biochemical catalysts that accelerates the processes of life.

Such laborious analysis is speeded by the high power of the synchrotron, which reduces the time needed to obtain an X-ray image. And the harm X rays do to biological systems is minimized when the radiation comes in the short bursts inherent in the synchrotron. Compared to conventional methods, more data can be obtained before the sample deteriorates. This feature enters into a new research instrument, the X-ray microscope. It sees more finely than does a conventional visible-light microscope, for the same reason that X rays make finer lithographic patterns than does visible light. Because of diffraction, no detail smaller than the wavelength of the illuminating light can be seen. With visible light, the limit is half a micrometer or 500 nanometers. The intense but not too destructive short- wavelength X-rays at NSLS are the heart of a microscope that has discerned features down to 60 nanometers across in chromosomes, cells, and bone cartilage.

And the pulsed light of the synchrotron provides new views of biological behavior. It is molecular structure changing in time that leads to biological function. In the human eye, for instance, a change in shape of the molecule called rhodopsin—a tiny atomic gate swinging shut in response to an incoming photon—begins the act of interpreting light by the brain. Each rapid blink of synchrotron light can "freeze" a different configuration of a molecule. The changes in rhodopsin, and in the amino acids that comprise a protein, have been studied in this way. Ultraviolet synchrotron light has also

Aerial view of the National Synchrotron Light Source at Brookhaven National Laboratory.

examined the shape of a protein occurring in the bacteria that causes Lyme disease, with its severe effects on heart, nervous system, and joints. The results elucidate how the body's immune system recognizes foreign organisms, a fundamental question whose answer may also aid in treating the disease.

Synchrotron light is more than a biological research tool. Clinical diagnostic medicine is also carried out at NSLS, in the coronary angiography project that uses synchrotron light to form images of the coronary arteries. These narrow conduits, no more than an eighth of an inch across, carry oxygenated blood to the heart muscle itself, with serious consequences if they become choked with fatty plaque. In the standard method of examination, a liquid that absorbs X rays is injected directly into the coronary arteries, through a long narrow tube called a catheter. This enhances a conventional X-ray image sufficiently to show the condition of the arteries, but the insertion of a catheter into a coronary artery has its hazards. The risk is lower if the high-contrast liquid is injected into a vein; then, however, it is diluted by the time it reaches the coronary arteries, which degrades the image.

With X rays from the synchrotron, physicians can use the safer injection into a vein. The high power and the choice of wavelengths combine to give a clear image, with the patient receiving no more radiation than in the conventional method. Since 1990 patients have come with their physicians to NSLS. They are examined in a facility designed to minimize the inevitable reaction to this unorthodox approach. The treatment room resides at the end of a beamline, but one that has been separated from the main floor. The patient enters it without seeing the enormous machine whose light will soon penetrate his body. Still, the room is not especially comforting, but no worse than other medical technology we have all confronted. I myself would much rather occupy its patient's chair than enter again the tight tunnel of a massive MRI machine, where claustrophobia can approach panic proportions.

That chair, resembling an old-fashioned barber chair, rests in line with the X-ray beam from the synchrotron. There the patient sits, after the high-contrast liquid has been injected into a vein. The members of the control and observation team work in an adjacent room, viewing the scene through glass that shields them from the radiation. They move the chair by remote control to briefly align the patient's heart with the beam. In a few minutes the image appears on a computer monitor, ready to be examined. Although the technique is highly promising, there is one worrisome aspect—what it would cost to build a single-purpose

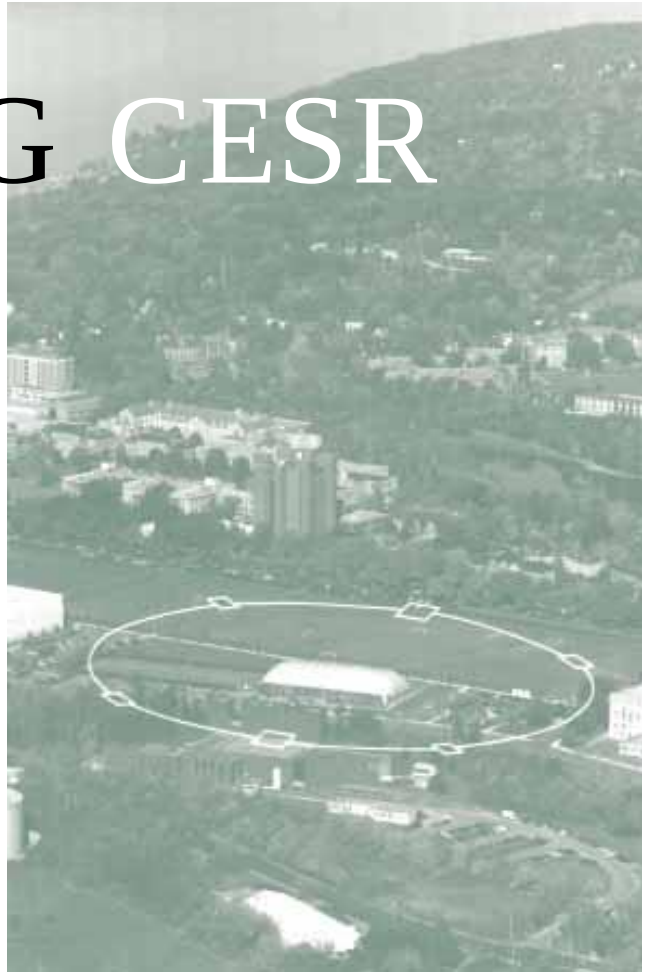
synchrotron devoted to clinical medicine. Improvements such as efficient magnets to control the electrons can reduce size and cost; but even a vastly scaled-down synchrotron is in the ten million dollar range.

DURING MY VISIT I spoke with Gwyn Williams of NSLS, who had provided the synchrotron expertise and equipment for our joint superconductor measurement. Like most working researchers, this mustachioed, British-born scientist was dressed casually, in jeans and running shoes. His devotion to the machine never flags, and he is always ready to talk about it, with such intense focus that he usually answered my question before I finished asking. He emphasized how young synchrotron science really is. NSLS has been running for over a decade, but it "takes ten years to get a synchrotron fully tuned up," he said. Improvements in this complex machine are still coming. Recently, for instance, it was noted that the beam of electrons wandered slightly as it dashed through the synchrotron tunnel. New controls have reduced this drifting, resulting in more stable light beams. Such improvements, along with novel approaches, are appearing in other designs. Synchrotron radiation laboratories, in fact, are springing up around the world—about forty, from proposed to operational, in fifteen countries. The newest in the United States include the Advanced Photon Source, whose ring two-thirds of a mile in circumference is located at the Argonne National Laboratory in Illinois; and the Advanced Light Source at the Lawrence Berkeley Laboratory, located in the same building that once housed a forerunner, one of the cyclotrons that Ernest Lawrence built.

That connection to a pioneering "atom-smashing" machine underlines an important theme in research with synchrotron light. In its earliest days, physics—and all science—was less differentiated than it is now. Only in our time has specialization reached the point where condensed-matter researchers, say, and elementary-particle physicists, seem to share precious little common ground. In a similar vein, "pure" and "applied" science and scientists often seem hardly to overlap. But although huge new accelerators have supplanted the synchrotron in cutting-edge elementary-particle research, this line of machinery has become essential for those who study living and nonliving matter at the level of atoms and molecules, crystals and biological cells; and for those who use light to develop electronic and photonic devices. The use of synchrotron light connects the table-top style of condensed matter research and biomedical science to the big-machine culture of high energy physics, and the societal impact of new devices to the philosophical purity of elementary particles—a subtle but significant contribution to the unity of science.

UPGRADING CESR

by KARL BERKELMAN



Experimental sensitivity to rare decay processes will be greatly increased by the upgrade of the Cornell Electron Storage Ring and its detector facility.

The Two Frontiers

OUR PRESENT PARTIAL UNDERSTANDING of the physical world is embodied in the Standard Model. It relates the behavior of matter in all its forms to the properties of a few fundamental constituents—the six kinds of quarks and six kinds of leptons. It unifies the phenomena of electromagnetism, weak decays, and the strong interaction that binds hadrons and nuclei, and explains them in terms of the exchange of several kinds of intermediate vector bosons—the photon, the W and Z, and the gluon. It successfully correlates the results of many experiments. But it is widely recognized as being incomplete.

How do the elementary constituents get their masses, and why do they have those particular masses? How does gravity relate to the other forces? Why are there six flavors of quarks and leptons, and are the quarks and leptons really fundamental or are they composites? What is the mechanism for the small violation of particle-antiparticle symmetry (CP violation) observed in K meson decays, and how did matter win out over antimatter in the Universe?

To answer these questions theorists have suggested various extensions to the Standard Model. These typically involve hypothetical particles that have not yet been discovered: heavier quarks and leptons, heavier copies of the W and Z intermediate bosons, Higgs bosons, supersymmetric partners of the known particles—squarks, sleptons, and so on.

Aerial view of the Cornell University campus, indicating the location of CESR, forty feet below the intramural athletic fields.

Why haven't we seen any of these particles? Maybe it is because they are unstable and decay too rapidly. So instead of looking for such a particle in the wild, we can try to create it at an accelerator. For the direct production of such new particles, the energy of the collision has to be far enough above the Mc^2 threshold for the creation of the new mass M. New particle production has historically been a successful route to exploration of new physics as frontier accelerator facilities have opened up new energy ranges. Here are a few examples, involving the discovery of the antiproton and of some particles containing heavy quarks.

$pp \rightarrow pp p\bar{p}$	Bevatron	1956
$e^+e^- \rightarrow \psi$	SPEAR	1974
$e^+e^- \rightarrow B\bar{B}$	CESR	1980
$pp \rightarrow t\bar{t}N^*\bar{N}^*$	Tevatron	1995

This is in fact the prime motivation for the next generation of accelerators—the Large Hadron Collider at CERN in Geneva, Switzerland, and the next linear e^+e^- collider wherever it may be built. But exploring new physics at the energy frontier is expensive, requiring billions of dollars for the accelerator and for the experiments.

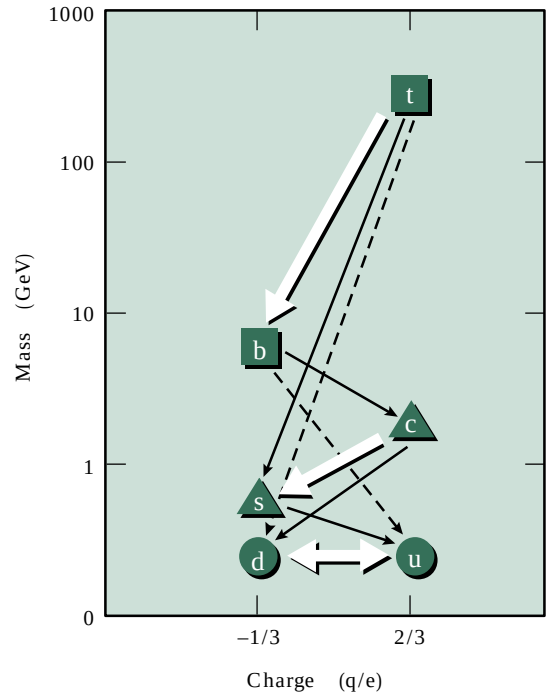
But there is another way. The Heisenberg Uncertainty Principle allows the momentary occurrence of an unstable high-mass particle in an intermediate stage of a multistep process even when the total energy available is less than the Mc^2 of the free particle. A familiar example is the evidence for the Z that came from mu-pair production experiments at the PETRA e^+e^- collider in Hamburg, Germany. Although the total energy was 45 GeV, the effect of the 91 GeV Z could be seen clearly in the forward/backward asymmetry caused by the interference of the usual $e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-$ amplitude and the $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ amplitude. In this way the Z mass was estimated before the Z was first produced and detected in the UA1 experiment at the CERN proton-antiproton collider.

Exploring high masses with lower energies gets you early access to new phenomena. But that doesn't make it easy. You have to understand the Standard Model prediction well, and your experiment has to be sensitive to small rates or accurate enough to detect small deviations from the predictions. Instead of the *energy frontier*, we might call this the *sensitivity frontier*. They are complementary. The sensitivity frontier is where you can get the first indication of new physics, and the energy frontier is where you make the more definitive explorations of the new phenomena.

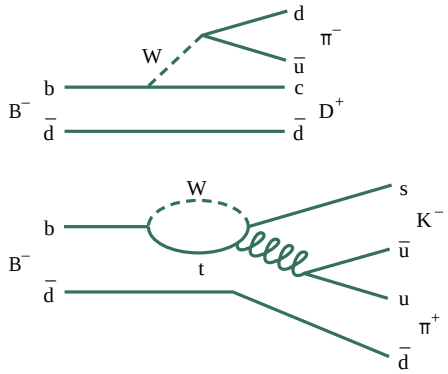
RARE *B* MESON DECAYS

B mesons are made of one b quark and one ordinary $\bar{u}$ or $\bar{d}$ antiquark. The rates for their decays are sensitive to the presence of high mass particles in intermediate states. To see why this is so, I first have to explain how quarks decay.

The illustration above shows the six quarks in mass versus charge. They are paired in three doublets of charge $(-\frac{1}{3}, \frac{2}{3})$: (d,u), (s,c), and (b,t). In the weak decay process a heavier quark can transform into its lighter partner by emitting a W boson that can subsequently materialize as a lepton pair or quark pair. There is also a smaller probability for decay to a quark in a different doublet.



The masses and charges of the six quarks. The arrows show the allowed flavor changing direct weak decay transitions with the relative probablilities indicated.



Feynman diagrams for two B *meson decay processes. A diagram represents the propagation and interactions of particles in space and time, with time plotted horizontally and a space coordinate vertically. The diagram on the top shows an example of a favored direct decay of the* B *meson,* B → Dπ*, in which the* b *quark emits a* W *boson and becomes a* c *quark. The* W *becomes a quark-antiquark pair. The diagram on the bottom shows an example of a rare two-step decay,* B → Kπ*, in which the* b *quark first becomes a* t *quark by emitting a* W *boson and then reabsorbs the* W *to become an* s *quark. Another quark-antiquark pair is produced through an intermediate gluon.*

These relative probabilities are suggested by the widths of the arrows in the figure on the previous page. They are called the "flavor-changing charged-current" decays.

Consider the case of the b quark. A decay to its heavier partner, the t, would violate energy conservation. The other two possiblilities, decay to c or u, have low rates because c and u are outside of the (b,t) doublet. As an alternative to these direct processes involving a change in the charge of the quark, the Standard Model also predicts a two-step process that results in a quark transition with no charge change, that is b-to-s (or $-d$) (see diagrams on the left). In these effective "flavor-changing neutral-current" decays the b makes two successive charge changing transitions, becoming a quark of the other charge (u or c or t) in the intermediate stage. The W boson that is emitted in the first step is reabsorbed in the second. The momentary violation of energy conservation in the intermediate stage considerably depresses the transition rate, but since the direct rate is also suppressed, the two-step b-to-s (or $-d$) decays have a chance to compete with the direct b-to-c (or $-u$) modes. The two-step flavor-changing neutral-current decays have been called "loop" or "penguin" decays. The latter name was invented by John Ellis of CERN, who had to pay off a debt by getting the word "penguin" published in *Phyical Review Letters*.

An analogous two-step process is responsible for the transition that can convert a $b\bar{d}$ neutral B meson into its $\bar{b}d$ antiparticle. The intermediate stage again involves the W and a quark of the other charge. When two of these processes—direct decay, penguin, particle-antiparticle oscillation—produce the same final state, the interference of the two amplitudes can lead to a violation of the particle-antiparticle symmetry called CP. CP violation has been seen in K decays and it is expected in B decays. One must either measure an asymmetry between the rates for some B meson decay mode and its corresponding antiparticle mode, arising from interference between the direct and two-step decays, or one must observe an asymmetry in the time evolution of of the decays of originally produced B^0 and $\bar{B}^0$, arising from an inteference between the $B^0 \leftrightarrow \bar{B}^0$ oscillation and the direct decay (see the article by Michael Riordan and Natalie Roe in the *Beam Line*, Vol. 26, No. 1, Spring/Summer 1996).

The first clear evidence for a penguin decay, $B \to K^*\gamma$, was reported by the CLEO experiment at CESR in 1993 (see the figure at the top of the next page). The quantitive comparison with theory had to wait until the next year's publication of the CLEO measurement of the inclusive branching fraction $(2.3\pm0.7)\times10^{-4}$ for the radiative B to any single- or multiparticle strange meson state $B \to X_s\gamma$, and for the recently completed Standard Model calculation, which predicts a compatible $(3.3\pm0.4)\times10^{-4}$.

Why all this interest in penguins? It is because some hypothetical massive particle representing a new extension of the Standard Model could replace one of the particles in the intermediate loop stage. The agreement between the CLEO data and the Standard Model prediction already places strict limits on possible new physics. For instance, if you added

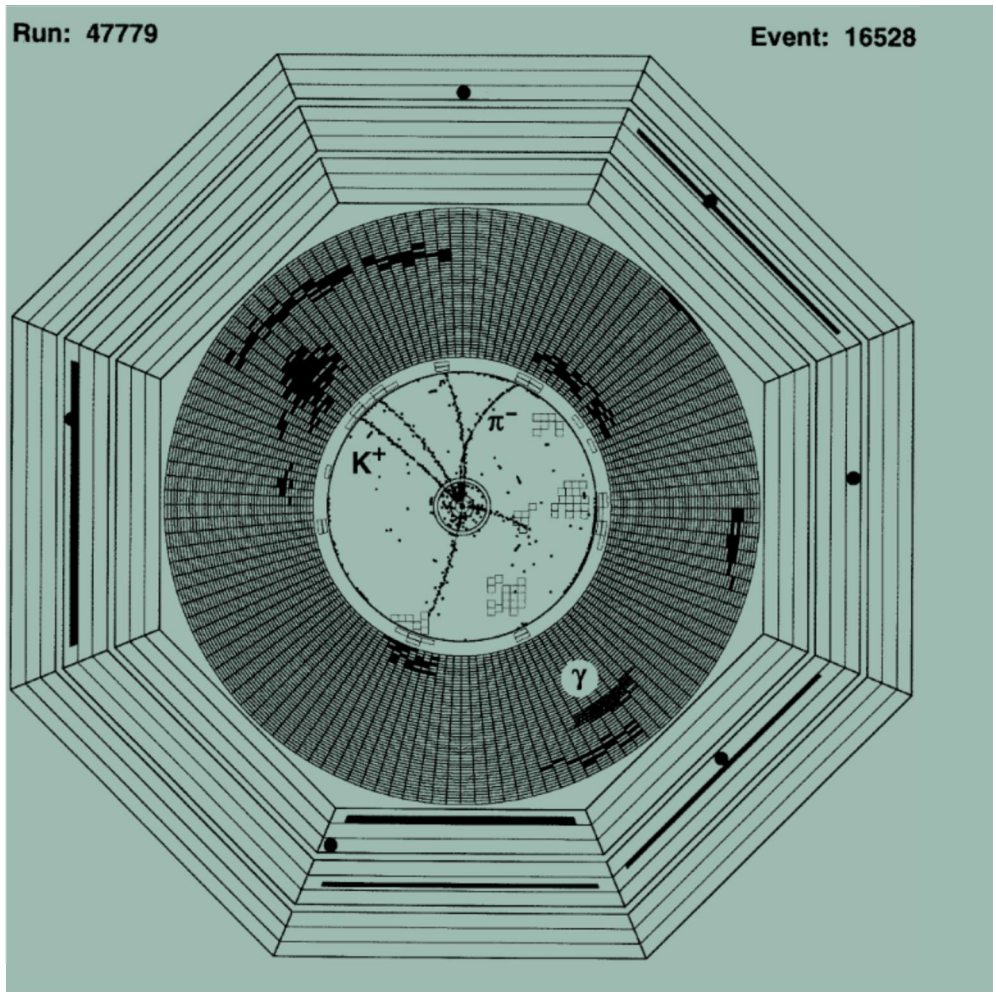
just a charged Higgs boson to the Standard Model, $M_{Higgs}c^2$ would have to be greater than 260 GeV to keep the $B \rightarrow X_s\gamma$ prediction compatible with the data. It is remarkable that the limit set by a *sensitivity* frontier experiment at the CESR 5 GeV storage ring can be very much more stringent than the limits of around 70 GeV set by the searches for charged Higgs production at the LEP *energy* frontier.

CLEO has seen evidence for other possibly penguin-dominated decays: $B^0 \rightarrow K^+\pi^-$ or $\pi^+\pi^-$, $B^- \rightarrow \omega K^-$ or $\omega\pi^-$, and similar final states without c quarks. The $K^+\pi^-$ mode is especially interesting, because of a possible CP-violating asymmetry between this rate and the $K^-\pi^+$ rate. So far, measurements of rare B meson processes—penguin decay rates as well as particle-antiparticle asymmetries—have not shown any deviation from the predictions of the Standard Model at the levels of accuracy implied by the rather sparse data samples available. Maybe they will, once we are able to produce more B mesons and reliably identify the rarest decay processes. These are the main motivations for the CESR/CLEO upgrade.

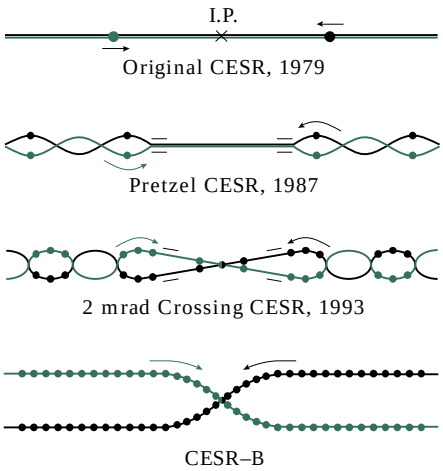
THE CESR UPGRADE

Our ability to observe rare events in CESR depends on its luminosity. If we think of colliding particles in terms of the cross-sectional area each presents to the other, then the rate for a particular collision reaction is the product of the cross section, measured in cm^2, and the luminosity of the storage ring facility, measured in units of cm^{-2} $seconds^{-1}$. You might expect the luminosity of CESR to vary as the product of the e^+ and e^- beam currents and inversely as the transverse area of the interaction region, but because the beam-beam interaction tends to increase the beam overlap area, the luminosity is proportional to only one power of beam current. For flat beams the other important factors are the vertical "depth of focus" β^* at the interaction point and the vertical beam-beam tune-shift parameter ξ, a measure of the beam density.

Over the 17 years that CESR has been operating, the accelerator physicists at Cornell have brought the β^* and ξ parameters pretty close to their limiting values. The only opportunity for major gains in luminosity is storing larger beam currents. In the original CESR design there was just one circulating bunch of particles in each beam. Instabilities, however, limit the amount of charge that one can stuff into a single bunch,



A computer reconstruction of a rare B decay event in the pre-upgrade CLE0-2 detector. The beam axis is in the center, perpendicular to the page. The cylindrical cesium iodide scintillation counter array is represented in a tunnel view to display the hit counters (in black). This event was one of 13 such events that heralded the discovery of penguin decays. It is interpreted as $e^+e^- \rightarrow B^0\bar{B}^0$ *followed by* $B^0 \rightarrow K^{*0}\gamma$ *(the penguin decay) and* $\bar{B}^0 \rightarrow D^+\rho^-$ *(a more conventional kind of B decay). The* K^*, D, *and* ρ *mesons are also unstable and decayed immediately, as indicated.*



Electron and positron beam orbits in the vicinity of the collision point in four configurations. From the top down they are the original CESR single-bunch configuration; the pretzel scheme with head on collisions; the upgrade pretzel with collisions at an angle; and a two-ring configuration. The drawings are not to scale.

so we had to find a way of circulating many bunches. In 1982 we considered a two-ring setup but opted instead for Raphael Littauer's single-ring scheme, in which the beams are separated by electric fields into two "pretzel" orbits that weave back and forth across each other. Multiple beam bunches can be cleverly spaced so that opposing bunches always miss each other except at the desired collision point. By 1991 the pretzel had produced a record luminosity of 2×10^{32} with seven bunches of particles in each beam.

We then revived the old two-ring plan as a way of storing even larger beam currents, but with the additional idea from Pier Oddone of Lawrence Berkeley National Laboratory that separate rings would allow one to store electrons and positrons with different energies. The asymmetric collision would boost the produced *B* mesons in the direction along the more energetic of the two beams. As Riordan and Roe explain in their *Beam Line* article, this would make it easier to see the time evolution of the decays, thus facilitating the observation of *CP* violation with neutral *B*'s. But CESR lost out to PEP2 in the competition for Department of Energy support, so the asymmetric *B* Factory is being built at SLAC (also at KEK), and the Cornell collider will remain a single ring with both beams at the same energy.

The Cornell accelerator physicists got to work immediately on their alternate plan, suggested by Robert Meller. In this scheme the two beams collide at a 0.23 degree angle to each other instead of head on, thus allowing up to 45 bunches to circulate in each pretzel orbit without interference. The bunches are not uniformly spaced but travel in nine trains, with up to five bunches per train. The bunches in a train are separated by 4.7 meters, while the trains repeat every 86 meters. Several modifications of CESR are necessary.

Electrostatic separators. The charged deflection plates that direct the electrons and positrons into their separate orbits had to be reconfigured in order to make the beams collide at an angle.

Final focus. The array of quadrupole focusing magnets on both sides of the crossing point had to be shortened and strengthened in order to accomplish the focusing in a distance less than the spacing between successive beam bunches. The first stage of this has been completed, to allow a bunch spacing of 9.3 meters. Superconducting magnets are now being constructed to permit 4.7 meter spacing.

Multibunch feedback. Wake fields trailing an intense electron or positron bunch can deflect the following bunches. Pickups sense the horizontal and vertical transverse motion of each bunch. High-power wide-band amplifiers feed the appropriately phased signals to deflection plates to restore the bunches to their correct orbits. This system is now operational. A future system will also damp longitudinal bunch excursions.

Vacuum system. Electrons and positrons traveling in magnetic fields emit X rays. This synchrotron radiation liberates gases from the vacuum chamber walls and causes severe heating. Chambers, pumps, valves, and other components have to be

upgraded in order to keep the residual gas pressure low for good beam lifetime and low experiment backgrounds.

Radiofrequency system. The radiated energy must be replaced in microwave cavities. These have traditionally been copper cells with shapes optimized to give the maximum accelerating electric field with minimum power dissipated in the walls. Unfortunately this optimization helps the cavity to resonate at frequencies higher than the fundamental accelerating mode. The wake fields of intense beam bunches passing through the cavities excite these higher modes, wasting power and destabilizing the beam. Although feedback can increase the stable beam current limit, we can raise the limit much more effectively by eliminating the higher modes in the cavities. This is done by making them out of superconducting niobium cooled to liquid helium temperature. Since practically no power is dissipated in the walls, one has the freedom to optimize the shape to suppress higher modes. Moreover, since less power is wasted, fewer cavities are needed. Replacing the present 20 cells of copper cavities in CESR with 4 new supeconducting cells will greatly increase the maximum stable beam current. The prototype cavity performed successfully in CESR; the first production cavity will be installed in 1997; three more will follow later.

The table at the top of the page lists the performance goals for the upgrade. The components already installed permit the ring to operate routinely now with 18 bunches per beam and a peak luminosity 4×10^{32}. If all goes well, the remaining upgrade modifications for 45 bunches per beam will be ready for installation in 1998.

THE CLEO UPGRADE

The CLEO collaboration comprises 209 members from 24 universities, from Harvard to Hawaii. The present CLEO-2 detector started operating in 1989. The illustration on page 24 shows the layout of components, including silicon and multiwire drift chambers for charged particle tracking, scintillation counters to measure time-of-flight, a cesium iodide scintillation counter array for photon shower detection, a 1.5 Tesla superconducting solenoid coil, and a muon detector interleaved with magnet iron. CLEO-2 represents the state of the art in detection efficiency and energy resolution for charged particles and photons.

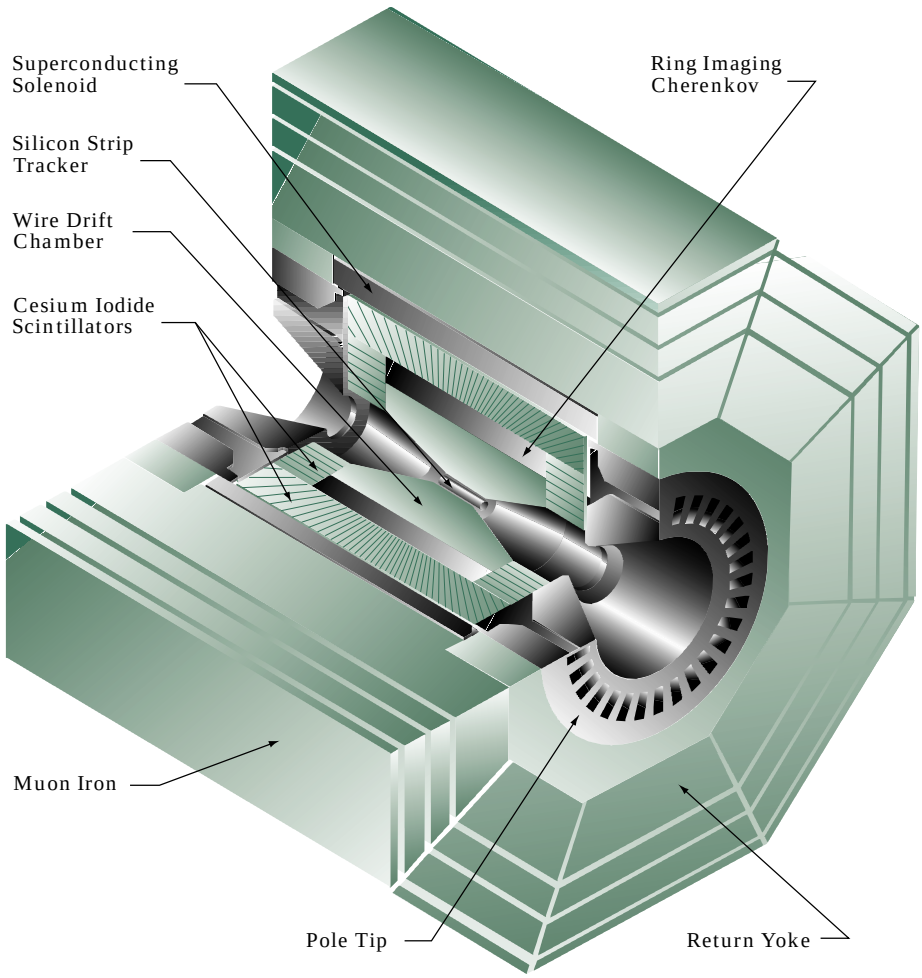
Although electrons and muons of all momenta are distinguished by interactions and penetration, the identification of pions, kaons, and protons has to rely on velocity measurements, combined with the momentum determined by the track curvature in the magnetic field. The velocity-dependent drift chamber ionization and the time-of-flight measurement suffice for particles with momenta below about 0.8 GeV/c, but at the higher momenta the ionization is only slightly dependent on particle velocity, and the flight times are indistinguishable. However, the rare *B* processes of interest produce kaons and pions with momenta up to 2.6 GeV/c, and to cover this momentum range we will have to use the velocity dependence

Goals for the Upgraded CESR

Beam energy	E = 5.3 GeV
Circumference	C = 768 m
Luminosity	L > 1.7×10^{33}/cm^{2}s
Number of bunches per beam	n_b = 45
Current per beam	I beam > 0.5 Amp
Vertical beam-beam tune shift	ξ > 0.03
Vertical depth of focus at IP	β^* = 1 cm
Number of rf cells in ring	n_c = 4
Total accelerating voltage	V_c = 7.2 MV
Total rf power	P_{tot} = 1.4 MW

The CLEO Collaboration

SUNY Albany	Cal Tech	Carleton
Colorado	Cornell	Florida
Harvard	Hawaii	Illinois
Kansas	McGill	Minnesota
Ohio State	Oklahoma	Purdue
Rochester	UC San Diego	UC Santa Barbara
SLAC	Southern Methodist	Syracuse
Vanderbilt	Virginia Tech	Wayne State



A cut-away view of the upgraded CLEO-3 detector. The axis of symmetry in the middle is the electron-positron beam line.

The Upgraded CLEO-3 Detector

Tracking		
double-sided silicon layers		4
drift chamber layers:	axial	16
	stereo	31
r.m.s. $\delta p_T/p_T$ at p_T = 2.5 GeV/c		0.5%
r.m.s. resolution in dE/dx per track		6%
acceptance solid angle		95%
High momentum π, K, p identification		
average photoelectrons per track		>12
K/π separation, standard deviations		>3.5
acceptance solid angle		80%
Electromagnetic calorimetry		
number of CsI scintillators		7800
r.m.s. $\delta E/E$ at E = 2.5 GeV		2%
acceptance solid angle		98%
Muon identification		
iron & proportional tubes		

of the angle of emision of Cherenkov light by the particles.

Adding a Cherenkov light detector to the CLEO detector without rebuilding the very expensive cesium iodide array and solenoid magnet means giving up some of the space now used for tracking. What's more, the present drift chamber occupies some of the space needed for the upgraded CESR quadrupole focusing magnets. To recover the resolution lost by downsizing the tracking chamber, we decrease its mass, thereby reducing the scattering of the particles, and we supplement the drift chamber by a more extensive silicon multistrip tracker near the beam pipe.

The CLEO-3 upgrade therefore consists of the following major new components: a ring-imaging Cherenkov detector using a lithium-fluorine radiator and a TEA photon converter with wire-and-pad readout; a downsized multiwire drift chamber with helium-based gas and thin end plates; a four-layer double-sided silicon microstrip detector, and faster trigger and data acquisition electronics.

Construction is proceeding on each of these systems with the goal of being ready for 1998 installation. The table at the left shows some specifications and projected performance figures for the upgraded detector.

The three rival detectors, CLEO, BaBar, and Belle, at the CESR, SLAC, and KEK colliders respectively, will have many similarities, but each will have its own advantages. In the CLEO detector the unboosted *B* decay products all have momenta below 2.6 GeV/c, thus making energy measurements more precise and the velocities of the different particle species more easily distinguishable. Since the *B*'s will not be boosted along the beam line, fewer decay products will be lost in the undetectable low-angle cone near the beam direction. On the other hand, since the *B*'s are produced almost at rest in the symmetric CESR collisions, the observation of the time evolution of the decays, while not impossible, will not be as straightforward as in the asymmetric B Factories. But that is just one of the potentially crucial experiments that might expose the shortcomings of the Standard Model. CLEO will have a good chance at other CP violation measurements and will contribute to the measurement of rare decay rates. No one knows where the payoff in new physics will come.

As CLEO has benefited from the rivalry with the ARGUS experiment at DESY, experimenters now look forward to friendly competition with the asymmetric B Factories.

Breaking the Picosecond Barrier

by HELMUT WIEDEMANN

Graduate students at SUNSHINE design, generate, and measure subpicosecond electron bunches.

MANY OF OUR MAJOR ADVANCES in understanding Nature have resulted from the invention and development of ever more powerful experimental instruments. In particular, particle accelerators and other particle and photon beam devices have made possible striking advances in high energy physics, materials science, biology and medicine, and other fields of scientific research. Today much of the development work in particle-beam and photon-beam research is directed toward producing beams with ever smaller diameters and angular divergences (smaller phase space). Our ability to compress more and more particles into smaller volumes, into the shortest pulse length or the narrowest energy spread, will powerfully affect our future progress in fundamental research that is based on particle beams. An example is the research potential of future linear colliders in high energy physics, which will depend critically on our ability to compress tens of billions of electrons into a tiny pulse with a diameter of only a few tens of nanometers and a pulse duration significantly less than one picosecond. Only then will the head-on collision of two such slugs of particles result in a collision probability for elementary-particle reactions that is large enough to be of interest to high energy physicists. In another application of great scientific significance, the high degree of cooperation among closely spaced electrons (bunch lengths less than about 100 femtoseconds) may make it possible to build a Free Electron Laser (FEL) that can generate, for the first time, coherent X rays at unparalleled brightness for basic research.

Sub-picosecond electron bunches generate coherent, far-infrared radiation pulses at wavelengths of 1 mm and 10 μm.

Developing such electron beams poses a fundamental challenge to beam physicists; this work is presently being pursued at a number of national research laboratories and universities throughout the world. In this article we will concentrate on a particular subset of these developments, the generation of femtosecond electron pulses. Only a few years ago such pulses could not have been produced and could not even have been measured. But great progress has been made recently, and we report here on some of these developments.

WHAT DOES A FEMTO-SECOND ELECTRON BUNCH LOOK LIKE?

First, we try to get some feeling for how short a time interval of, say, 100 femtoseconds actually is. There are 1,000,000,000,000,000 or 10^{15} femtoseconds (fsec) in 1 second. In that one second light can travel a distance equal to seven and a half times around the earth, or almost the distance from earth to the moon. In spite of this incredibly high speed, during a time interval of 100 fsec light would travel only 30 micrometers (or about 1/1000th of an inch). In a 100 fsec electron pulse all the electrons are thus contained in a slug of charge about 1/30th of a millimeter long. The natural repulsion between the electrons caused by their electric charge must be overcome and kept compensated during acceleration and beam transport. Nature helps here in the sense that in relativistic particle beams (where the particles travel at speeds close to the velocity of light), the destructive space-charge forces are compensated as the particle energy increases. This requires that the particle beam be accelerated as rapidly as possible after low-energy bunch compression so that the compressed bunch in effect becomes "frozen." Of course, practical imperfections introduce perturbations in the transport systems of high-density particle beams; the task of beam dynamics physicists and engineers is to detect such sources and to design equipment that will reduce the perturbations to an acceptable level.

WHY DO WE NEED SUCH SHORT PULSES?

As noted earlier, the development of future linear colliders depends critically on the attainment of sub-picosecond (10^{-12} sec) electron bunches with cross sections of only a few tens of nanometers (10^{-9} m). Only such tiny and highly populated electron bunches will provide sufficient collision probabilities (luminosity) to generate the rare high-energy physics events that are the subjects of basic research in this field. Beams with nanometer cross section can be sustained only over a very short distance, which is the reason why electron pulses of less than one picosecond duration (about 300 fsec or less) are needed. Even shorter pulses are required for X-ray free electron lasers (FEL). Such X-ray lasers are the only way to produce coherent X rays at extremely high brightness. They function like ordinary FELs except that the buildup of electromagnetic radiation must occur in a single passage of an electron beam through an undulator magnet. In ordinary FELs the radiation is contained in an optical cavity made of reflecting mirrors, and it interacts many times with the electron beam. This is not possible at X-ray wavelengths where no highly reflective mirrors exist. Extremely high density electron beams are thus required for single-pass X-ray FELs, and the recent developments in beam physics have approached a level of sophistication which suggests that such a laser generator is possible.

An added feature of a single-pass FEL is the fact that its sub-picosecond pulse duration would make it possible to study the dynamics of atomic and molecular systems. Many chemical or biological reactions, for example, occur on a sub-picosecond time scale and often are characterized by one or more intermediate states. Because of the very short time scale, such states cannot as yet be studied.

Sub-picosecond electron bunches can also be used directly to generate high brightness, coherent, far-infrared radiation pulses in a spectral regime between wavelengths of 1 millimeter and 10 micrometers where so far only very few high brightness FELs exist. The extreme compression of electrons into sub-picosecond pulses

causes them to "cooperate" with each other in the generation of coherent far-infrared radiation. In an electron pulse that is long compared to the wavelength of the radiation emitted, each electron radiates independently from all others; in contrast, the radiation intensity emitted from a bunch that is short compared to the wavelength is greatly enhanced. More explicitly, in a long bunch, the radiation intensity from two electrons is twice that of one electron, while the radiation intensity of two electrons very close together is four times that of a single electron. Putting N electrons into close proximity results in a radiation intensity proportional to N^2 instead of N, and this can result in a total increase of radiation intensity by a factor of 10^8 or more for short pulses compared to long pulses. Furthermore, this radiation is coherent, polarized, and comes in very short pulses.

Far infrared radiation is produced whenever an electron beam passes, for example, through a magnetic field (synchrotron radiation), a dielectric material (transition radiation, Cherenkov radiation) or travels close to a periodically corrugated surface (Smith-Purcell radiation). A wealth of physics is waiting for such sources in areas such as surface physics, high-temperature superconductors, and the dynamics of large biomolecules.

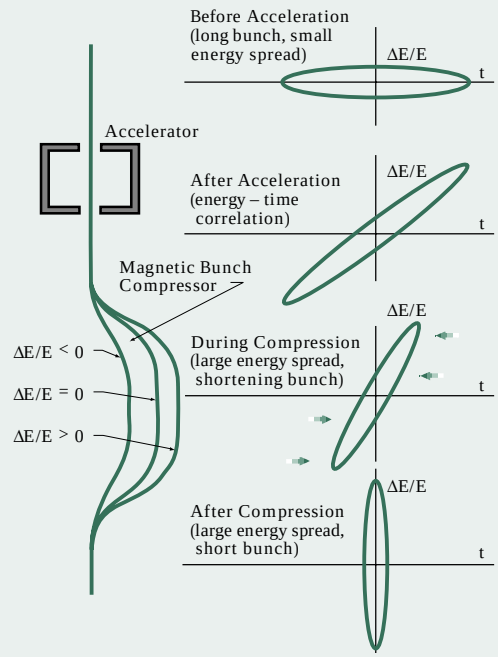
BUNCH COMPRESSION

There are no known methods for directly producing sub-picosecond electron pulses of sufficient intensity. While femtosecond lasers together with photocathodes can in fact be used to produce short pulses, the achievable intensities are insufficient for the desired applications. The only way to create intense sub-picosecond pulses known so far is first to produce pulses with the desired intensity but longer duration, and then to apply some sort of bunch compression. That is possible if the electrons have different properties as a function of their location along the bunch. Exploiting this, one can cause electrons with different properties to respond differently to external forces and thereby rearrange their position along the bunch. For example, if the electron energy changes monotonically from lower values in the head of the bunch to an ideal design energy in the center and to higher values in the tail of a bunch, one can exploit this beam property for bunch compression in a magnetic chicane.

This energy variation along the bunch can be generated by fast cycling radiofrequency fields in an accelerating section (see box on the right). Consider an electron beam arriving at the accelerating section just when the field is about to change its sign but is still negative. Electrons in the head of the bunch then would be decelerated. By the time the center of the bunch arrives the field has reached the zero point, and then increases monotonically to accelerate the electrons behind the bunch center. As the figure shows, the more energetic electrons at the back of the bunch travel along a shorter path through the chicane because they are deflected less than the electrons in the bunch center, and thus start to catch up with them. Conversely, the less energetic electrons in the head of the bunch are deflected along a

Bunch Compression

IN THE CASE OF A CHICANE-TYPE bunch compressor (see figure below), a long, relativistic electron bunch with small energy spread is "accelerated" in a linear accelerator section at zero phase so that the particles in

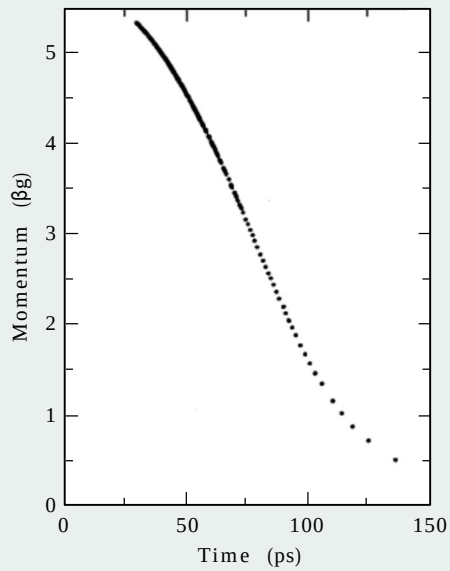


the head of the bunch lose energy, those in the tail gain energy, and those in the center are unaffected. The beam is assumed to be relativistic (all particles travel close to the velocity of light) and passes through an asynchronous bend (chicane), where the higher energy particles in the bunch tail travel a shorter path than the lower energy particles in the head, thus leading to bunch compression. This compression is achieved at the expense of the relative energy spread, $\Delta E/E$, to fulfill Liouville's theorem.

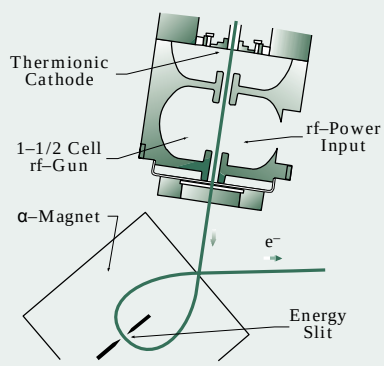
A second, further acceleration of this beam from energy E_0 to E_1 could reduce the relative energy spread again by a factor E_0/E_1 due to adiabatic damping. After sufficient acceleration the energy spread would become small again, and a new step of bunch compression could be implemented. This procedure would obviously require a long linear accelerator of the sort available only in high energy physics facilities like SLAC and is not of practical interest for laboratory experimentation.

RF Gun and Beam Properties

SUB-PICOSECOND ELECTRON BUNCHES can be produced from a radiofrequency (rf) gun with a thermionic cathode and a magnetic bunch-compression system. The rf gun at SUNSHINE consists of 1-1/2 cells of an S-band linear accelerator and produces a train of 2000 to 3000 microbunches separated by 350 psec in each main pulse. The illustration on the left shows the phase-space distribution for one microbunch at the exit of the gun. The uniform momentum-time correlation of the particle distribution shown is a prerequisite for successful magnetic bunch compression. Fast acceleration in the rf gun to relativistic energies of 2.6 MeV diminishes the emittance-diluting effects of space-charge forces and results in a particularly small distribution in energy-time phase space.

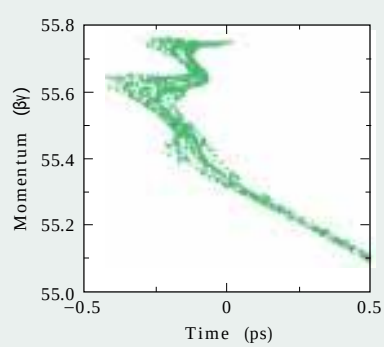


To compress the electron bunches from 20 to 30 picoseconds to less than one picosecond, an α-magnet is used. This magnet has the shape of the left or right half of a quadruple with a mirror plate terminating the fields across the vertical midplane. Unlike a beam passing through a quadrupole along the axis, the beam enters the α-magnet at an angle of 49.29 degrees with respect to the axis, as indicated in the figure on the right. Particles entering at this angle follow a closed loop similar to the letter α and exit the magnet exactly at the entrance point independent of the particle momentum. The beam dynamics in an α-magnet have been worked out in detail; the momentum-dependent path length s_0 is given as a function of field strength by



$$s_0\,(\text{cm}) = 19.2\sqrt{\frac{\beta\gamma}{g(\text{T/m})}},$$

where g is the field gradient of the α-magnet. In the illustration on the right, the numerically simulated particle distribution of the previous graph is shown after compression and acceleration to 28 MeV. Setting the energy slit in the α-magnet appropriately, one can filter out that part of the beam which represents the shortest bunch length, for example the range $55.5 < \beta\gamma < 55.8$.



longer path and then start to fall back toward the center of the bunch. The bunch would reach its shortest length at the exit point of a correctly designed magnetic bunch compressor. From there on the bunch length would be "frozen in" for highly relativistic particles traveling with almost the speed of light, and assuming that we ignore any perturbations.

The shortest electron bunches achieved so far, about 100 fsec rms, have been generated at SUNSHINE (the Stanford UNiversity SHort INtense Electron source), which is an accelerator research facility operated by Stanford graduate students. Here, the electron source is a radiofrequency electron gun that directly generates the monotonic energy variation along the pulse that is required for bunch compression. This differs from the previous technique in that the higher energy particles are in the head of the bunch, and the bunch compressor is an alpha magnet in which the higher energy electrons follow a longer path than those of lower energy particles (see box on the left).

Performing bunch compression is relatively straightforward once the particle beam has been prepared properly. Preserving an ultra-short bunch over longer distances is a much more difficult matter. The shortest bunch length achievable at SUNSHINE is limited by the transverse motion of the electrons. On a femtosecond time scale, a finite divergence of the particles of only a fraction of a degree can cause considerable bunch lengthening because the particles traveling at an angle with respect to the beam axis must

be refocused again and again, resulting in an oscillatory path. Such a path is obviously longer than that of a particle following the beam axis, and as a consequence particles traveling along at an angle with respect to the beam axis fall behind, and the bunch is thereby lengthened. The degree of collimation that can be achieved on the transverse beam divergence of the particle beam ultimately determines the shortest bunch length that can be preserved along a beam transport line.

BUNCH LENGTH MEASUREMENT

How do we know just how short is "short"? Conventional time-domain methods of measuring short pulses are simply not adequate to resolve pulse lengths in the femtosecond domain. Traditionally, one would use a streak camera to observe very fast events. In such a camera, a light pulse derived from the electron pulse to be measured strikes a photosensitive screen. Using the photoelectric effect, low energy electrons are released with a temporal distribution that resemble the original electron pulse to be measured. The low energy electron beam is then deflected transversely by rapidly varying electric fields and thereby inscribes a transverse trace on a fluorescent screen. In this way, the longitudinal position of any electron is transformed into a transverse position which can be measured on the screen. The pulse length can be deduced from the transverse width of the trace on the screen. The advantage of this instrument is that the detailed particle distribution of a single bunch can be observed. The disadvantage is its high cost, complexity of operation, and most significant its limitation to pulses of the order of one picosecond. Faster streak cameras are under development by industry, but these developments have not kept pace with the growing ability to generate femtosecond electron pulses.

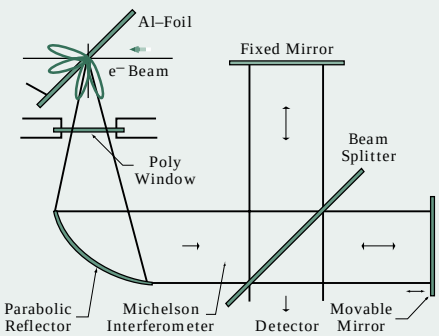
Hung-chi Lihn built the first far infrared Michelson interferometer optimized to measure electron bunches as short as 100 fsec rms at SUNSHINE.

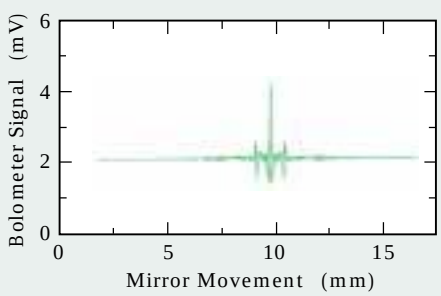
The alternative to time-domain bunch-length measurements with streak cameras is frequency-domain methods designed to measure subpicosecond pulse durations. In particular, an autocorrelation method that is widely used in the femtosecond laser community is also applicable to subpicosecond electron pulses. The application to particle beams is based on the observation that the coherent part of the radiation emitted by short electron bunches in the form of, for example, transition radiation has a spectrum that is the Fourier transform of the particle distribution. Thus any system that can measure the coherent radiation spectrum can be used for bunch-length measurements. The time-resolution problem has been eliminated—independent of how short the bunch might be—because the radiation spectrum is derived directly from the particle distribution. The only limitations that occur are related to possible spectral changes in the properties of the optical components (windows, mirrors, gratings, beam splitters, and detectors) used in the measuring apparatus. Different kinds of optical spectrometers can be used, depending on the expected bunch length and frequency spectrum. This frequency-domain bunch-length measuring system was proposed by Walter Berry; Hung-chi Lihn built the first far infrared Michelson interferometer optimized to measure electron bunches as short as 100 fsec rms at SUNSHINE. Berry and Lihn shared the 1996 Faraday Cup Award for this development.

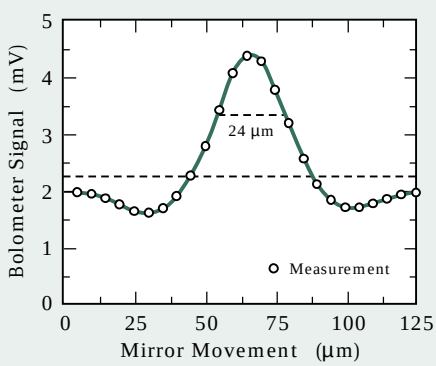
Transition radiation is emitted when the electron beam passes through a thin metal foil (see sidebar on the next page). This radiation is guided into a Michelson interferometer, where it is split by a far-infrared beam splitter into two equal parts, each representing the temporal distribution of the particle beam. One part is reflected from a fixed mirror, and its intensity distribution represents the particle distribution to be measured. The other part of the radiation is reflected from a movable mirror and is used to probe the radiation pulse from the fixed mirror. In order to measure any length dimensions, we need a yardstick at the scale of the object to be measured. In this instrument, one part of the split radiation pulse is used as the yardstick to measure the other part. After splitting, each pulse follows a different path through the interferometer towards the detector. By changing the position of the movable mirror, the path legnth of one of the pulses is changed, and the two pulses

Michelson Interferometer

COHERENT ENHANCEMENT OF RADIATION occurs over a frequency range which is the Fourier transform of the longitudinal particle distribution; measurement of the electron bunch length is therefore reduced to the observation of the coherent frequency spectrum. At SUNSHINE, a far-infrared Michelson interferometer developed to measure the frequency spectrum has made it possible for the first time to measure particle pulses as short as 100 fsec rms. As shown in the figure on the left, the electron beam passes through a thin aluminum foil to produce transition radiation. By measuring the radiation intensity with a room-temperature pyroelectric bolometer (Molectron PI-65) as a function of the path-length difference in both arms of the Michelson interferometer, an interferogram (see figure below) is obtained which is the Fourier transform of the radiation spectrum. Since the spectrum is the Fourier transform of the particle distribution, we have a direct measurement of the bunch length in the form of the interferogram. The Michelson interferometer actually performs the Fourier transform of the spectrum automatically in the form of the interferogram. The full width at half maximum of the central peak above the baseline in the interferogram is nearly equal to the bunch length. However, since the beam splitter introduces frequency-dependent effects caused by the interference of reflected radiation from both surfaces, some corrections have to be applied to obtain the actual bunch length. The degree of required correction depends on the thickness of the beam splitter compared to the bunch length.







may arrive at the detector about the same time or completely separated in time. The detector signal is sensitive to the arrival times of the two pulses. It gives one signal amplitude when both pulses arrive at different times and an increasing amplitude as both pulses partially or completely overlap in time at the detector. Observing the increase and decrease of this signal as the mirror is moved allows one to measure the bunch length, which is directly proportional to the movement of the mirror. This method of splitting a pulse and using one part to probe the other is called an autocorrelation measurement.

OUTLOOK

The short bunches that are needed for the next linear colliders or for X-ray FELs have not yet been obtained at the required particle intensity. However, the present state of our understanding and experimentation has brought such potential research tools much closer to realistic projects which may well become possible within the next few years. Coherent, polarized far infrared radiation can already be derived from state of the art short bunches at relatively low cost over a large wavelength range between 40 μm and 1 mm with high brightness comparable to that of FELs, and greatly exceeding that of black body radiation and synchrotron radiation. Having reached a solid foothold on this time scale, beam physics will begin again to question the limits and prepare for the next step.

Astrophysics 1996

by VIRGINIA TRIMBLE

Highlights of fiscal 1996 included a plethora of peculiar planets, gobs of geronto-galaxies, and many things in between.

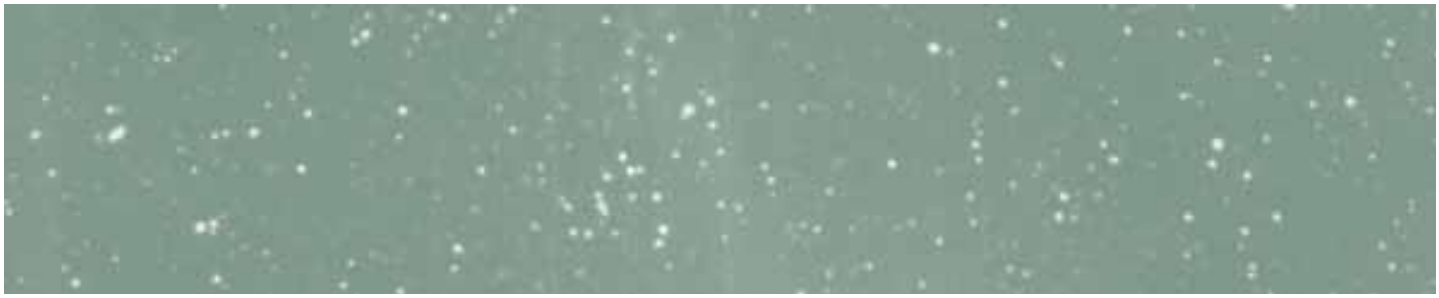
EXTRA-SOLAR-SYSTEM PLANETS

As the autumn 1995 leaves began to fall, we had firm evidence for 12 substellar objects in orbits around stars, three planets orbiting one short-period pulsar, discovered by Alex Wolszczan, and the nine orbiting Old Sol, with credits to Clyde Tombaugh (who died January 17th just as this was being written), Adams and Leverrier, William Herschel, and either Nicolas Copernicus or a Zinjanthropan named Og, depending on your point of view. Since then, the number has roughly doubled, with contributions coming from six of the (at least) seven possible ways of looking. And yet the solar system remains unique.

Some of the new discoveries are almost certainly true planets; others are probably brown dwarfs; and some occupy an uncertain territory between. How can you tell which is which? The table on the next page shows some distinguishing features (excluding great red spots and other birthmarks not visible at large distances). Naturally I like best the ones (formation mechanism and internal structure) that are hardest to determine outside the solar system. There must be some really good log-log plot on which one could display the old and new companions insightfully. This one probably isn't it, but

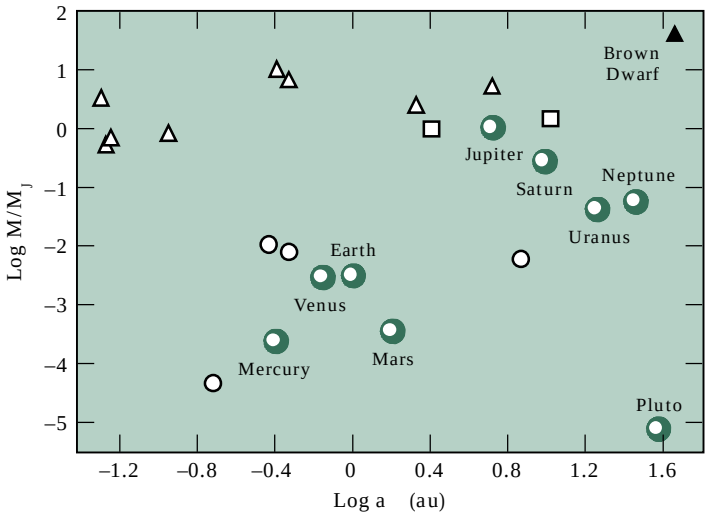
"I am the owner of the sphere, of the seven stars and the solar year."

—Ralph Waldo Emerson



How to Tell a Planet from a Brown Dwarf in Four Easy Lessons

Property	Planets	Brown Dwarfs
Mass	0.00001 to 10× Jupiter smaller is an asteroid	10 to 85× Jupiter bigger is a star
Orbit	fairly circular near equatorial plane of primary	optionally eccentric random orientation possible
Formation	in a disk around primary	separate condensation center
Internal Structure	core of rocks and metals surrounded by gases	chemically homogeneous degenerate gas (mostly hydrogen and helium)



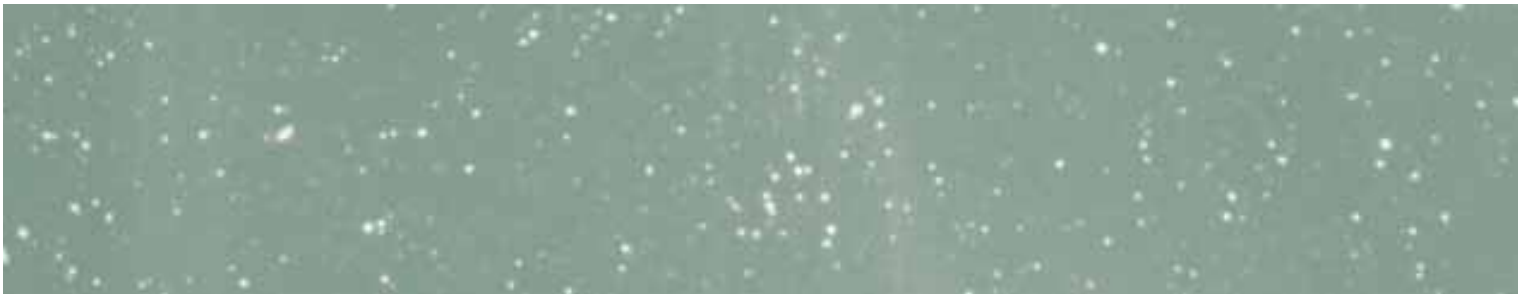
Planets old and new, plotted in units of mass (relative to that of Jupiter) versus semi-major axis of the orbit (in astronomical units, the earth-sun distance), logarithmically in both cases. Green circles (including Pluto) indicate orbits of high excentricity. White triangles are the companions discovered from radial velocity measurements. Squares are astronometric companions (discovered from proper motion residuals), White circles are companions of pulsars, and the lonely triangle in the upper right corner is clearly a brown dwarf.

is the best I have been able to think of—a plot of planet (etc.) mass vs. distance from the primary star in logarithmic units. The solar system, in addition to having more planets than anybody else, occupies unique territory in such a plot. Elsewhere, the planets with masses like that of the earth orbit pulsars, not aging low mass stars; the planets with masses like that of Jupiter are all closer (most much closer) to their parent stars than is our Jupiter; and brown dwarfs are (fortunately) like nothing in our family. Some of the uniqueness is a matter of time and technology. The sensitive searches are not yet old enough to have found orbit periods of a dozen years or more and are not yet sensitive enough to have picked up earth masses unless the central star carries a very precise clock with it.

How have all these been found? First of the techniques to succeed was careful monitoring of rotation periods of pulsars. These periods are the steadiest clocks we know, and motions of a pulsar orbiting its center of mass with a companion produce measurable Doppler shifts. The Wolszczan trio has been augmented by timing residuals in the 0.7 second pulsar B0329+54, indicative of an Earth-mass (or larger) planet in a fairly eccentric, 16.9 year orbit. Because of the long period, orbit coverage is not yet complete enough to give the result a very high confidence level, and there is a hint of an additional, three-year period.

The second technique is direct imaging at optical or infrared wavelengths. This led to the candidacy of Gliese 229B for the title of "first companionate brown dwarf," with a probable mass of 20–60 Jupiters and an orbital radius of 44 times the earth-sun distance (astronomical unit), as projected on to the plane of the sky. GD 165B is the next strongest candidate for resolved, companion brown dwarf, while Gliese 105C* has been

**It would be perfectly reasonable for you to ask how stars get their names, and I promise to explain one of these issues. Meanwhile, think of them as like cats. Only the cat knows its own, true, ineffable name. Socks, Percival, Betelgeuse, and Ashurbanipal are random labels assigned so that we can talk about them. (Only optimists attempt to talk to either.)*



definitely promoted (or demoted?) to hydrogen-burning status, or class "star". Numbers that come from this and most other methods are inherently lower limits to both mass and orbit size by a factor sin *i*, where *i* is an angle between our line of sight and the orbit plane.

Third comes optical or infrared spectroscopy, which, by demonstrating the presence of both methane and water-vapor ("steam") lines in the atmosphere of Gl 299B put it definitely at a temperature less than 1000K, where no true stars live. Another spectral signature, the presence of lithium, has, in the same time frame, served to put a handful of single, non-companion, objects into the brown dwarf box. Brown dwarfs and low mass stars mix themselves fairly thoroughly over an eon or two, and lithium fuses at such low temperatures that it can remain in the star only if there is no serious hydrogen fusion anywhere therein.

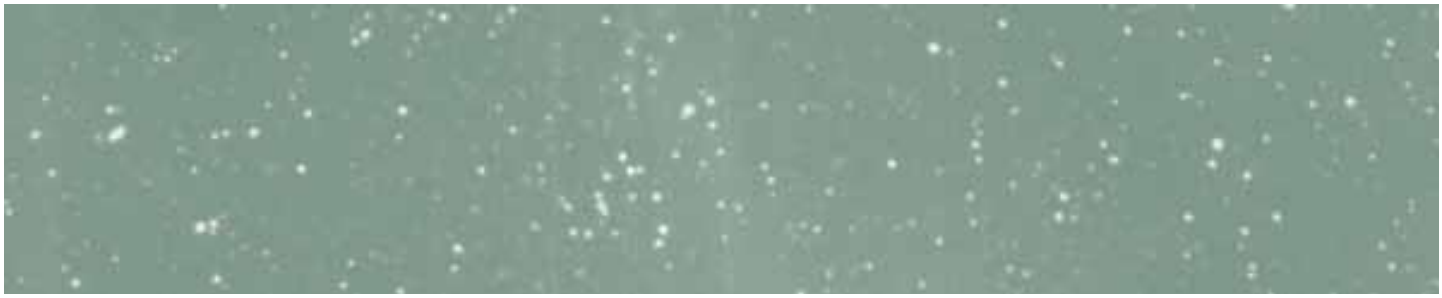
The fourth technique, looking for Doppler shifts in optical spectra of likely parent stars, has been the most spectacularly successful. Most astronomers can probably remember exactly where they were when they first heard the name 51 Peg in October 1995 (and most non-astronomers will wonder what a 51 Peg is, but we have agreed not to ask that question this week). The star had been on two monitoring programs, so that its 4.23 day orbit period, mass limit of 0.5 Jupiters, and so forth, were quickly confirmed. It has been joined, so far, in the published additional literature, by five additional massive planets, only one of which, 47 UMa is far enough away from its parent star to feel like Jupiter (chilly). The others, sometimes called hot Jupiters, are not at any risk of boiling away or being torn apart, but formation in situ seems improbable. Never mind. We have ways to drag planets inward (probably as many models as hot Jupiters at the moment). Three or more additional companion brown dwarfs found in separate, but similar surveys have also surfaced in the past year or two. Because the planet searches could easily have found brown dwarfs (but did not), and not conversely, one is tempted to conclude that planets are genuinely the more common sort of entity. Products of these radial velocity searches are now common enough for statistical arguments to apply to values of sin *i*, and we can say that most are truly of low mass, and not just artefacts of orbit orientation.

Paul Butler, left, and Geoff Marcy in the Keck control room. Their search for extrasolar system planets has been the most successful to date, partly because they have had the insight to use an iodine gas cell as a source of comparison lines to guarantee accurate, repeatable velocity measurements and partly because they have worked very hard.

Method five is the oldest of all, the search for small wiggles in the motion of stars across the sky ("proper motion residuals" is the approved term if you want to talk about them in public). The demise some years ago of two putative companions to Barnard's star left the technique in mild disrepute, but (as Jack Benny said about "The Horn Blows at Midnight") there is a whole new generation coming along that will never know. Anyhow, Lalande 21185 probably has one or two planets with Jupiter-like masses and large orbits.

The sixth possibility is to see transient fading when a planet in a nearly edge-on orbit passes across the face of its parent star. One report of such an event in the brightness of CM Draconis implies a planet with a size close to that of Jupiter and an orbit period of at least a few months.

In addition to merely shouting Eureka, astronomers can actually say a couple quantitative things about planets and brown dwarfs. First, although we now count them as "many," they are nevertheless sparse enough on the



sky that they are not a major contributor to local dark matter. Second, they seem to tie up rather well with increasing evidence for dusty disks around many very young stars and protostars. Such disks probably really do form families of planets around many solar-type stars.

Oh. Did you want to hear about the seventh method for discovering planets? That's when something lands in your fish pond and somebody gets out and tells you that he is from the planet Alpha Venega, which orbits the third star on the left.

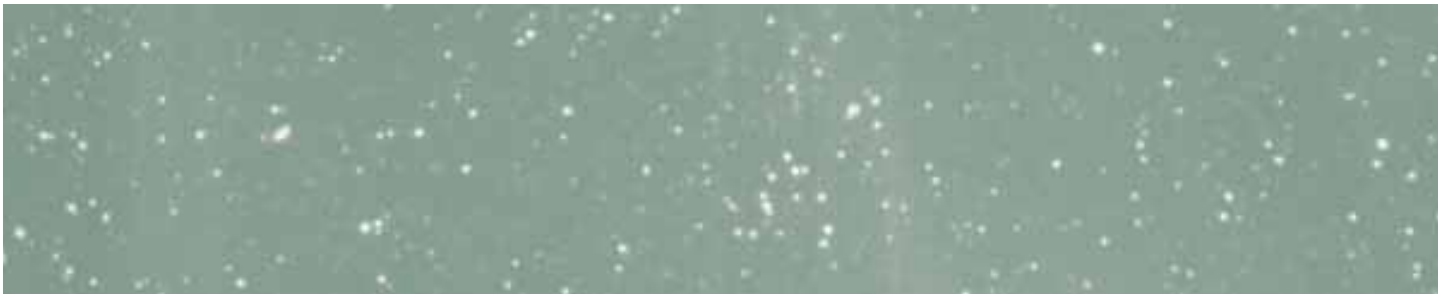
STAR-FORMING GALAXIES AT HIGH REDSHIFT

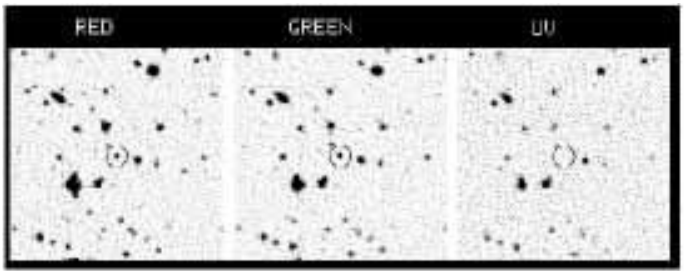
A year or two ago, this section would have been called (in fact was called) "primordial galaxies," and there weren't any. Now that the title has changed, there are an enormous number. This really is, in part, a result of looking at the problem in a slightly different way. But it comes mostly from a sudden flood of new images and spectra, many the products of the Hubble Space Telescope and the Keck I telescope. The objects so imaged are not, in fact, very much like either the galaxies we see here and now or what we were expecting long ago and far away. By way of reminder, light travels at the speed of light, and so distant things are necessarily seen as they were when the light left. Unfortunately, both "distant" and "when" if you want units like furlongs or miles and seconds or years are both model dependent. (This is a technical term, meaning that the numbers depend a lot on your choice of the expansion rate of the universe, its deceleration rate, etc, not just an all-purpose insult). The observed quantity is redshift of spectral lines, $z = \Delta\lambda/\lambda$. Yes, z can be bigger than one; no this does not violate special relativity or anything else sacred; and no, there is no unique way to turn z into a velocity. "Distant" in this context means $z \gtrsim 2$–3, corresponding to the era when the temperature of the 2.7K radiation was 8–11K.

A prototypical primordial galaxy was supposed to be the forerunner of a giant elliptical or the bulge of a big spiral (like the Milky Way), experiencing its first vigorous burst of star formation, so that ultraviolet radiation from hot, massive stars would ionize lots of gas. Most gas in galaxies is hydrogen, and so the expected signature was (redshifted) Lyman alpha emission, the line at 1216 Å emitted when the electron falls back from $n = 2$ to $n = 1$. The vast majority of searches for such emission have failed, except when the target area was close to a previously-identified quasar or radio galaxy, with a known redshift. The traditional excuses have been either that the ultraviolet line was absorbed by dust or that galaxy formation wasn't done in the hypothesized way. The answer is (as is frequently the case), some of each. Most of the new, high redshift galaxies and parts of galaxies are not strong Lyman alpha emitters. In addition, they don't look much like proto-ellipticals or proto-bulges. Most are compact and not enormously bright, and one's impression is that they are either bits and pieces that will eventually merge to make galaxies of recognizable types or that they are highly localized regions of star formation in something that will later "turn on" all over. Typical star formation rates are a few solar masses per year.

The winning technique also relies on the properties of hydrogen, but absorption rather than emission. Just shortward of the ionization limit at 912 Å, hydrogen is very opaque indeed, to the point where wavelengths $\lesssim$ 900 Å, at rest relative to us, used to be called the "unobservable ultraviolet." At redshifts $z \geq 3$, 912 Å begins to move into the color bands that we can observe from the ground (and into the standard color filters of HST). Thus, if you have a number of images of the same part of the sky, taken through infrared, red, yellow, blue, and ultraviolet filters, galaxies at large redshift may be quite bright and even quite blue in the first four images, but they will disappear completely in the fifth, U, image. For still larger redshifts, this "ultraviolet dropout" moves into blue and even yellow parts of the spectrum.

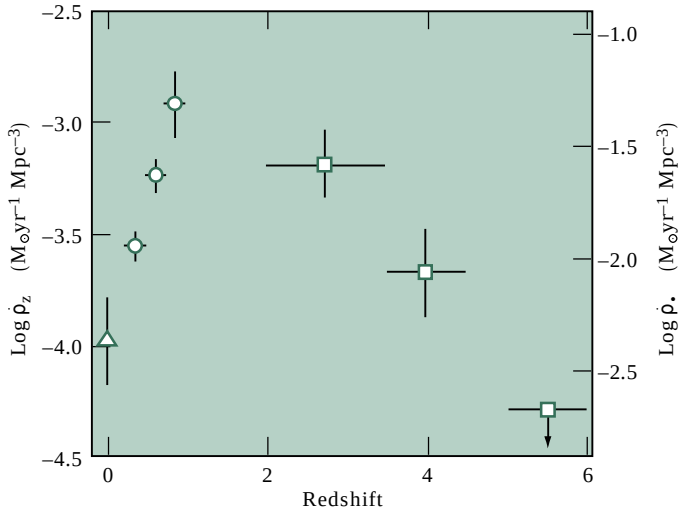
Ultraviolet dropout was pioneered by Charles Steidel and his colleagues at Caltech, looking first at the environs of known quasars and then at apparently blank bits of sky. They confirmed their estimated redshifts with Keck spectra and pronounced them good. The quintessential bit of "blank sky" is the Hubble Deep Field, a few square minutes in a region where HST's view is never





A graphic illustration of the "ultraviolet dropout" method of locating high redshift galaxies. The object in parentheses in each of the three images is quite conspicuous through both red and green filters (and in fact somewhat brighter in the green, indicating that it is intrinsically fairly blue), but completely absent in the right-hand ultraviolet image. This means that its redshift is large enough for the absorption edge due to neutral hydrogen to have been shifted into the U passband. (Courtesy Charles Steidel, California Institute of Technology)

Charles Steidel



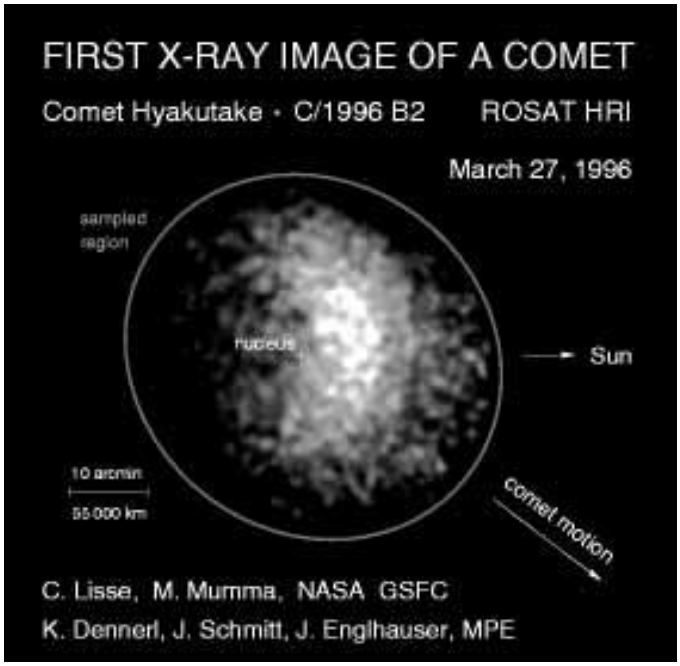
The rate of formation of massive stars (or of new heavy elements in massive stars) as a function of redshift as derived from numbers and brightnesses of high-redshift, star-forming galaxies. The upper limit at z = 5.5 comes from the paucity of V-band drop-outs in the Hubble Deep Field. [From Piero Madau in Star Formation Near and Far, Proc. 7th Annual Astrophysics Conference in Maryland, Eds. S. S. Holt and G. L. Mundy, (AIP, New York), in press.]

blocked by earth or sun, chosen precisely because it hosts nothing very bright in ordinary photographs (or even infrared, X ray, or radio images). Robert Williams, the current director of the Space Telescope Science Institute, made two rather brave decisions. First, to use a very large number of HST orbits to image this scrap of sky at several wavelengths. And, second, to release the data for public analysis immediately. Since the December 1995 release, preprints, papers, and pontification have proliferated. Real redshifts for uv-drop-out galaxies are accumulating rapidly as well. Redshifts up to $z \approx 4$ are well represented, and some candidates for z = 5–6 remain to be confirmed.

Important conclusions are (a) star formation is underway at or before $z = 4$ and is truly rampant at z = 1–3; (b) the earlier epoch of star formation made ellipticals and bulges, while the peak near $z = 1$ was making disk and irregular galaxies; (c) high z morphologies include some smooth-ish spheroids, some disks (but none with grand design spiral arms), and lots of "other," that is shapes implying interactions, mergers, and the like; and (d) the history of star formation correlates well with the history of how the universe became enriched in the heavy elements that only massive stars can make. Progress is also being made (but not to the point where I can list the answer) on some old questions about when and how galaxies came to be clustered, whether all ellipticals come from the merger of disk galaxies, and on the role in the great scheme of things of the large number of faint, blue, galaxies that turn up when you start trying to count absolutely everything in sight.

IN AND AROUND THE SOLAR SYSTEM

The Galileo mission to Jupiter (which dropped a probe into the interior in 1996) is still busily imaging its satellites. Two of my favorite results are (a) that high speed



winds and turbulence persist so far down into the Jovian atmosphere that the primary energy source must be heat escaping from the interior (earth's winds, waves, and weather are, of course, driven by energy from the sun) and (b) that the moon Ganymede has a partially molten interior, its own dynamo magnetic field, and changing surface features that act a bit like plate tectonics and continental drift on earth.

Comets are, of course, things you go outdoors on a clear evening to see. Thus, as Hyakutake crossed the skies a year or so ago, I habitually asked colleagues, "Have you seen the comet?" Imagine my surprise when Joachim Trümpler of the Max Planck Institute in Munich e-said, "Yes. In X rays." Sure enough, the ROSAT X-ray satellite had detected the first known cometary emission. A couple of previous visitors have since been recovered in archival data. The emitting region is always more or less crescent shaped, and the hot gas responsible seems to be the result of solar wind particles hitting the gaseous front of the comet.

Life in or on a Martian meteorite? When I was a child, the phrase "I don't think so" was an expression of genuine doubt. Very occasionally, the real world intrudes into my office sufficiently to make me aware that this is no longer entirely the case, and I have been looking for a context in which to attempt the new meaning.

IN AND AROUND THE MILKY WAY

"I want one too," astronomers who study our own Galaxy have been saying about black holes ever since evidence began to mount up that they are common at the centers of other galaxies (some, though not all of which are quasars and other sources of excitement). The case for something very compact and as massive as a million or so stars at our center has grown gradually stronger over the years. The alternative has always been some other very compact, rather dark configuration, like a cluster of neutron stars. The alternative has now been ruled out by the completion of a pair of projects to measure velocities along the line of sight and in the plane of the sky of stars very near the galactic center. No cluster of stars could be compact enough to live inside the volume with the large velocity dispersion. The remaining alternatives are, therefore, a tight cluster of small black holes or one big one. In a logical universe, people who dislike the whole idea of black holes and don't want any in the real world would vote for the single big one, while enthusiasts should favor the cluster of little ones; but I suspect that an actual opinion poll would turn out the other way around.

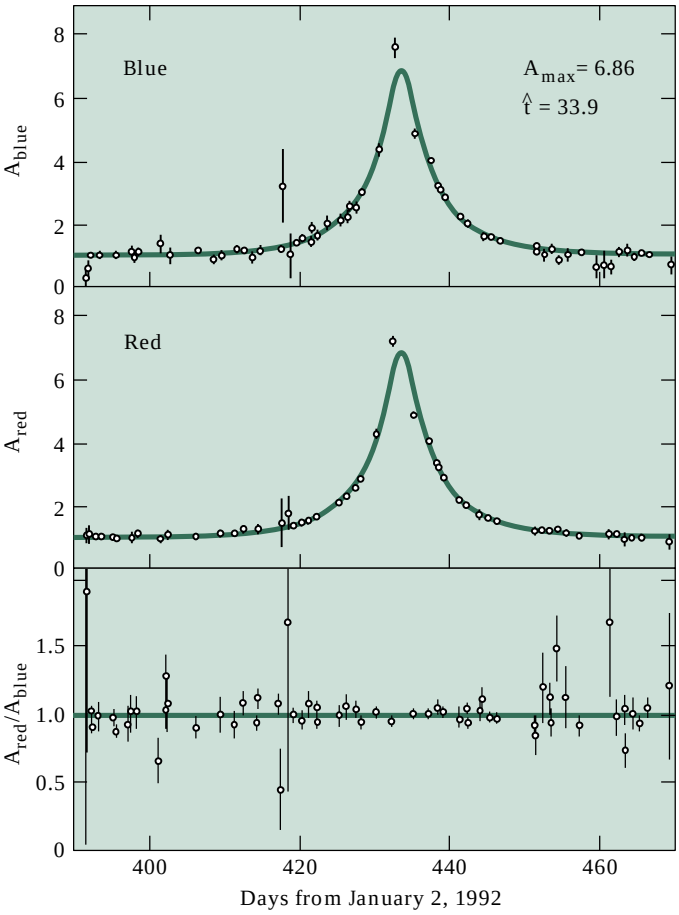
Up until the other day (it was a Saturday in December 1995, in fact), an X-ray burster was an X-ray burster and an X-ray pulsar was an X-ray pulsar, and Mark Twain hadn't met either one of them.* Although both are

**The author is, of course, aware that the line is stolen from Kipling, not Twain, and that the two knew each other reasonably well. This is called literary license.*

neutron stars, pulsars are regular variables at the rotation period of a star with a magnetic field sufficiently strong to channel accreting gas ("accretion powered pulsars") or outflowing relativistic fluids ("rotation powered pulsars") into the vicinity of their magnetic poles, leading to a corresponding modulation of the outgoing radiation. Such strong fields ($\approx 10^{12}$ G) are associated with neutron stars early in their lives (or at least in their lives as accretors). Bursters, on the other hand, are nonperiodic, though with characteristic time scales, and are the result of sporadic accretion or sporadic explosive fusion of helium accumulated on neutron star surfaces. The previously known examples were all low-mass X-ray binaries, meaning that the gas donors were solar-type stars or smaller and that the neutron star fields were less than about 10^{10} Gauss, leaving the stars with fairly uniform surfaces.

On December 2, 1995, the Compton Gamma Ray Observatory spotted the first source that does both. Now called GRO J1744-28 (dial this at your peril), it showed periodic modulation at about 0.5 seconds but also about 200 irregularly timed bursts of 8 to 30 seconds or more in the first nine days, and an orbit period of 11.8 days. It has turned off and back on again a time or two in the intervening 1.2 years and has become a bit of a nuisance, nearly saturating the CGRO burst detectors and keeping them from seeing more interesting (or anyhow more mysterious) gamma-ray bursts of other kinds. A number of modelers concur that the bursts are of the variable accretion type, though they disagree about whether it is the accretion rate, the magnetic field strength, or some other combination of properties that must be very finely tuned to allow both kinds of variability in a single source.

We have worried before in these pages (*Beam Line* Vol. 22, No. 3, Fall 1992; Vol. 25, No. 1, Spring 1995) and elsewhere about the age of the universe, how well it is known, and whether it presents problems for people who think they know other things about the universe, like the Hubble constant or the density. Most discussions focus on clusters of old stars (globular clusters) found in the halo of our galaxy. A few have considered the decay of uranium and thorium to lead in the solar system and how long ago the U and Th must have formed to make things come out right. If the synthesis had happened in a single burst of star formation, we would be home clear. But galaxies don't work that way, and the



The first microlensing of a star in the Large Magellanic Cloud found by the MACHO group, in January 1992. The top two panels show the brightness versus time over about two months in blue and red light. The bottom panel is the ratio of red to blue luminosity. The time symmetric profiles (best seen in the fitted curves in the top two panels) and the invariant color shown in the bottom panel are signatures that distinguish lensing events from intrinsic variability of stars. (Courtesy Kim Griest, University of California, San Diego)

"time back to first synthesis" depends a good deal on what you assume about the history of star formation.

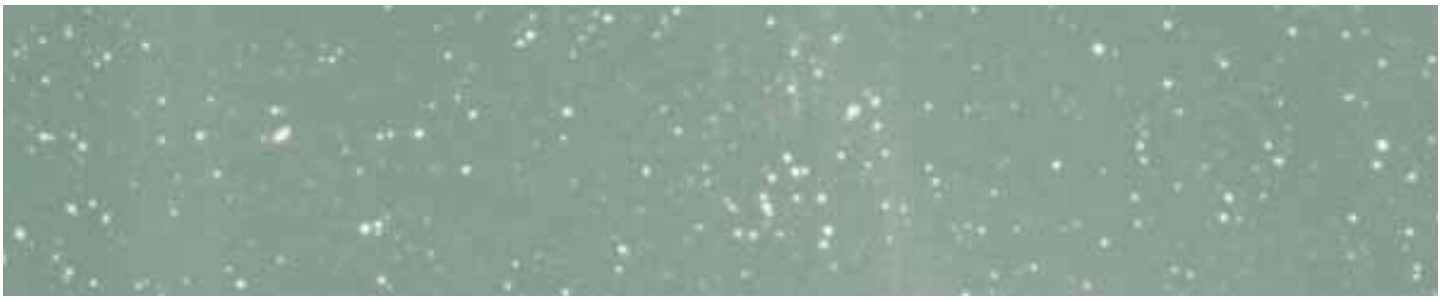
Residual uranium and/or thorium would be a better cosmic chronometer if the solar system were older (though of course we would probably not be around to worry about the problem). The detection of thorium in one old (halo, population II) star is, therefore, a major advance. The discoverers cannot say anything about the amout of Pb^{208} that much of the Th^{232} has decayed into. But they can measure the thorium/europium ratio and (reasonably) assume that it is smaller than the production ratio because some of the thorium has decayed, and the europium has not. The implied stellar age is 15.2 ± 3.7 billion years, much the same sort of number that has come out of other considerations. We hope that the discoverers are busily writing observing proposals to look for thorium in a few additional very old stars!

Gravitational microlensing by (probably) stars or substellar objects in the halo of the Milky Way starred in a couple of press releases during the year. The official two-year sample has 7 ± 1 events in the direction of our neighbor, the Large Magellanic Cloud. Mercifully, only the first year's data (three events) appeared in the refereed literature during the official year, and this spares me from having to decide whether to be complacent, puzzled, or panic-stricken by the set of seven durations and amplitudes and their possible decodings into masses, velocities, and locations of the stars(?) responsible. All three reactions and some others have appeared in preprints-by-pundits. The problem is that the simplest possible interpretation of the events puts the lensing objects in a mass range of 10 to 50 percent the mass of our sun, where they ought to be detectable by other methods (and are not).

IN AND AROUND THE UNIVERSE

The amount of deuterium left from nuclear reactions in the hot, dense early universe (a.k.a. Big Bang or Tremendous Space Kablooie) is very sensitive to the density of stuff involved in the reactions. Qualitatively, this is easy to see. If there are lots of protons and neutrons around, the average deuteron will easily find some and burn through to helium. If not, not. The community has lived fairly happily for a decade or two with the ratio of deuterium to ordinary hydrogen being something times 10^{-5} (implied by the local interstellar gas and by the gases in Jupiter's atmosphere). What one really wants, of course, is the ratio in gas that hasn't had stars and galaxies monkeying around with it. Certain clouds responsible for absorption lines in the spectra of distant quasars are a reasonable candidate, and the year has seen a sort of tug of war between groups of observers, each with an accompanying entourage of theorists, who have found clouds with D/H around 10^{-5} and groups who have found clouds with D/H about a factor of 10 bigger. The debate is still at the scientific duel stage (scurrilous adjectives at 10 paces). I suppose the wise thing is to bet on the less interesting answer, since then one will have either the satisfaction of being right or the satisfaction of learning something new and exciting about the universe. This is sort of like choosing a book you have to read anyhow if you are trying to read yourself to sleep. At least one objective is bound to be accomplished.

Supernovae in very distant galaxies ought to be useful probes of something or other. Perhaps one could use them to measure the Hubble constant, or the slowing of the cosmic expansion, or the geometry of the universe, or to test even more fundamental points like whether the universe is really expanding at all. The general idea was published the year the author's parents were married, and the first serious search for supernovae at redshifts of 0.1 or more started nearly a decade ago. It found one event. And then, with a new search, there were two. Now, suddenly, they are being published by the dozen in Circulars of the International Astronomical Union. The current record redshift is 0.75, more than enough for any of the cosmological tests you might want to perform. A good many foothills remain to be got out of the way before the mountains can be moved, but we can already rule out a couple of variant universes (for instance with redshifts proportional to age rather than distance and redshifts caused by photons simply losing energy as they travel). This is one area I definitely want to keep an eye on in 1997–98.



AND ALL THE REST

The literature of astronomy has not quite reached the 200,000 papers per year attributable to physics, but it's getting there. Every paper is, presumably, a highlight at least to its authors, and my choice of items here and in the longer paper from which this is drawn is necessarily arbitrary, biased, and various other words you might think of (especially if your particular favorite topic isn't here). And there is still more coming, so stay tuned to your favorite preprint shelf, whether wooden or Webbed.

Suggestions for Further Reading

THESE ITEMS AND MANY DOZENS OF OTHERS from the 1996 astronomical literature are discussed by Virginia Trimble and Lucy Ann McFadden in *Publications of the Astronomical Society of the Pacific* for February 1997. Lucy Ann did the solar system part, and Virginia is to blame for nearly all the rest. For more about Mark Twain and Rudyard Kipling, see C. C. Park "The River and the Road" in *American Scholar*, Vol. 66, No. 1, 1997, p. 43.

DATES TO REMEMBER

Jun 29–Jul 2	20th Anniversary Symposium: 20 Beautiful Years of Bottom Physics, Chicago, IL (Dan Kaplan, Department of Physics, Illinois Institute of Technology, Siegel Hall, 3301 S. Dearborn, Chicago, IL 60616 or b20@hepl.iit.edu)
Jul 3–9	High Energy Physics International Euroconference on Quantum Chromodynamics: QCD 97: 25th Anniversary of QCDS, Montpellier, France (QCD Secretariat, Laboratoire de Physique Mathematique et Theorique, Universite Montpellier II, Place Eugene Bataillon, F-34095 Montpellier Cedex 05, France or qcd@lpm.univ-montp2.fr)
Jul 7–11	7th International Symposium on Heavy Flavor Physics, Santa Barbara, CA (flavors@hep.ucsb.edu)
Jul 28–Aug 1	18th International Symposium on Lepton-Photon Interactions (LP 97), Hamburg, Germany (LP97 Coordinator, DESY, D-22603 Hamburg, Germany or LP97@desy.de)
Aug 4–15	25th SLAC Summer Institute on Particle Physics: Physics of Leptons, Stanford, CA (Lilian DePorcel, Conference Coordinator, SLAC, Box 4349, Stanford, CA 94309 or ssi@slac.stanford.edu)
Aug 4–Sep 5	Aspen Workshop on New Physics at LEP2 and the Tevatron, Aspen, CO (Aspen Center for Physics, 700 W. Gillespie, Aspen, CO 81611 or jane@acpl.zgsw.com)
Aug 19–26	International Europhysics Conference on High-Energy Physics (HEP 97), Jerusalem, Israel (D. Lellouch, Scientific Secretary, Weizmann Institute, Rehovot, Israel, or hep97@www.hep97.ac.il)
Sep 1–12	CERN Accelerator School (CAS 97): Accelerator Physics, Gjovik, Norway (Mrs. S. Von Wartburg, CERN Accelerator School, AC Division, 1211 Geneva 23, Switzerland or suzanne.von.Wartburg@cern.ch)

CONTRIBUTORS

EMLYN HUGHES is an Associate Professor of Physics at Caltech and was recently named one of the 1997 Sloan Research Fellows. He received his PhD from Columbia University in 1987 working with the neutrino physics group of the Nobel Laureate Jack Steinberger at CERN. After a year of atomic physics post doctoral work at the Ecole Normale Superieure in Paris, he joined SLAC as a research associate in 1988. In 1992, he received the Panofsky Fellowship and remained at SLAC until 1995 when he joined the faculty at Caltech. His work at SLAC concentrated on experiments involving scattering polarized electrons off polarized targets to study the spin structure of the proton and neutron. He is presently spokesperson of SLAC experiments E142 and E154.

SIDNEY PERKOWITZ, a native New Yorker, was educated at the Polytechnic Institute of Brooklyn and the University of Pennsylvania. In 1969, he joined Emory University, where he is Charles Howard Candler Professor of Physics. He has held visiting appointments, and is Adjunct Professor of Humanities at the Atlanta College of Art. His 150 publications include papers and monographs about the optical properties of solids, essays, and the book *Empire of Light* (New York: Henry Holt, 1996) for general readers. He is preparing a wall chart tracing 20th century physics for the centennial of the American Physical Society in 1999.

KARL BERKELMAN is a Professor of Physics at Cornell University and the Director of the Laboratory of Nuclear Studies, which operates CESR, the Cornell Electron Storage Ring. He has been a member of the CLEO collaboration since its beginnings in the late 1970s, and before that he was active in electron scattering experiments at the Cornell electron synchrotron. He has also enjoyed several sabbatic years at Frascati, DESY, and CERN. His recent research interests have concentrated on rare *B* meson decays of the sort discussed in his *Beam Line* article.

A Fellow of the American Physical Society, HELMUT WIEDEMANN has dedicated most of his career to accelerator physics—in particular storage ring physics for colliding beams and synchrotron radiation production. He has served as a consultant to new starts of synchrotron radiation sources in Brazil, Taiwan, and Thailand. He received his PhD from the University of Hamburg and joined SLAC as assistant director for design coordinaton of the PEP storage ring in 1975 after a ten-year stint at DESY in Hamburg, Germany. He became an adjunct professor at Stanford University in 1980 and three years later accepted a joint appointment as Professor (Research) in the department of Applied Physics and SSRL. He presently concentrates on teaching graduate students in accelerator physics.

VIRGINIA TRIMBLE has been trying since January to find time to get a new picture taken. If she succeeds, the first two copies are for the passport agency (her permit to be an Ugly American having expired in April) and the third one is promised to the editor for *Beam Line*. If she fails, she will be unable to atend several overseas conferences this summer, which will free up enough time to write something for the next issue.