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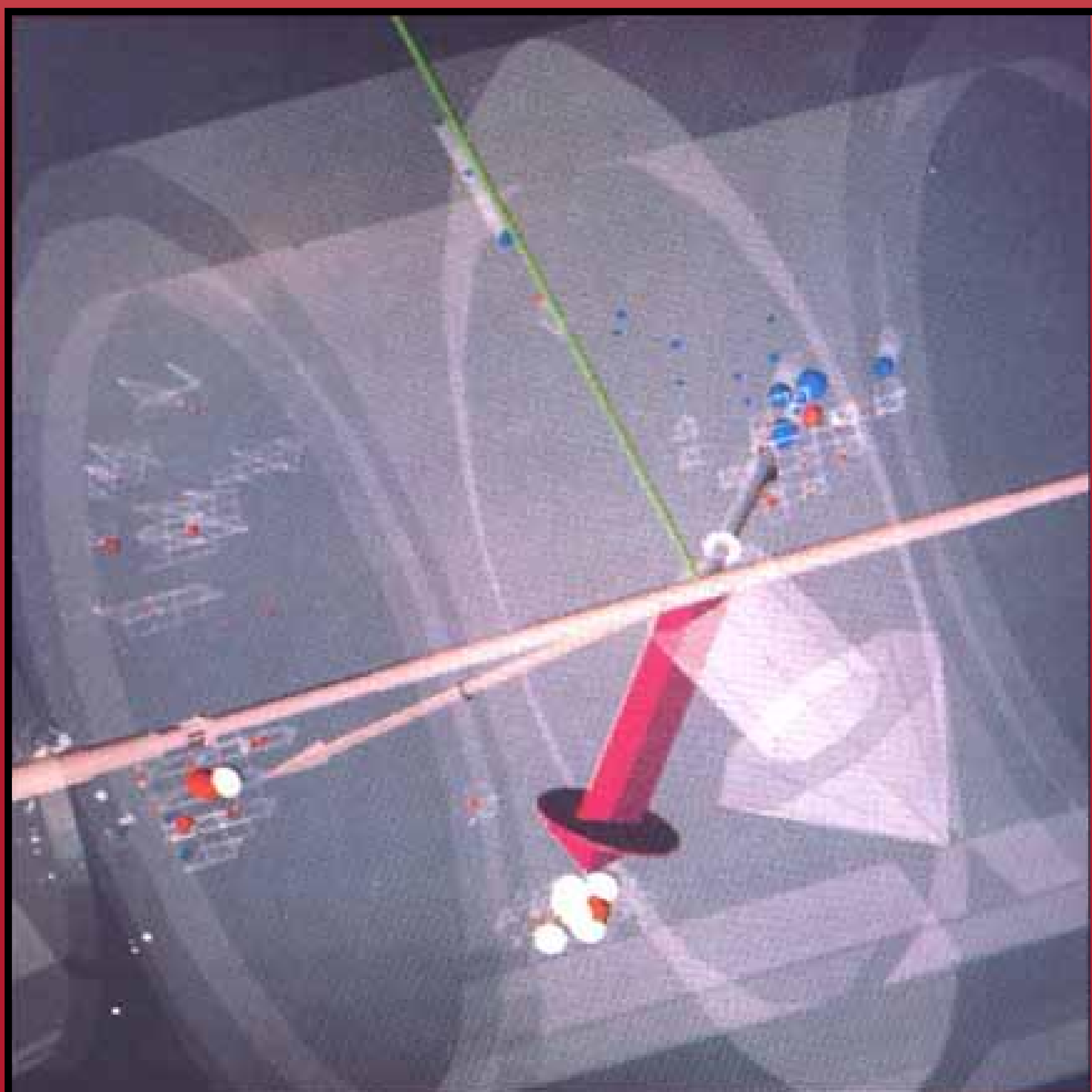

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

FALL 1995 VOL. 25, NUMBER 3

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Cover: Display of a top quark candidate event with an electron (the large magenta arrow), a muon (green tube), two jets (gray and pink arrows), and the missing transverse momentum carried by neutrinos (large light arrow). The arrow widths are proportional to the energy carried by the object. The lattice work shows the cells of the calorimeter showing significant energy deposit. The spheres represent the amount of energy deposited in the calorimeter cells (orange and white for electromagnetic deposits and blue for hadronic deposits). The faint shadings represent the edges of the sub-detectors. The same dilepton event is shown as a lego plot on page 12. More such displays can be found on the World Wide Web at http://d0sgi0.fnal.gov/art_souvenir/art_souvenir.html.

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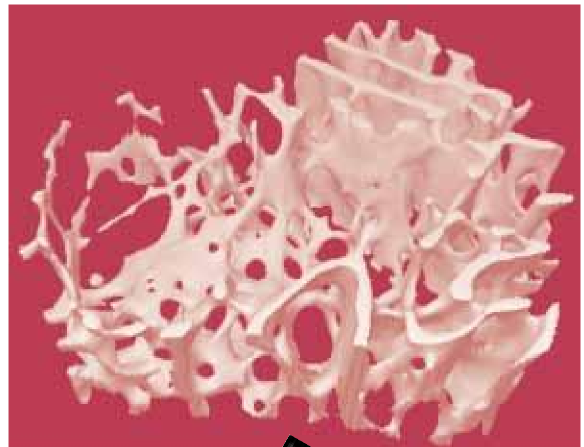

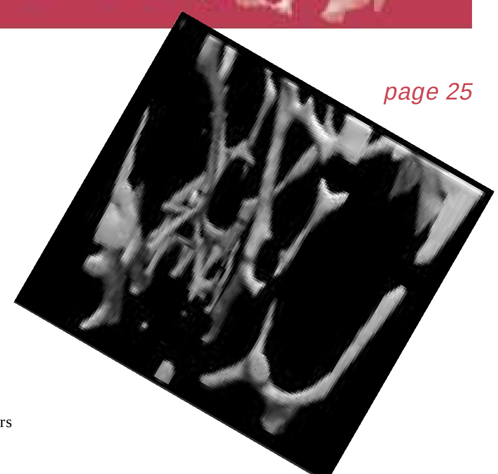

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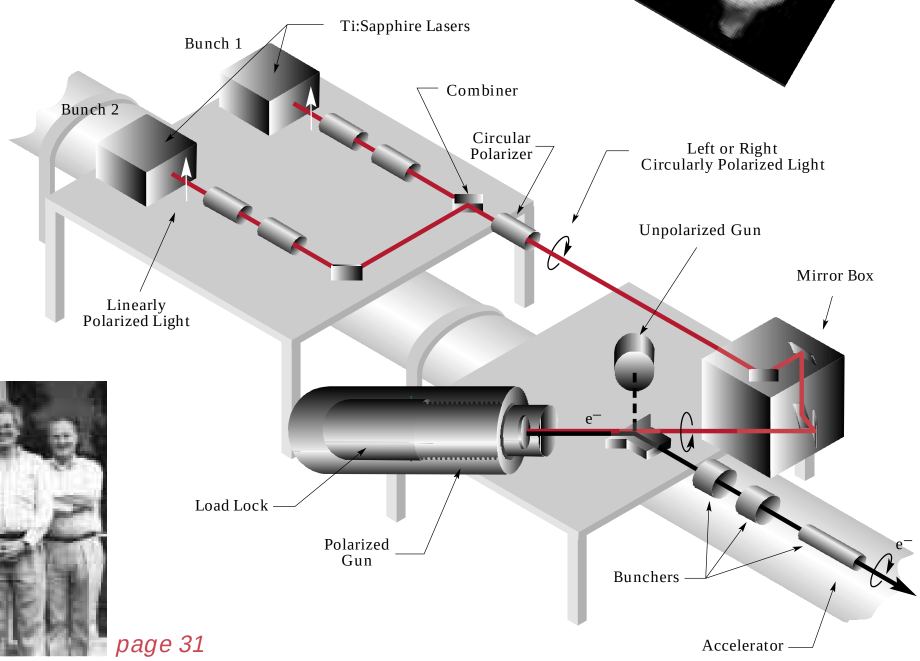

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GUEST EDITORIAL

James Bjorken (Bj), who played a central role in the development of the quark-parton model at SLAC from 1963–1979, spent ten years at Fermilab in 1979–1989, including a period as Associate Director of Physics. He is presently co-spokesperson of the Fermilab test/experiment T864 in the Tevatron collider which he describes as being "closer to Roentgen in style than to CDF or to DØ." Since returning to SLAC in 1989, he has been active in theoretical and experimental activities.

THE FEATURE ARTICLE in the summer issue of the *Beam Line* was the serendipitous discovery of X rays 100 years ago by Wilhelm Roentgen. Upon observing fluorescence occurring some distance away from a Crookes tube he was operating, he set aside his duties as university rector and teacher and retreated into his laboratory to work alone, sharing nothing with colleagues. He reemerged six weeks later with his discoveries ready for publication and for the subsequent press conferences.

In this issue is featured the particle-physics discovery of the year, that of the top quark. It is at an opposite extreme, a programmed discovery under way for most of a decade at Fermilab, featuring two competing experimental groups, the CDF and DØ collaborations, each consisting of 400 to 500 physicists, plus countless engineers, technicians, and support personnel, especially the many members of the Fermilab Accelerator Division who provide the essential ingredient of the colliding beams. This article is written by the spokespersons of the two competing collaborations and tells much of how scientific discovery is done in such an extreme social environment. Each collaboration is a community in itself, with three branches of governance, robust bureaucracy and organization charts, and a considerable level of specialization.

It happens that over the last year or two I have spent a lot of time at Fermilab, much of it precisely halfway between these behemoth detectors. So I watched with interest and bemusement the excitement of the chase, along with the frustrations, the impatience, the fatigue, the anxieties, and some of the inevitable politics. I witnessed the awkward first stage of CDF evidence, when four short draft papers were by compromise merged into a very long paper. I even promised CDF collaborators to read the thing and did, carefully, beginning to end, and found it a classic—a masterful exhibit of how science results should (but seldom do) get reported. Throughout I maintained a somewhat dour posture toward those CDF/DØ crowds, baiting them regarding their obsessive pursuit of top to the apparent neglect of all else (not quite true of course), including that hidden piece of New Physics Beyond the Standard Model lurking undetected in their data. But when the top quark results eventually bubbled up to the surface, I could not do anything but be bouyed by them as well, joyful in the occasion and deeply respectful of the magnitude of the accomplishment.

The history of physics is full of near-simultaneous discoveries by separate individuals or groups, and with that often has come acrimony and controversy, from Newton and Leibnitz to Richter and Ting, and down to the present time. There has been competition between CDF and DØ as well. In fact, it was built in from the beginning by then-director Leon Lederman, who visited CERN's big collaborations, UA1 and UA2, while they were discovering intermediate bosons *W* and *Z* and searching for the top quark. At CERN, it was vital to have two collaborations as checks and balances, and Lederman upon his return strongly encouraged the creation of the present DØ collaboration, something which was not in the works prior to that. And the ensuing CDF/DØ competition has served for constructive purposes; I have never seen this competitiveness to be corrosive. The evidence is in these pages for the reader to see, in the very fact of co-authorship and in the nature of the interactions between the collaborations as described in the article. This piece of competition has been a class act.

Not only has this been true between the collaborations, but it seems also to have been the case within them. This is no mean feat, since harmony within a big group of strong individualistic physicists of great talent and often even greater ego is not easy to maintain. I can do no better than quote here what is found near the end of the article, and I do this without regrets for creating some redundancy:

> In the end, the chief necessity for the convergence on the top discovery was the willingness of a collaboration to abide by a majority view. Securing this willingness requires extensive attention to the process—of being sure that all shades of opinion, reservations, and alternate viewpoints are fully heard and understood. It is more important perhaps that each point of view is carefully listened to than that it be heeded. A fine line in resolving these viewpoints must be drawn between autocracy and grass-roots democracy. The process must have the confidence of the collaboration, or its general effectiveness can diminish rapidly.

These are not mere words, but an account of successful actions. In this increasingly fractious world of ours, it should be read and taken to heart by all those who despair of progress being made through reasoning and consensus.

James Bjorken

DISCOVERY
of the
TOP QUARK

by BILL CARITHERS
& PAUL GRANNIS

Two leaders of the Fermilab experiments that isolated the top quark tell the adventure of its discovery.

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MANKIND has sought the elementary building blocks of matter ever since the days of the Greek philosophers. Over time, the quest has been successively refined from the original notion of indivisible "atoms" as the fundamental elements to the present idea that objects called quarks lie at the heart of all matter. So the recent news from Fermilab that the sixth—and possibly the last—of these quarks has finally been found may signal the end of one of our longest searches.

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CDF Collaboration

Argonne National Laboratory
Istituto Nazionale di Fisica Nucleare, University of Bologna
Brandeis University
University of California at Los Angeles
University of Chicago
Duke University
Fermi National Accelerator Laboratory
Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare
Harvard University
Hiroshima University
University of Illinois
Institute of Particle Physics, McGill University and University of Toronto
The Johns Hopkins University
National Laboratory for High Energy Physics (KEK)
Lawrence Berkeley Laboratory
Massachusetts Institute of Technology
University of Michigan
Michigan State University
University of New Mexico
Osaka City University
Università di Padova, Instituto Nazionale di Fisica Nucleare
University of Pennsylvania
University of Pittsburgh
Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa
Purdue University
University of Rochester
Rockefeller University
Rutgers University
Academia Sinica
Texas A&M University
Texas Tech University
University of Tsukuba
Tufts University
University of Wisconsin
Yale University

But the properties of this fundamental constituent of matter are bizarre and raise new questions. In particular, the mass of the top quark is about forty times that of any other—a fact which suggests that perhaps it plays a fundamental role in the question of how the mass of any object arises.

IN 1964 Murray Gell-Mann and George Zweig proposed the quark hypothesis to account for the explosion of subatomic particles discovered in accelerator and cosmic-ray experiments during the 1950s and early 1960s. Over a hundred new particles, most of them strongly interacting and very short-lived, had been observed. These particles, called hadrons, are not elementary; they possess a definite size and internal structure, and most can be transformed from one state into another. The quark hypothesis suggested that different combinations of three quarks—the up (u), down (d), and strange (s) quarks—and their antiparticles could account for all of the hadrons then known. Each quark has an intrinsic spin of 1/2 unit and is presumed to be elementary, like the electron. So far, quarks appear to have no size or internal structure and thus represent the smallest known constituents of matter. To explain the observed spectrum of hadrons, quarks had to have electric charges that are fractions of the electron charge. The u quark has charge 2/3 while the d and s quarks have charges −1/3 (in units where the electron charge is −1).

The observed hadron spectrum agreed remarkably well with the expected states formed from combinations of three quarks or a quark-antiquark pair. Quarks also seemed to form a counterpart to the other class of elementary particles, the leptons, which then included the electron (e) and muon (μ) (both with unit charge) and their companion chargeless neutrinos, ν_e and ν_μ. The leptons do not feel the strong interaction, but they do participate in the electromagnetic interactions and the weak interaction responsible for radioactive decays. They have the same spin as the quarks and also have no discernible size or internal structure.

But most physicists were initially reluctant to believe that quarks were anything more than convenient abstractions aiding particle classification. The fractional electric charges seemed bizarre, and experiments repeatedly failed to turn up any individual free quarks. And—as became apparent from studies of fundamental theories of quarks and leptons—major conceptual problems arise if the numbers of quarks and leptons are not the same.

Two major developments established the reality of quarks during the 1970s. Fixed-target experiments directing high energy leptons at protons and neutrons showed that these hadrons contain point-like internal constituents whose charges and spins are just what the quark model had predicted. And in 1974 experiments at Brookhaven National Laboratory in New York and Stanford Linear Accelerator Center (SLAC) in California discovered a striking new hadron at the then very large mass of 3.1 GeV—over three times that of the proton. This hadron (called the J/ψ after its separate

	Electric Charge	First Family	Second Family	Third Family
QUARKS	+2/3	up (u)	charm (c)	top (t)
	-1/3	down (d)	strange (s)	bottom (b)
LEPTONS	-1	electron (e)	muon (μ)	tau (τ)
	0	electron neutrino (ν_e)	muon neutrino (ν_μ)	tau neutrino (ν_τ)

names in the two experiments) was found to be a bound state of a new kind of quark, called charm or *c*, with its antiquark. The *c* quark has a much greater mass than the first three, and its charge is 2/3. With two quarks of each possible charge, a symmetry could be established between the quarks and the leptons. Two pairs of each were then known: (u,d) and (c,s) for quarks and (e,ν_e) and (μ, ν_μ) for leptons, satisfying theoretical constraints.

But this symmetry was quickly broken by unexpected discoveries. In 1976 experiments at SLAC turned up a third charged lepton, the tau lepton or τ. A year later at Fermi National Accelerator Laboratory in Illinois a new hadron was discovered called the upsilon or Υ, at the huge mass of about 10 GeV; like the J/ψ, it was soon found to be the bound state of yet another new quark—the bottom or *b* quark—and its antiparticle. Experiments at DESY in Germany and Cornell in New York showed that the *b* quark has spin 1/2 and a charge of −1/3, just like the *d* and *s* quarks.

With these discoveries, and through the development of the Standard Model, physicists now understood that matter comes in two parallel but distinct classes—quarks and leptons. They occur in "generations" of two related pairs with differing electric charge—(+2/3, −1/3) for quarks and (−1, 0) for leptons (see chart above). Ordinary matter is composed entirely of first-generation particles, namely the *u* and *d* quarks, plus the electron and its neutrino. But the third-generation quark doublet seemed to be missing its charge +2/3 member, whose existence was inferred from the existing pattern. In advance of its sighting, physicists named it the top (t) quark. Thus began a search that lasted almost twenty years.

USING THE RATIOS of the observed quark masses, some physicists naively suggested that the *t* might be about three times as heavy as the *b*, and thus expected that the top would appear as a heavy new hadron containing a $t\bar{t}$ pair, at a mass around 30 GeV. The electron-positron colliders then under construction (PEP at SLAC and PETRA at DESY) raced to capture the prize, but they found no hint of the top quark.

In the early 1980s a new class of accelerator came into operation at CERN in Switzerland, in which counter-rotating beams of protons and antiprotons collided with an energy of about 600 GeV. The protons and antiprotons brought their constituent quarks and antiquarks into collision with typical energies of 50 to 100 GeV, so the top quark search could be extended considerably. Besides the important discovery of the *W* and *Z* bosons that act as carriers

DØ Collaboration

Universidad de los Andes
University of Arizona
Brookhaven National Laboratory
Brown University
University of California, Davis
University of California, Irvine
University of California, Riverside
LAFEX, Centro Brasileiro de Pesquisas Físicas
Centro de Investigacion y de Estudios Avanzados
Columbia University
Delhi University
Fermi National Accelerator Laboratory
Florida State University
University of Hawaii
University of Illinois, Chicago
Indiana University
Iowa State University
Korea University
Kyungsung University
Lawrence Berkeley Laboratory
University of Maryland
University of Michigan
Michigan State University
Moscow State University
University of Nebraska
New York University
Northeastern University
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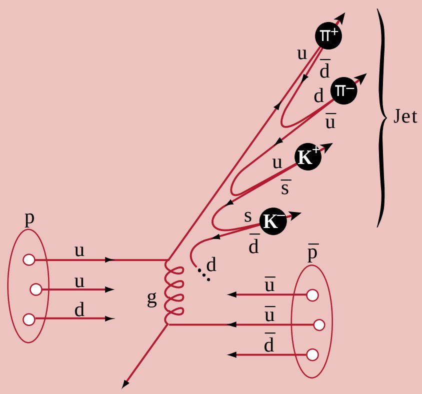
Northwestern University
University of Notre Dame
University of Panjab
Institute for High Energy Physics, Protvino
Purdue University
Rice University
University of Rochester
Commissariat à l'Energie Atomique, Saclay
Seoul National University
State University of New York, Stony Brook
Superconducting Super Collider Laboratory
Tata Institute of Fundamental Research
University of Texas, Arlington
Texas A&M University

Jet Production



A **COLLIDING PROTON** (p) and antiproton ($\bar{p}$) bring together quarks *uud* and $\overline{uud}$. In this example, a u and $\bar{u}$ scatter by exchanging a gluon (g), the carrier of the strong nuclear force. Like all quarks, the scattered u quark possesses the strong interaction "charge" called *color*. The strong attraction of the u quark color to the other quark color charges prevents it from escaping freely. Energy from the collision region is converted to matter in the form of quark-antiquark pairs. The antiquark (with anti-color) joins with a quark to produce a colorless meson which is free to escape.

In this example, the primary scattered u quark is accompanied by ($d\bar{d}$), ($u\bar{u}$), ($s\bar{s}$), and ($d\bar{d}$) created pairs, leading to the formation of π^+, π^-, K^+, and K^- mesons, all traveling in similar directions and forming a "jet" of particles that may be detected in the experiment. (The remaining d quark will be joined to one of the other spectator quarks in the collision.)

of the unified electroweak force, the CERN experiments demonstrated another aspect of quarks. Though quarks had continued to elude direct detection, they can be violently scattered in high energy collisions. The high energy quarks emerging from the collision region are subject to the strong interaction as they leave the scene of the collision, creating additional quark-antiquark pairs from the available collision energy (using $E = mc^2$). The quarks and antiquarks so created combine into ordinary hadrons that the experiment can detect. These hadrons tend to cluster along the direction of the original quark, and are thus recorded as a "jet" of rather collinear particles. Such quark jets, previously sensed at SLAC and DESY, were clearly observed at CERN and became a key ingredient in the next round of top quark searches.

With the advent of the CERN collider, and in 1988 the more powerful 1800 GeV collider at Fermilab, the search for the top quark turned to new avenues. At the large masses now accessible, the $t\bar{t}$ bound state was unlikely to form and isolated top quarks were expected. For masses below that of the W boson, W decay into a t and $\bar{b}$ could predominate. Some indication of this process was reported in 1984 by the CERN UA1 experiment, but it was later ruled out by the CERN UA2 and Fermilab CDF experiments. By 1990 CDF had extended the top mass limit to 91 GeV, thus eliminating the possibility for W decay to top.

IN 1992, the DØ detector joined CDF as a long Tevatron run began. Further searches would have to rely on the production of separate t and $\bar{t}$ quarks from annihilation of incoming quarks and antiquarks in the proton and antiproton, with subsequent decays into observable particles (see box on the right). The design of DØ stressed recognition of the telltale leptons and jets over as large a solid angle as possible. Meanwhile CDF had installed a new vertex detector of silicon microstrips near the beams intended to detect short-lived particles that survive long enough to travel a millimeter or so from the interaction point. This detector was particularly good at sensing the presence of the b quarks characteristic of top decay. Another method of tagging b quarks, by detecting their decays into energetic leptons, was used by both experiments. Thus the two experiments, while searching for the same basic decay sequence, had rather complementary approaches.

With the data from this 1992–93 run, progress accelerated. First, DØ published a new lower limit of 131 GeV on the possible top mass from the absence of events with the characteristic dilepton or single lepton signatures. This paper turned out to be the end of the line in excluding top masses. Up to then, with the absence of an excess of candidate events, the analyses had tended to restrict the event sample, so as to set as high a limit on the mass as possible. But by summer of 1993, CDF noticed that the top mass limits were not improving with additional data, due to a growing handful of events that passed all preassigned criteria. Naive (in retrospect) estimates of their statistical significance triggered intense activity to review the results and prepare a draft publication with the goal of publishing the results by the October 1993 $p\bar{p}$ Workshop in Japan. As the analysis was too complex for a single journal letter, CDF planned a series of four papers in *Physical Review Letters* (PRL)—two devoted to the counting experiments in the two search topologies; one describing the kinematics of the events and giving an estimate of the top mass; and a fourth to bring it all together with the overall significance, conclusions, and top production cross section. In a heated argument at the October collaboration meeting, it became clear both that the mass and kinematics sections needed more work and that the "four PRL" format was not working well. CDF decided instead to prepare a single long *Physical Review* article, to concentrate on the remaining holes in the analysis, and to forego any public discussion of new results.

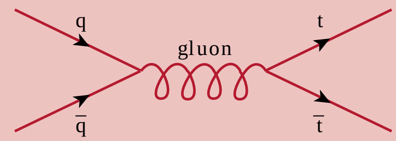
By the next CDF collaboration meeting in late January, the counting experiments were complete, the mass and kinematics analyses had made real progress, and the single long draft was in reasonable shape. The big remaining issues were the wordings of the title and conclusions section and the "between the lines" message that they sent to the community. Traditionally, scientific publications about new phenomena use certain key phrases: "Observation of" indicates a discovery when the case is unassailable; "Evidence for" means the authors believe they are seeing a signal but the case is not iron-clad; and "Search for" implies the evidence is weak or non-existent. Within every collaboration, there is a wide spectrum of comfort levels in claiming a new result. On one end of CDF, a few physicists felt that no publication should occur until the collaboration consensus was for "observation." The other end of the spectrum felt that the data were already in that category. Finally, CDF settled on a conservative interpretation and was careful to disclose even those results that contra-indicated top.

The pressure within CDF to publish increased enormously as the winter 1994 conferences approached. In addition, pirated copies of the *Physical Review D* manuscript were circulating widely and rumors (some astoundingly accurate and others comically off-base) were flying about the globe. The rumor mill churned once again when CDF withdrew its top talks at the LaThuile and Moriond Conferences. An April CDF Collaboration meeting was the watershed event, as the group hammered out the final wordings. After a virtually unanimous agreement on the final draft, the collaboration spokespersons finally notified Fermilab Director John Peoples of their intent to publish.

This CDF analysis found 12 candidate events that could not be easily explained on the basis of known backgrounds (which were predicted to be about six events). The odds for background fluctuations to yield the observed events were low—about 1 in 400—but not small enough to warrant the conclusions that the top had been found. Under the hypothesis that the data did include some $t\bar{t}$ events, the mass of the top was estimated to be 175 GeV±20 GeV. The cross section for $t\bar{t}$ production was determined to be about 13.9 picobarns, larger than the theoretical prediction of 3–7 picobarns.

Top Production and Decay

FOR TOP QUARK MASSES above $M_W + M_b$, top production proceeds mainly through annihilation of incoming quarks and antiquarks from the beam particles.



The q and $\bar{q}$ fuse briefly into a gluon, the carrier of the strong force, and then rematerialize as t and $\bar{t}$ quarks traveling in roughly opposite directions. The top quarks have a very short lifetime (about 10^{-24} seconds) and decay almost always into a W boson and a b quark ($t \to W^+b$; $\bar{t} \to W^-\bar{b}$). The b quarks evolve into jets seen in the detectors. The W^+ and W^- have several decay possibilities:

$$
\begin{aligned}
W^\pm &\to e^\pm \nu \qquad &&\text{(fraction = 1/9)}\\
&\to \mu^\pm \nu &&\text{(fraction = 1/9)}\\
&\to \tau^\pm \nu &&\text{(fraction = 1/9)}\\
&\to q\bar{q} &&\text{(fraction = 2/3).}
\end{aligned}
$$

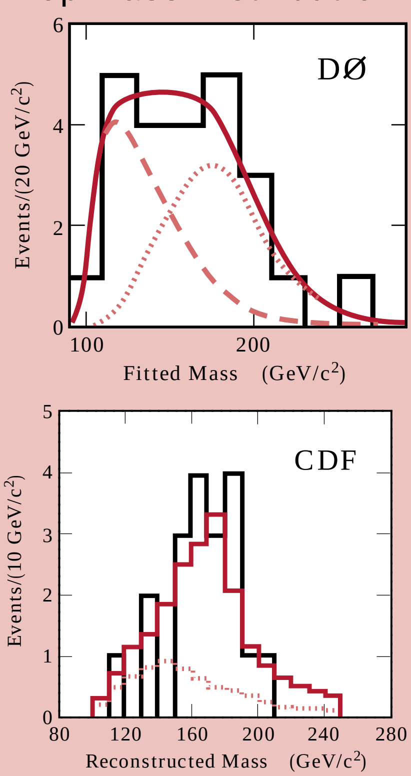
The q and $\bar{q}$ from W decays appear as jets. The final states containing τ's are difficult to isolate and were not sought in the experiments. The final state with both W's decaying into $q\bar{q}$, though relatively copious, are buried in huge strong interaction backgrounds. The remaining decays, studied by both CDF and DØ, can be categorized by the number leptons ($l = e$ or μ) from the W decays:

Dilepton channel:
$t\bar{t} \to W^+bW^-\bar{b} \to l^+l^-\nu\nu b\bar{b}$

Single lepton channel:
$t\bar{t} \to W^+bW^-\bar{b} \to l^+\nu q\bar{q} b\bar{b}$
or $l^-\bar{\nu} q\bar{q} b\bar{b}$

The dilepton channels are relatively free from background but comprise only 5 percent of all $t\bar{t}$ decays. The single lepton channels give larger yields (30 percent of all decays) but have substantial backgrounds from W + jets production processes which must be reduced.

Top Mass Distribution



The mass of the top quark can be reconstructed from the energies and directions of its decay products as measured in the detectors using the conservation laws for energy and momentum. Since the top quark has a unique mass, the data (indicated by the black histograms) should show a "peak" in the reconstructed distribution. The non-top background (the red dashed curve for DØ and the red dotted curve for CDF) has very different shapes. A simulation is required to provide the correspondence between the measured jet energies and the parent quark momenta. The red dotted curve for DØ shows the expected contribution from top for the best fit value of the top mass. The solid red curve shows what a simulated top quark mass distribution would look like when added to the background, and these curves should be compared to the actual data.

DØ used the period while CDF was preparing its publication to re-optimize its own earlier analysis, focusing on higher mass top. By April 1994, DØ was also in a position to show some of its new results, which were subsequently updated in the summer Glasgow conference and published in *Physical Review Letters*. DØ also had a small excess of top-like events but with smaller statistical significance; its analysis was based upon the dilepton and single-lepton channels with a combination of lepton tags and topological suppression techniques to reduce background. Nine events were observed, compared with an expected background of about four, giving odds for a background fluctuation of about 1 in 40. The excess events corresponded to a cross section of 8.2±5.1 picobarns. The expected yield of $t\bar{t}$ events was virtually the same for DØ and CDF. Taken together, these results from CDF and DØ were not sufficient to establish conclusively the existence of the top quark.

The final chapter in finding the top quark began with the resumption of the collider run in late summer 1994. The performance of the Tevatron was the key to the success. The Tevatron involves a collection of seven separate accelerators with a complex web of connecting beam lines. Many technical gymnastics are required to accelerate protons, produce secondary beams of antiprotons from an external target, accumulate and store the intense antiproton beams, and finally inject the counter-rotating beams of protons and antiprotons into the Tevatron for acceleration to 900 GeV. Enormous effort had been poured into understanding and tuning each of the separate elements of the process, but until summer 1994 the intensity of the collider was disappointing. During a brief mid-summer break, however, one of the Tevatron magnets was found to have been inadvertently rotated. With this problem fixed, beam intensities rose immediately by a factor of 2. With the now good understanding of the accelerator, a further doubling of the event rate was accomplished by spring 1995. In a very real sense, the final success of CDF and DØ in discovering top rested upon the superb achievements of the Fermilab Accelerator Division. The improved operations meant that the data samples accumulated by early 1995 were approximately three times larger than those used in the previous analyses, and both experiments were now poised to capitalize on the increase.

By December, both collaborations realized that the data now on tape should be enough for a discovery, if the earlier event excess had been approximately correct. In fact, the experiments do not keep daily tallies of the number of events in their samples. The physicists prefer to refine their analysis techniques and selection parameters in order to optimize the analysis on simulated events before "peeking" at the data. This reticence to check too often on the real data stems from the desire to avoid biasing the analysis by the idiosyncrasies of the few events actually found. At the beginning of January, DØ showed a partial update in the Aspen Conference using some new data but retaining previous selection criteria; these results had increased significance, with only a 1 in 150 chance of background fluctuations.

Its simulations showed that for the large-mass top now being sought, even better significance could be obtained. Recognizing that the statistics were nearly sufficient, the collaboration began working in high gear to finalize the selection criteria and obtain the last slug of data before a late-January Tevatron shutdown. In mid-January, CDF updated all of its data; with all of the pieces assembled side by side, it became clear that the collaboration had the necessary significance in hand for claiming a discovery. The CDF process was now considerably streamlined by the experience of producing the earlier top quark papers.

By February, both CDF and DØ recognized that convergence was imminent. Both worked around the clock to complete all aspects of the analyses. Even though each collaboration knew that the other was closing fast and in the process of writing its paper, there were still no formal exchanges of results, nor of intended timing. Some copies did leak out—for example, drafts left on printers in institutions with physicists on both collaborations and computer hacking from one collaboration to another. The one avenue of cross-fertilization that seems not to have operated was through couples with one person in each group!

On February 24, CDF and DØ "Observation" papers were submitted to *Physical Review Letters* (PRL); public seminars were scheduled at Fermilab for March 2. By agreement, the news of the discovery was not to be made available to the physics community or news media until the day of the seminars. In spite of all efforts, word did leak out a few days before. (*Los Angeles Times* reporter, K. C. Cole, called a distinguished Fermilab physicist to get an explanation of statistical evidence presented in the O.J. Simpson trial. The physicist used, as illustration, "the recent statistical evidence on the top quark from CDF and DØ," and Cole swiftly picked up the chase.)

In its paper, CDF reported finding six dilepton events plus 43 single-lepton events (see box on the next page for more details); it concluded that the odds were only one in a million that background fluctuations could account for these events. DØ, in its paper, observed three dilepton events plus 14 single-lepton events and concluded that the odds were two in a million that these could have been caused by backgrounds. The top quark masses reported by the two experiments were 176±13 GeV for CDF and 199±30 GeV for DØ. And both experiments gave consistent results, although somewhat below CDF's earlier value for the $t\bar{t}$ production cross section (see box on the next page for more detailed information).

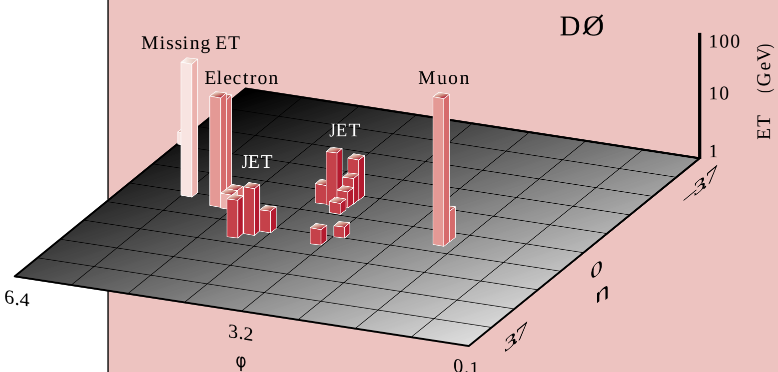
The top quark appears to be a point-like particle; it has no internal structure that we can discern. As one of the six fundamental constituents of matter, it has properties very similar to the up and charm quarks, with the exception of its remarkable massiveness and its very short lifetime. The top quark is about 200 times more massive than the proton, about forty times that of the second heaviest quark (the *b*), and roughly the same as the entire mass of the gold nucleus! Surely this striking obesity holds an important clue about how mass originates.

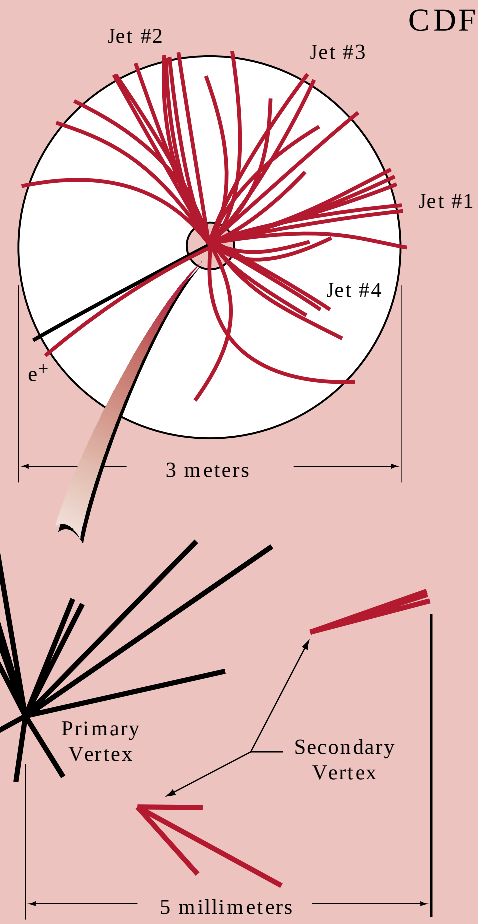
World Wide Web Statistics

BOTH THE CDF and DØ World Wide Web pages can be accessed from the Fermilab home page at http://www.fnal.gov/ (click there for top quark discovery). Since the announcement of the discovery of the top quark last March, the CDF and DØ home pages have received over 100,000 hits each. There were 2279 hits on the CDF page alone on the day after the announcement. Six months after the discovery, the Fermilab top quark page is receiving about 200 hits a day.

CDF AND DØ RESULTS

THE RESULTS FROM THE TWO COLLABORATIONS were remarkably similar. CDF found 6 dilepton events with a background of 1.3; 21 single-lepton events in which 27 cases of a *b* quark tag by the vertex detector (with 6.7 background tags expected); and 22 single-lepton events with 23 cases of a *b* tag through leptonic decay (with 15.4 background tags expected). DØ found 3 dilepton events (0.65 background events); 8 single-lepton events with topological tagging (1.9 background events); and 6 single-lepton events with *b*-to-lepton tags (1.2 background events). A particularly striking example of a dilepton event with very energetic electron, muon, and missing E_T (due to the neutrinos), plus two jets, is shown below from the DØ data. The plot shows the detector unfolded on to a plane, with the energy of the various objects indicated by the height of the bars. This event has a very low probability to be explained by any known background. The probability that background fluctuations could explain the observed signal was one-in-a-million for CDF and two-in-a-million for DØ—sufficiently solid that each experiment was able to claim the observation of the top independently.





Additional studies helped to establish that the new signal was indeed the top quark. Both experiments were able to show that the candidate events were consistent with the expected presence of *b* quarks. The single-lepton channel events should have one *W* boson that decays to a $q\bar{q}$ final state, and the data showed the expected enhancement in the di-jet mass.

Finally, both experiments made a measurement of the top quark mass, using the single-lepton events. In this study, the missing neutrino from one *W* decay must be inferred and the mass of the parent top quark deduced from a constrained-fit procedure. This mass fitting is complicated by the need to identify the correct combination of jets with parent quarks in the decay and to accommodate the tendency of the strong interaction to generate additional jets. The two experiments obtained consistent results for this mass measurement: 176±13 GeV for CDF and 199±30 GeV for DØ.

The rate for observing $t\bar{t}$ pairs is controlled by the strong-interaction production cross section. Each experiment evaluated this cross section at their mean mass value; CDF obtained $6.8^{+3.6}_{-2.4}$ picobarns, and DØ obtained 6.4±2.2 picobarns. These values are consistent with the theoretical prediction within the combined experimental and theoretical error, although the tendency for the measurements to fall above theory is interesting and if it persists could indicate that new physics is at play.

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Left to right: Giorgio Bellettini, Paul Grannis, John Peoples, Hugh Montgomery, and Bill Carithers following the seminars announcing the simultaneous discovery of the top quark at Fermilab by the DØ and CDF collaborations. Grannis and Montgomery are the co-spokesmen for the DØ Collaboration, John Peoples is the Director of Fermilab, and Carithers and Bellettini are the co-spokesmen for the CDF Collaboration. The collaborations presented their results at seminars held at Fermilab on March 2, 1995.

MODERN HIGH energy physics experiments are unique institutions; though large enough to require formal organizations and governance procedures, they remain voluntary collaborations of individual scientists who have banded together to permit achievements that a few physicists could not accomplish by themselves. But lacking the usual structures of large organizations—the ability to hire and fire, or to rigorously assign jobs to individual workers—they rely to a very large degree on the existence of a shared purpose and consensus for their constructive operation.

Although about 430 physicists participate in each collaboration, the number active in the top studies is much less—roughly 50 directly engaged at a significant level. This results from the broad scope of collider experiments; the range of tasks needing attention is very large. The physics research being done by the collaborations is widely dispersed over five major areas (top search, bottom-quark physics, strong-interaction studies, electroweak boson measurements, and searches for new phenomena). Within these physics groups there are perhaps 50 active analyses under study at any given time. Often these other analyses contributed synergistic techniques to aid the top search; for example, studies of jets by the strong-interaction group entered directly into measurements of the top mass.

A diversity of tasks occupy the members of the collaborations. In addition to running the experiment around the clock and attending to its maintenance, constant attention must be given to optimizing the event selection process (only ten interactions out of every million can be kept for analysis) and to improving the software algorithms for selecting particles in the data. Work must continue to improve the overall computing and software environment. New detector development is conducted with an eye to future upgrades, and major design and building projects are underway for future runs. The experiments are so big that reviews by the collaborations themselves, the Laboratory, and external committees continually occur. Finally, with collaborations of these sizes, group psychologists, financial analysts, and tea-leaf readers are needed!

The techniques for the top quark search and measurement of its mass developed over several years. For most important aspects (and some minor ones) several different approaches were developed by rival subgroups or individuals. This multiplicity is valuable for cross-checking results and as a tool for natural selection of the strongest methods, but such competitiveness and rivalry can also be debilitating. In some cases, the winner in these rivalries can be established on purely technical grounds—but often the basis for decision is clouded, as the alternatives have both pros and cons. Adjudicating among these contenders is a difficult and time-consuming problem. In some cases, the choice is made through a survival-of-the-fittest process—the approach first brought to full maturity, with documented error analyses and cross-checks, is chosen. Consensus plays an important role in rejecting some alternatives; experts not involved in a particular question can wield considerable influence in rejecting some weaker approaches. When the issues have sufficiently crystallized, special advisory panels drawn from the rest of the collaboration can be very useful in helping to define the direction. The last resort of turning the issue over to the "managers"—the spokespersons or physics group conveners—is successful primarily when the rivals have agreed that they are unable to resolve their differences. Fortunately, this rarely happens.

Effective communication on many levels is an essential ingredient of successful performance in the large collaborations. For the top studies, weekly meetings of a half dozen subgroups of the top analysis discuss problems and status; as many additional meetings occur on related analysis topics such as electron identification; and a more general meeting brings together all the threads. Video conferencing and electronically posted minutes of the meetings help keep those not at Fermilab involved, although most active participants travel there frequently. Informal documents prepared on sub-topics, intended only for internal use, proliferate and are disseminated electronically across the globe. Electronic mail is an essential component; colleagues working a continent apart on related problems can conduct an almost on-line dialog. Discussion and argument over fine points of interpretation can generate a flurry of productive messages among five or six experts. At the other end of the scale, there remains an essential role for formal presentations of work to the full physics group and full collaboration at regular intervals. Repetition is usually necessary to bring the non-experts to a reasonable degree of familiarity with the issues and methods, and to build acceptance of new work.

To what extent did CDF and DØ interact during the time of the top search and discovery? At a formal level, very little. New results from each collaboration were periodically shown at conferences and public presentations, so the broad outlines of each group's approach were known, but beyond that there were no direct interactions. The grapevine was of course active, with lunch-table conversations among individuals, but much of the information exchanged in this way was the anecdotal account of the day and was often outmoded by the next. There were probably several reasons for this relative isolation of two groups working toward a common goal. At one level both groups realized that the independence had real scientific value. Guarding against making a discovery by subconsciously shaping the analysis is an ever-present worry; by keeping the walls between CDF and DØ fairly high, this possibility could be minimized. Also, the two groups felt the heat of competition; for each, no doubt, the dream of being first to recognize the top was a powerful incentive to be rather closed-mouthed about innovations and progress.

The history of the top search over the final two years shows evidence of this competitiveness and friendly rivalry at work. As the more senior collaboration, CDF had developed its techniques over time to a relatively refined state. It started the race for top with the UA2 experiment in 1988 and had been denied success only by top's extraordinary massiveness. CDF would have been disappointed to lose the race to the newer DØ experiment. On the other hand, the Tevatron performance in the 1992–1994 era improved so much that the data in hand was almost all acquired after DØ's start-up, so the two experiments could work on almost equivalent data sets. DØ, with its strengths of excellent lepton identification and full solid angle coverage, was able to develop powerful tools for suppressing unwanted background; it was of course determined to make its mark as the brash newcomer by converging on the top. But the competition remained friendly and supportive throughout; it also promoted a quality of work and depth of understanding that would have been difficult otherwise. And the ultimate scientific value of two independent results was enormous.

How do hundreds of authors agree on a single paper in a timely fashion? This too is a sociological challenge! The process for writing the final papers began in late January. DØ appointed primary authors—one for a short letter paper and one for a longer paper ultimately not used. The top group designated a few individuals as its authorship committee, bringing the necessary range of expertise to the authors. The collaboration review was conducted in large part through an appointed editorial board of ten physicists including authors, drawn from widely diverse portions of the collaboration. The editorial board spent days carefully reviewing the backup documentation, probing the analysis for consistency and correctness. It also helped to revise the paper's language to make it accessible to the widest possible audience. The completed draft was distributed to the full collaboration by electronic mail, and comments were solicited from all. Well over a hundred written comments were received (plus many more verbal ones), all of which were addressed by the board. The revised paper was again circulated for concurrence of the collaboration before submission to PRL.

CDF appointed a chief author to be assisted by a group advising on the sections of their expertise. Simultaneously, a review committee (dubbed a "godparent" committee within CDF) was appointed. The draft and responses to questions were always accessible to the collaboration electronically, both on the World Wide Web (with security) and via ordinary files on the Fermilab computer.

In the final convergence to a result, it was necessary to come to grips with rather large differences of scientific style among the collaborators. Some could find in any result, no matter how thoroughly cross-checked, the need for further investigation. Some were wary of any interpretation beyond a statement of the basic experimental numbers. Others favored a more interpretative approach. Finalization of the paper itself required the resolution of these oft-conflicting outlooks on what makes good science.

In the end, the chief necessity for the convergence on the top discovery was the willingness of a collaboration to abide by a majority view. Securing this willingness requires extensive attention to the process—of being sure that all shades of opinion, reservations, and alternate viewpoints are fully heard and understood. It is more important perhaps that each point of view is carefully listened to than that it be heeded. A fine line in resolving these viewpoints must be drawn between autocracy and grass-roots democracy. The process must have the confidence of the collaboration, or its general effectiveness can diminish rapidly.

What did the physicists of CDF and DØ feel on completion of the top discovery experiments? Certainly relief that the quest was complete. Also

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Happy and relieved physicists who have completed PhD theses using the DØ experiment assemble in the DØ main control room. Students and postdoctoral candidates are the lifeblood of the experiment and have made contributions to every aspect of it. Pictured are Brad Abbott, Purdue; Jeff Bantly, Srini Rajagopalan, Northwestern; Dhiman Chakraborty, Terry Heuring, Jim Cochran, Greg Landsberg, Marc Paterno, Scott Snyder, Joey Thompson, Jaehoon Yu, Stony Brook; Regina Demina, Northeastern; Daniel Elvira, Cecilia Gerber, University of Buenos Aires; Bob Hirosky, Gordon Watts (CDF), Rochester; Jon Kotcher, New York University; Brent May, Arizona; Doug Norman, Maryland; Myungyun Pang, Iowa State.

Others who have completed theses on DØ but not pictured are Rich Astur, Bo Pi, Sal Fahey, Michigan State; Balamurali V., Notre Dame; Ties Behnke, John Jiang, Domenic Pizzuto, Paul Rubinov, Stony Brook; John Borders, Sarah Durston, Rochester; Geary Eppley, Rice; Fabrice Feinstein, Alain Pluquet, University of Paris Sud; Terry Geld, Michigan; Mark Goforth, Robert Madden, Florida State; Ray Hall, Thorsten Huehn, University of California, Riverside; Hossain Johari, Northeastern; Guilherme Lima, LAFEX/CBPF; Andrew Milder, Alex Smith, Arizona; Chris Murphy, Indiana; Haowei Xu, Brown; Qiang Zhu, New York University.

pride that such an elusive quarry had been trapped and that the two independent experiments had drawn so similar a profile of the top quark. Virtually all in both collaborations could take justifiable pride for their personal contributions to the discovery—an effective electronics controller for the high-voltage system was as essential for the discovery as devising the selection criteria for the top quark events. Despite the many strains introduced by the frenetic pace, the process of discovering the top was for most the scientific event of a lifetime. Graduate students, postdocs, junior and senior faculty, and scientists worked together on equal footing, with the contributions of the youngest as significant as those from the oldsters. Though for most scientists, solving the many small daily problems gives sufficient satisfaction to keep them hooked on physics, reaching a milestone touted as a major discovery was a special thrill not to be forgotten.

After the public announcements of the discovery, a new challenge arose in interacting with the news media, representatives of member institutions, and other scientists to explain and comment on the results. The media blitz caused strains of its own. As each physicist had contributed in some major way to the discovery, most wanted to share in the public limelight. In the unfamiliar world of public exposure, some strains and disappointments emerged, but the opportunity to explain the significance of the work to the general public was for most a rewarding and educaional experience.

How long did the euphoria of the discovery last? There were indeed celebrations, but by a week after the public announcements it was back to business, both on the top studies and on the dozens of other analyses in progress.

DOES THE DISCOVERY of the top quark close the chapter on our understanding of the fundamental building blocks of matter? Surely not—it is truly just the beginning. Though we now have found the long-awaited sixth quark, with properties as predicted, much more accurate measurements are needed. Dozens of questions about how the top is produced and how it decays are clamoring for answers. Does the extraordinarily large top quark mass hold clues to the nature of symmetry breaking or to the origin of mass? Do the regularities observed for the lighter quarks hold for the top? Are there signs of new particles that decay into the top? Or are there exotic new objects to be found in top decays? The very massive top is unique among quarks in that it does not live long enough to be bound into hadrons, so it provides a testing ground for the study of a single “bare” quark. As happens so often in physics, the latest great discovery should serve as the crucial tool for the next advance in understanding the composition of matter.

by JOHN LEARNED & MICHAEL RIORDAN

In Water or Ice?

Physicists are building four huge particle-detector arrays to do high energy neutrino astronomy.

THE GHOSTLIEST of elementary particles, neutrinos have fascinated particle physicists for half a century and become the objects of intense research these past few decades. Because they interact very weakly with matter, these "little neutral ones" also provide scientists a unique way to peer inside stars and supernovae. Thermonuclear processes occurring within the cores of these celestial objects generate profuse streams of energetic neutrinos that easily penetrate the outer layers and travel enormous distances, to be recorded here on Earth by huge underground detectors.

Now, after twenty years of development, neutrino astronomy is about to forge on to its next great challenge: the study of high energy neutrinos from cosmological sources *outside* the Milky Way. In four corners of the globe, four teams of physicists are racing to build the first full-fledged high energy neutrino telescopes. And in a remarkable example of international scientific cooperation, these teams are collaborating with one another and with other interested groups on the design of a truly gargantuan neutrino telescope—encompassing a cubic kilometer in total volume—that they hope to complete by early in the following millennium.

THE ASTROPHYSICAL neutrinos observed thus far by underground detectors arrived at the Earth with energies of roughly a million electron volts (1 MeV) or more. Much lower than this and they become essentially impossible to detect—although they are perhaps the most plentiful particles in Nature, even more common than photons. Physicists have good reason to believe that every single cubic centimeter of the Universe contains over six hundred neutrinos. With an exceedingly tiny mass equivalent to just a few electron volts, these ubiquitous spooks would constitute the dominant portion of all the matter in the Universe, its much sought-after "dark matter" or "missing mass."

The observation of MeV neutrinos has allowed astrophysicists to examine the physical processes responsible for stellar burning and supernovae explosions. By determining the intensities and energies of the neutrinos spewing forth from these objects, we have in essence been able to measure their internal temperatures. And discrepancies between the predicted and observed fluxes of solar neutrinos arriving at the Earth's surface strongly suggest that we may be witnessing the results of new and fundamentally different physics. (See "What Have We Learned About Solar Neutrinos?" by John Bahcall, in the Fall/Winter 1994 *Beam Line*, Vol. 24, No. 3.)

For at least 20 years, however, many physicists have recognized that the best place to do neutrino astronomy is at extremely high energies over a trillion electron volts (1 TeV)—the realm of Fermilab energies and beyond (see box on next page). Because the probability of a neutrino's interacting grows in proportion to its energy, so does the ease with which we can detect it and determine where it came from. Thus, for neutrino astronomers TeV energies are truly the experimenters' dream.

They are also the astrophysicists' and cosmologists' dream, too, for TeV neutrinos give us the only practical way to observe physical processes occurring at the very center of galaxies—particularly the active galactic nuclei (AGN's) that have lately become a hot research topic. Nowadays many scientists suspect that the variety of highly energetic cosmic beasts distinguished by their various peculiar radiations are all in fact just different manifestations of a galaxy with an AGN, viewed in various perspectives and at various times in its evolution. Most believe that these AGN's are the sites of galaxy-class black holes a million to a billion times as massive as the Sun; they swallow up stars, gas and dust while belching back perhaps 10 percent of their feast in wildly transformed ways. Such a tiny, massive object was recently shown to exist at the core of the elliptical galaxy M87, which is practically in our own cosmological backyard.

According to one recent scenario, there is a standing shock wave outside the event horizon of the black hole, a bit like the standing waves in a river that delight white water enthusiasts. Infalling matter carries magnetic fields, which are drastically compressed and intensified by the tremendous force of gravity when the matter slams into this shock wave. Charged particles are accelerated to high energies as they ricochet back and forth between magnetized regions, like a ping pong ball between a pair of converging paddles. Energetic pions created in this process rapidly decay into pairs of gamma rays or into muons and neutrinos. The gamma rays initiate particle showers and generate a hellish photon cloud from which only the neutrinos can easily escape, streaming away with perhaps half the total energy emitted by this bizarre object.

This process can explain the intensities of X rays and ultraviolet radiation emitted by some AGN's, from which the flux of high energy neutrinos can then be inferred. A number of theorists have now estimated this flux; they agree that a significant (meaning measurable) flux exists up to about 1–10 PeV (1,000–10,000 TeV). Quite apart from the great interest in using such high energy neutrinos to observe AGN dynamics, the prospect of detecting them has naturally spurred particle physicists to build big neutrino telescopes. For the foreseeable future, we have no chance of producing such particles in earthbound accelerators.

Of course, this is only one particular model that may in fact be wrong. Over the decades we have dreamed of doing high energy neutrino astronomy, many promising models have come and gone. But the established existence of extremely high energy cosmic rays, with energies up to a hundred million TeV, means that TeV neutrinos must also be plentiful in the Universe. Given what we know about particle physics, it is inconceivable that such tremendous energy could be concentrated into photons and protons without a substantial amount of it spilling over into the neutrino sector.

There are a number of more "prosaic" sources of high energy neutrinos coming from within the Milky Way galaxy itself. One source is the shock waves generated by a supernova, in a mechanism analogous to that described above for AGN's. Another is the lighthouse-like particle beam thought to be emanating from its pulsar remnant. X-ray binaries—in which neutron stars blaze away, fueled by feeding off their companion stars—have also been suggested to be a potent neutrino source. Whatever the case, TeV neutrinos from our own galaxy are absolutely guaranteed. The existing flux of high energy cosmic rays, mostly protons wandering about the galaxy, trapped by its magnetic fields, will lead to collisions with dust and gas, generating neutrinos that come from the galactic plane. Observing these neutrinos may help us solve the still

Optimum Energies for Neutrino Astronomy

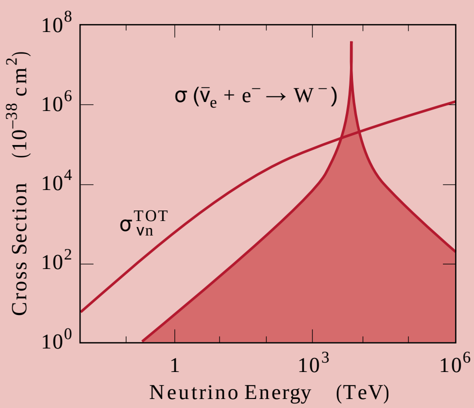
BECAUSE THEIR DETECTABILITY improves steeply with energy, neutrinos of TeV energies and above have long been viewed as the natural starting point for neutrino astronomy. But since the flux of neutrinos falls off with energy, an optimum must exist.

Factors favoring higher energies include the increasing neutrino cross section (their probability of interacting with matter); the increasing range of the muons produced in these interactions (which means the sensitive volume of a detector grows with energy); the decreasing angle between such a muon and its parent neutrino (and thus the point source direction, yielding better resolution); and the increasing signal-to-noise background ratio between astrophysical neutrinos and those produced in Earth's atmosphere.

The last factor is a bit speculative but has pretty good justification. These background neutrinos are produced by ordinary charged cosmic rays interacting with air molecules. As the energy increases, a smaller and smaller fraction of the secondary particles produced in these collisions can decay into neutrinos before hitting the Earth. Such local, atmospheric neutrinos constitute the background against which point sources of astrophysical neutrinos must be resolved. Because the atmospheric neutrino spectrum is expected to fall off more steeply than those of many astrophysical neutrino sources, higher energies are clearly preferred.

While all of the above factors favor higher energies as something like E^4, they begin to saturate at a point that is typically in the energy region 1–10 TeV. This turns out to be the optimum range to begin doing neutrino astronomy.

The neutrino cross section is given as a function of energy in the graph. It spans a range from 0.01 TeV (10^{10} eV) to 10^6 TeV (10^{18} eV, or 1 EeV); the lower end of this range corresponds to the energies of neutrinos produced at earthbound particle accelerators, while the upper end approaches the highest energies so far encountered in cosmic rays. The shaded curve peaking at 6.4 PeV represents the cross section for the interaction of electron antineutrinos with atomic electrons, leading to the production of the W^- boson in what is known as the "Glashow resonance." Over the energy range from 4 to10 PeV, this striking process dominates all the other neutrino interactions. Because of this large cross section, such electron antineutrinos will not penetrate through the Earth; instead, they must be absorbed in such relatively short distances (depending on energy) as a few kilometers.



mysterious puzzle of the origin of cosmic rays.

A much more exotic potential source is the gamma-ray bursts recently found to populate the sky uniformly in all directions. If these weird objects are indeed occurring outside our galaxy, as most astronomers now believe, then a large fraction of a solar mass is being converted into energy in each event. The neutrino flux that some think must accompany these tremendous bursts of energy might well be seen by underground detectors now being built. Such an observation would of course help with understanding the nature of these enigmatic cosmic explosions.

Finally, big neutrino telescopes will be important aids in searching for a key component of dark matter—the vast halo of weakly interacting massive particles, or WIMPs, thought to cluster about the Milky Way and most other galaxies. Often thought to be supersymmetric particles left over from the Big Bang, these WIMPs should become concentrated inside the Earth's core and that of the Sun due to glancing collisions with atomic nuclei there. Occasionally a WIMP would encounter its antiparticle and annihilate it, however, producing a spasm of other particles. But only neutrinos can escape these core regions and reach our detectors, which would then record fluxes of high energy neutrinos coming from the centers of the Earth and Sun. The big neutrino telescopes now being built or contemplated will be sensitive to WIMP masses from 10 GeV to 1 TeV, covering essentially the entire range of masses expected for the lightest particles predicted by supersymmetric theories.

High energy neutrino astronomy can open a surprising new window on the Universe, with implications for distance scales from the largest to the smallest.

And with a large enough neutrino telescope, we can study inner space as well as outer space. By counting the flux of neutrinos and antineutrinos hitting the detector from different directions, one could measure their attenuation in the Earth and do "Earth tomography"—much like computer-aided tomography, or CAT scans, are done on people using X rays. With sufficient statistics, neutrino telescopes will be able to measure the density of the Earth's core, for example, a feat that is not possible by any other means.

The possibility of completely unanticipated discoveries is also a potent reason for building big neutrino telescopes. The history of astronomy has shown us time and again that the most important observations by a new kind of device were not even predicted when the first such instrument was being built. High energy neutrino astronomy can and almost surely will open a surprising new window on the Universe, with implications for distance scales from the largest to the smallest. It will bring us a grand sense of witnessing a new projection of the life that exists outside the murky cave in which we find ourselves.

SCIENTISTS WORKING on neutrino detection have realized for decades that the Cherenkov radiation generated by neutrino interaction products in water (and ice) provides an inexpensive way to build large-volume detectors. Charged particles speeding through transparent media at velocities near the speed of light throw a cone of blue light in the forward direction. Sensitive detectors can "see" these particles at distances on the order of 100 meters in deep, clear ocean water (which has a characteristic attenuation length of 50 m). Large photomultiplier tubes sensitive to this blue light are available for a few thousand dollars apiece. The typical cost of such a photosensor module (including electronics, cabling and housing) comes to about $10,000 each. As each module covers an effective area of 100 m2, the cost per square meter for such detectors is roughly $100—far cheaper than typical accelerator-based detectors (but at the cost of poorer resolution).

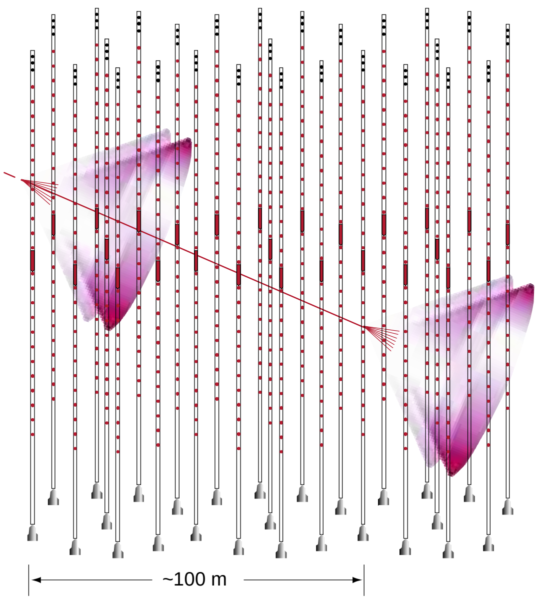
Whenever a muon neutrino (or antineutrino) interacts with an atomic nucleus by the exchange of a W particle, it produces a muon that carries off the bulk of the neutrino's energy. Because muons have a long lifetime and do not interact very strongly with matter, they can carry the news of neutrino collisions a very long way—*kilometers* in the case of very high energy neutrinos. A muon produced at PeV energies, for example, can travel 20 kilometers. It is no wonder that neutrino detectors currently under construction have focused upon muon detection in order to attain the large target volumes needed.

The precision with which we can measure the direction of the muon—and that of the neutrino producing it—will depend largely on how well we can determine the exact times at which its Cherenkov light strikes the individual modules. Fortunately, the latest generation of large-area photomultipliers has such good time resolution (a few nanoseconds) that we can expect to attain an angular resolution of about a degree for TeV muons that traverse the entire array. Neutrino telescopes will not be able to challenge optical or radio telescopes in this department, but their angular resolution improves gradually with energy. And statistical techniques can be used to refine our measurements still further, so that we may eventually be able to pinpoint a neutrino source to perhaps a hundredth of a degree.

Electron neutrinos and tau neutrinos do not produce prompt, high energy muons—and neither do muon neutrinos when they exchange a Z particle with the struck nucleus. In these cases we have to observe the cascades of secondary particles (mostly hadrons, few of which travel very far) produced by the recoiling quarks in the struck nuclei. For Cherenkov detection of these large cascades, we must position the modules with typical spacings determined by the mean transparency of our medium to blue light. Therefore the sensitive target volume of our array for detecting cascades grows only as the total volume surrounded by it—unlike that for detecting muons, which increases as the area of the array. At the scale of several kilometers, however, these two begin to converge—a good thing because we can learn a lot by detecting all types of neutrinos simultaneously.

A unique and interesting phenomenon to watch for is the production of W^- particles by 6.4 PeV electron antineutrinos striking electrons within the target volume. The cross section for this interaction is much greater than for all other weak interaction processes at this energy; if there happen to be lots of electron antineutrinos in the mix, it should lead to a nice spike in the distribution of cascade energies. Aside from the aesthetic pleasure of finding this so-far unobserved fundamental process, it will give us a good energy calibration and a handle on the fraction of electron neutrinos at this energy.

With a large enough detector array we may be able to observe what we call "double-bang" events produced by tau neutrinos of a few PeV. Upon striking a nucleus in our target volume, such a neutrino will often produce a tau lepton that travels about a hundred meters before decaying. There will be one cascade at the point of collision and another at the point of tau decay, connected by a softly ionizing particle between the two. The first cascade will contain about half the energy of the second, on average; both should be easily visible, generating about 100 billion photons apiece. With a sufficient sample of these double-bang events, we would be able to measure the percentage of tau neutrinos at energies of a few PeV; by



A typical "double-bang" event that might be observed in a very large neutrino telescope, produced by interaction of a multi-PeV tau neutrino. It generates a huge shower, together with a tau lepton that travels around 100 meters before decaying in a second shower with about twice the energy of the first.

Expt	Location	Depth (km)	Medium	Size of Array Height (m)	Size of Array Width (m)	No. Strings	No. Modules	Estimated Year of Operation
AMANDA	Antarctica	1–2	ice	390	110	16	478	2000
Baikal	Siberia	1.1	lake	70	43	8	96[a]	1997
DUMAND	Hawaii	4.8	ocean	230	106	9	216	1997
NESTOR	Greece	3.7	sea	220	32	7[b]	168	1997

[a]1 module contains 2 photomultiplier tubes
[b]1 tower is equivalent to 7 strings.

comparing this ratio with those of electron and muon neutrinos, we will be able to study neutrino mixing with unmatched sensitivity to mass differences. The observation of such events would also be strong evidence for neutrino mass.

In addition to sampling the Cherenkov light produced by interacting high energy neutrinos, physicists have considered the possibility of detecting the radio and sound waves generated by their violent collisions with matter. Small radio pulses occur because oppositely charged particles in a cascade generate opposing microwave signals that do not completely cancel (owing to the fact that its electrons migrate further than its positrons). The best available medium for detecting such pulses appears to be polar ice, which will transmit microwaves for kilometers at temperatures below –60°C. Acoustic pulses occur because cascades deposit heat energy instantaneously in narrow cylinders up to about 10 meters long. Detecting the sound waves generated (with typical frequencies of 20 kHz) will be difficult, but it may be possible in the very quiet deep ocean for neutrinos with energies above a few PeV. Both techniques show good promise for extending neutrino astronomy to ultrahigh energies and to truly gargantuan volumes, but both will probably have to ride piggyback first on a Cherenkov-light detector in order to demonstrate their feasibility.

FOUR LARGE detectors of high energy neutrinos are now in various stages of design and construction. They sport the names DUMAND (in the Pacific Ocean off Hawaii), AMANDA (in ice at the South Pole), Baikal (in Lake Baikal, Siberia) and NESTOR (in the Mediterranean Sea near Greece). All are at least ten times larger than their low-energy brethren—such as Japan's SuperKamiokande detector—in their enclosed volumes and muon-catching area, and their threshold energy sensitivity is typically a thousand times higher.

Having begun life in a series of late-1970s workshops, DUMAND is the elderly sibling of the other projects. As currently envisioned, it will consist of nine strings of photosensor modules in an octagonal array (with one string at the center) submerged over 4 km deep off the Big Island of Hawaii. This array will enclose about 2 megatons of water and have an effective area of 20,000 m^2 for the detection of energetic muons, with an angular resolution of about a degree. Since the early 1980s, a group of physicists from Europe, Japan, and the United States has been working from the University of Hawaii, doing R&D on this project—acquiring valuable experience in how to apply the techniques of high energy physics to the deep-ocean environment.

Each DUMAND string contains 24 photosensor modules spaced 10 m apart along its instrumented section—plus floats to provide the necessary tension, hydrophones, environmental sensors and an electronics package. It is tethered to the ocean bottom with a remotely commandable release to facilitate recovery and allow reconfiguration of the array if desired. The electronics unit communicates with all the sensors and sends a data stream to shore (including optical, acoustic, environmental and housekeeping data) via fiber-optic cable through a common junction box.

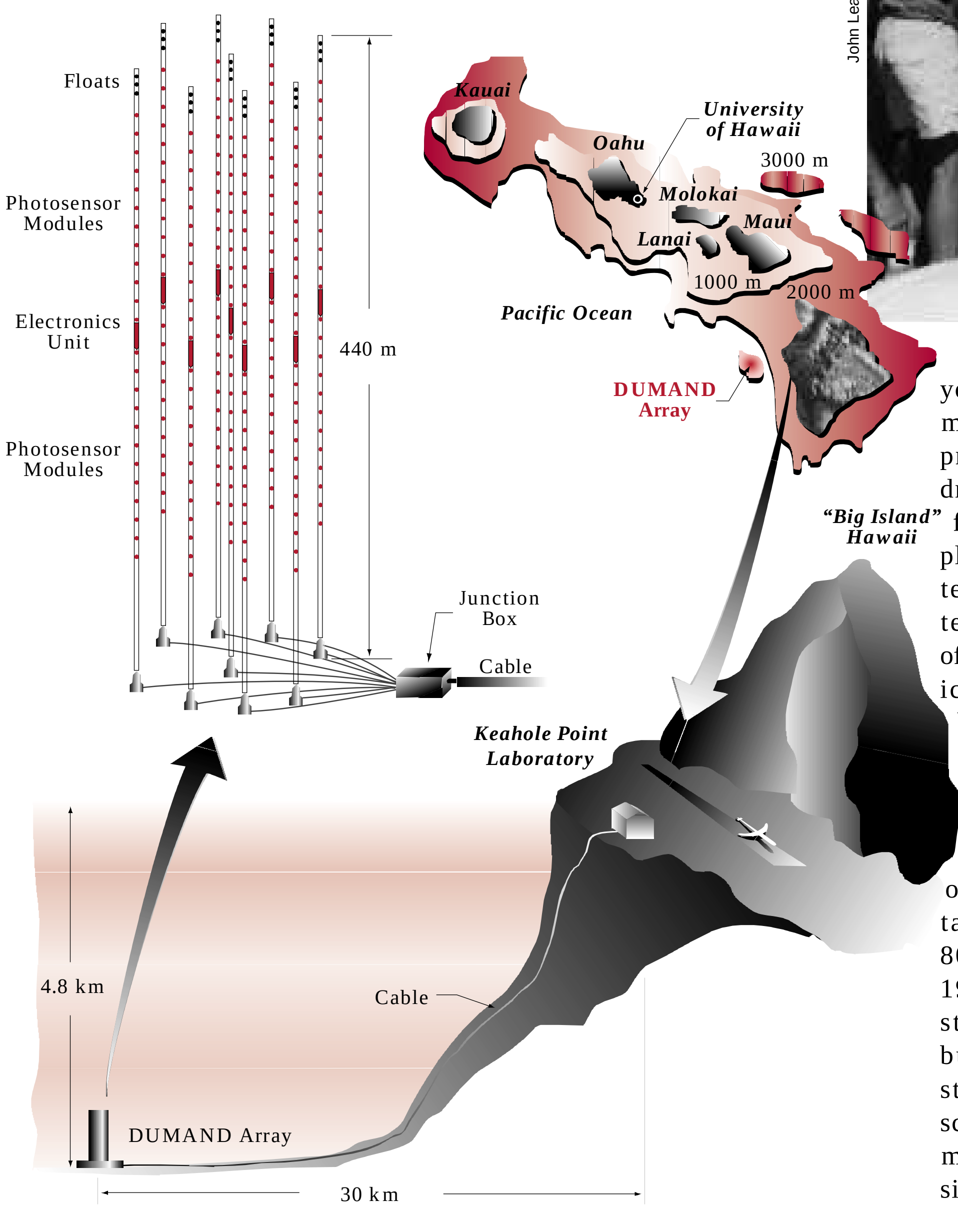
In December 1993 the collaboration successfully laid the shore cable along the ocean bottom from the experimental site 30 km west of the Big Island to the laboratory at Keahole Point. Attached to this junction box before deployment, the first detector string worked well for a short time but its electronics package failed due to a leak. Data acquired before this failure confirmed expectations about the overall system performance and background counting rates. After further ship-suspended tests in the winter of 1995–96, placement of three complete strings will occur in the summer of 1996.

Having begun South Pole operations in 1991, AMANDA is the

Right: Physicists deploying the first DUMAND string from the deck of the research vessel T. G. Thompson in December of 1993. One of the optical photosensors hangs in midair as the central electronics package is readied for submersion.

Bottom: Artist's conception of the planned DUMAND array and its deep-sea location off the Big Island of Hawaii. The cable and junction box are now in position; another attempt to install the first of nine strings of photosensors and other detectors will occur in 1996.

John Learned



youngest of the four projects but has made impressive progress. Its approach is simple: use hot water to drill holes in the Antarctic ice pack, freeze photomultiplier tubes in place, and use standard electronics techniques to get a large neutrino detector built rapidly with a minimum of new technology development. The ice is very cloudy near the surface but was expected to be spectacularly clear at some depth beyond about 500 m.

Led by the University of Wisconsin, the collaboration installed four of the planned six strings, each containing 20 modules, at depths of 800–1000 m during the summer of 1993–94. Upon activating these strings, however, physicists found bubble densities in the ice substantially higher than anticipated; scattering of light from these bubbles made accurate signal timing impossible. In effect, AMANDA has blurry

A well-clad physicist stands beside the hot-water drill used to bore the first four AMANDA holes 1000 meters into the Antarctic ice cap at the South Pole. This equipment will be used to bore additional holes to depths of about 1500 meters during the austral summer of 1995–96.

vision—as if it were looking for muons through translucent glasses.

The big question is whether the ice clarity improves enough with depth to permit a full-scale experiment this austral summer (1995–96). Drilling costs grow with depth, and expensive fiber-optic techniques may be needed to obtain good timing. AMANDA will run out of ice at about 2500 m, although the team may give up if the clarity is still poor at1500 m. With the observed low light absorption in ice, however, the array might still make an excellent calorimeter—and microwave detection techniques hold great promise in this medium, too.

A group of Russian and German physicists building the Baikal detector includes some of the elders in this field, who began work about the same time as DUMAND. The deepest (1.4 km) clear lake in the world, Lake Baikal was chosen in the hopes of avoiding the major background flux of light due to radioactivity, but there appears to be an obscure, unanticipated source that varies with time—making it about as noisy as the deep ocean. One advantage is Baikal's ability to place and retrieve instruments in winter, without use of ships. Its unique cable-laying method uses a sled with a huge saw to cut a slot in the ice, through which a following sled unreels the cable as both drive shoreward; the slot rapidly freezes behind. So far 36 modules (each with two photomultipliers acting in coincidence) have been placed, with data being recorded and analyzed at a shore station. This group has suffered from the lack of funding and high-technology materials, but the recent addition of the DESY laboratory in Hamburg, Germany, to the collaboration brings great hope of solving these problems.

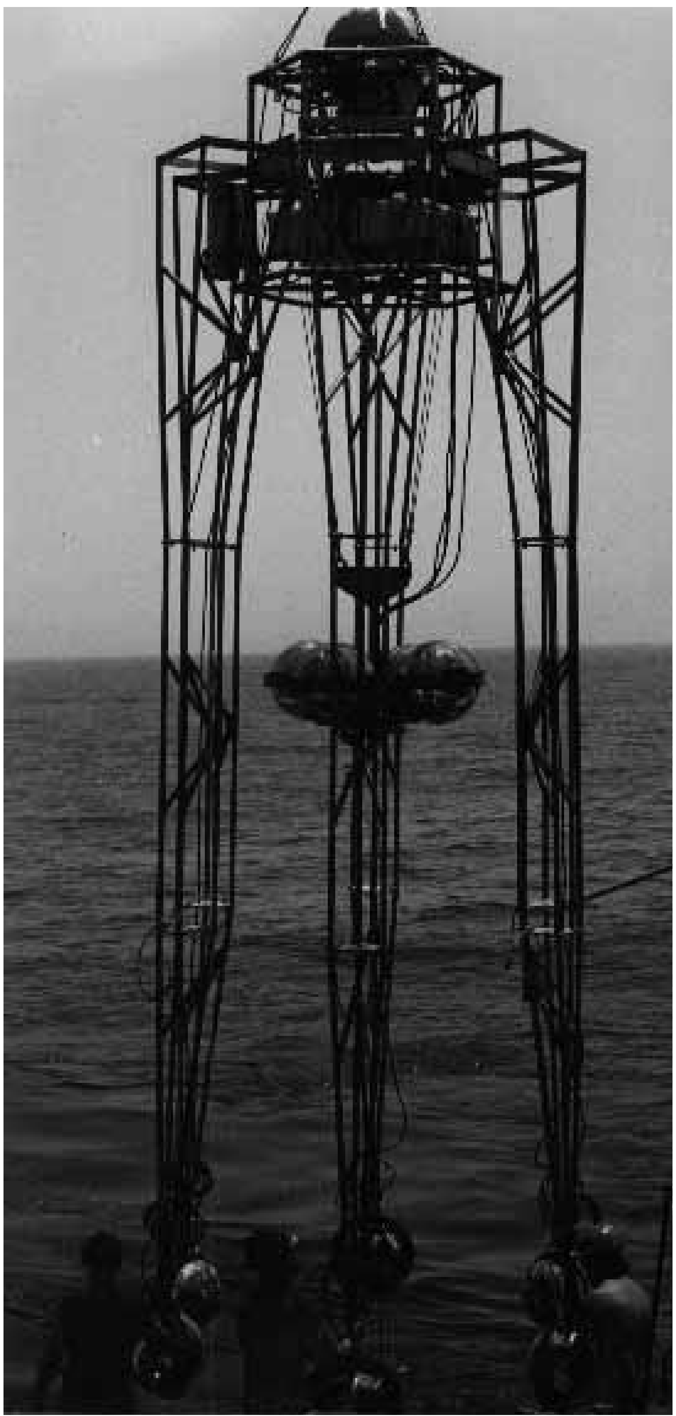
Planned for a deep-sea site southwest of Pylos, Greece, NESTOR is closest in concept to DUMAND. At a depth of 3.5 km the Mediterranean is surprisingly clear; a good site has been located and studied a mere 20 km from shore. This site is also close to a line extended from CERN through Italy's Gran Sasso Laboratory, so that a proposed neutrino beam might be extended to the detector to permit a search for neutrino oscillations. The detector array will be a hexagonal cluster of seven towers, each standing 450 m tall and containing 12 umbrella-like floors with 14 modules per floor. Installation of the first tower is expected to occur in 1997. Led by the University of Athens, the NESTOR collaboration includes teams of physicists from France, Greece, Italy and Russia—among them a Saclay group that provides the support and infrastructure of a major French national laboratory.

EVER SINCE the late 1970s it has been clear to neutrino astronomers that an array filling an entire cubic kilometer is really needed to begin serious work in the field. Everyone recognizes that we are really building demonstration devices—perhaps big enough to find a few exciting things—as exploratory stepping stones to the huge detector we really need to finish the job. Many independent calculations have converged upon a cubic kilometer as the appropriate volume. Such a

Right: One of the Baikal detector modules being lowered through the ice together with cabling and electronics. Each module consists of two photosensors in two separate pressure-resistant glass spheres.

Bottom: A prototype NESTOR "floor," which consists of 14 photosensors in an umbrella-like array, being lowered into the Mediterranean Sea off Greece. Slated for initial deployment in 1997, each tower in this neutrino telescope will consist of 12 such floors, whose arms open radially once in the water.

Bob Morse



Leo Resvanis

device should function well in detecting neutrinos from point sources, the galactic plane, gamma-ray bursters, AGNs and WIMPs.

In 1994 there were several meetings at which physicists discussed the idea of forming a world collaboration to design and build such a gargantuan detector. The AMANDA and DUMAND teams plus a few newcomers have been working with the Jet Propulsion Laboratory, a major national laboratory in Pasadena, California, with the big-project experience needed in such an effort, which is clearly beyond the capability of a single university. The Saclay group joined NESTOR partly in order to gain experience towards building such a facility. Many of us hope to merge these two efforts into a single international project.

One thing we are all proud of in this emerging field is the tremendously supportive interaction among the physicists involved. Although there is lots of competition, as all of us naturally want to be first with any important discovery, we realize that by helping each other we also help ourselves in the long run. All four teams have meanwhile got their work cut out for them. No cubic-kilometer detector will ever begin construction until we can get at least one (and hopefully more) of the current generation up and counting neutrinos. Only then will we have the information we need to decide whether the next step for neutrino astronomy should occur in water or ice.

Osteoporosis–New Insights

by JOHN KINNEY

Synchrotron radiation is giving us new insights into causes and treatments for osteoporosis.

OSTEOPOROSIS IS A DISEASE characterized by fragile bones that results in fractures. Half of women over seventy will have a fracture as a result of osteoporosis. For many of them, this will lead to a decline in their quality of life and independence. These fractures, which often occur with little or no injury, are usually a result of reduced bone mass. Accordingly, research on osteoporosis has focused on those factors that affect bone mass, such as estrogen deprivation, age, and physical activity. Treatments to control osteoporosis have been largely based on trying to maintain or to increase skeletal mass; however, significant overlap exists between the bone mass of normal individuals and those with osteoporosis. This overlap has resulted in investigation into factors other than low bone mass, such as structural properties and bone quality, to explain the higher frequency of fractures among individuals with osteoporosis.

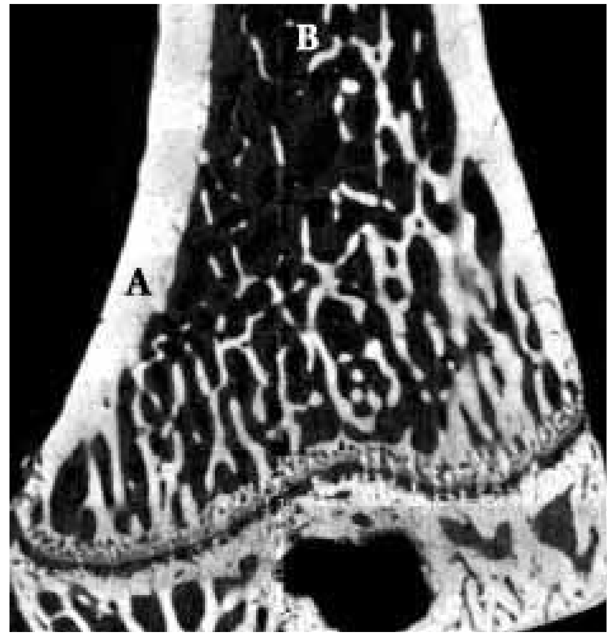
Bone is the hard, marrow-filled calcified tissue that forms the skeleton. Near the joints a porous spongy-like bone fills much of the marrow space as seen in the illustration on the right. This spongy bone aids in transferring the stresses of motion to the hard outer shell called the cortex. The spongy bone (frequently referred to as trabecular bone) is composed of an interconnected structure of curved plates and struts. One of the age-related changes that accompanies bone loss is a decrease in the amount of spongy bone. In normal people the volume occupied by this spongy bone decreases with age. This decrease in bone volume is apparently due to a loss in the number of struts and a severing of the interconnections, as opposed to a general uniform thinning of the elements. Many questions regarding the development and treatment of osteoporosis could be answered if the architecture of the spongy bone—and how it changes with disease and age—were better understood.

BONE STRUCTURE CHARACTERISTICS

About a hundred years ago, an English reverend named Abbott published a small book titled **Flatland**. It was a story of a two-dimensional world occupied by polygons. The protagonist was a square who, one day, was visited by a sphere. The sphere carried the square above Flatland, and allowed him to view his three-dimensional counterpart, the cube. Upon returning to Flatland, the square set about to enlighten his two-dimensional world about the existence of a three-dimensional universe. Unfortunately, the square was never able to provide convincing proof of the third dimension to his fellow inhabitants of Flatland and was eventually labeled a heretic and spent his remaining days in prison.

Though this book was intended as a social satire, it points out the difficulties describing three-dimensional structures using only two-dimensional views. The science of reconstructing three-dimensional information from two-dimensional views is called stereology. With stereological methods it is possible to estimate volume fractions and surface areas of particles or voids from just a few flat microscopic sections cut from an object.

Stereological methods are currently used to estimate three-dimensional properties of bone from two-dimensional or planar sections. These methods allow calculation of the volume fraction and surface areas of the spongy bone. It is also possible to quantify other structural features of the bone required to explain bone formation, resorption, and



An X-ray tomographic microscope image of a thin section of leg bone in a rat. The thick bone (A) surrounding the marrow cavity is the cortical bone, or cortex. The thin, web-like bone (B) within the marrow cavity is the spongy bone. The earliest stages of osteoporosis involve the resorption of spongy bone and a breaking of its interconnections.

structure. The application of stereological principles has provided important clues as to how a bone's structure affects its properties and is altered by disease and aging. Unfortunately, as we understand better the complex structures and properties of biological systems, we begin to exceed the ability of stereological methods to describe the critical aspects of the structure. In particular, conventional stereological methods begin to collapse when questions arise regarding how the spongy bone networks are connected. For example, one of the easiest questions to pose about any structure is to ask how many objects are contained within it. Indeed, it is impossible to answer the basic question "how many?" from a limited number of two-dimensional views or sections. A complete three-dimensional visualization is necessary.

Questions such as "how many" relate to the topological structure of an object. For any three-dimensional structure, the topology can be described with three variables: *i)* the number of separate particles ("how many"); *ii)* the interconnectedness of the particles (number of handles or pathways connecting different parts of the object); and *iii)* the number of enclosed surfaces (for example, bubbles, voids, or entrapped particles). These variables are extremely valuable for describing the process of a disease like osteoporosis and the mechanical behavior of calcified tissues.

In the past, quantifying these topological variables required time-consuming, artifact-prone serial sectioning of entire specimens. In serial sectioning, a specimen is imbedded in a rigid holder, and a shallow cut is made that just exposes the interior. The surface is polished, stained, and photomicrographed. Then another cut is made parallel to the original one. This fresh surface is then polished, stained, and photomicrographed. This procedure is repeated until the entire specimen has been examined. The micrographs from each section are then digitized, and a volumetric image is created. In order to quantify the interconnectedness of the spongy bone in a small animal, it would be necessary to obtain 50 to 100 sections from each one. This explains why this method is rarely used.

Another disadvantage with sectioning is that it can only be performed on dead animals. This requires a large number of animals to study at each time point in an experiment. For example, in an experiment that tests the effectiveness of a bone-growth drug at a single dose, it is necessary to have control animals, estrogen-deficient animals (induced by removing the animal's ovaries), and treated animals. If six animals are required at each time point for statistical accuracy, and if we examine bone loss in the ovariectomized animals at three time points, and then examine treated, controlled, and ovariectomized animals at three additional time points after treatment, a minimum of 78 animals would be required for this simple study. If, on the other hand, it were possible to examine living animals, then time-point sacrifice would no longer be necessary. In this case, only 18 animals would be required, and the results would have greater statistical significance because repeated measures would be performed on the same animal. The savings in the number of animals becomes even greater as the sophistication of the experiment increases. Hence, there is a strong motivation for developing imaging methods that provide the same information as serial sectioning—but on living animals.

An alternative method for reconstructing three-dimensional images is X-ray computed tomography or CT (see "Positron Emission Tomography" in the Summer 1993 *Beam Line*, Vol. 23, No. 2). Because little or no sample preparation is required for CT, tomographic methods provide a cost-effective alternative to serial sectioning, and can, in principle, be used on living animals. CT is most frequently used as a medical diagnostic (higher resolution CT scanners have been developed, but they have not been approved for use on humans). Unfortunately, the present resolution is not high enough to image spongy bone with the accuracy required for quantitative measurements. To be useful as a substitute for conventional methods, the resolution of the CT method must be improved a hundred-fold over the newest instruments. This requires a new type of X-ray source and improved detectors.

COMPUTED TOMOGRAPHY WITH SYNCHROTRON RADIATION

The attenuation of X rays through a sample is a sensitive measure of atomic composition and density. By measuring the X-ray attenuation coefficient as a function of position within a sample with CT, a three-dimensional image of the sample can be obtained. Subtle compositional and structural changes from one position to the next appear as differences in the X-ray attenuation. As long as the spatial resolution is small with respect to the features of interest, the three-dimensional X-ray images obtained from these measurements will provide valuable structural information.

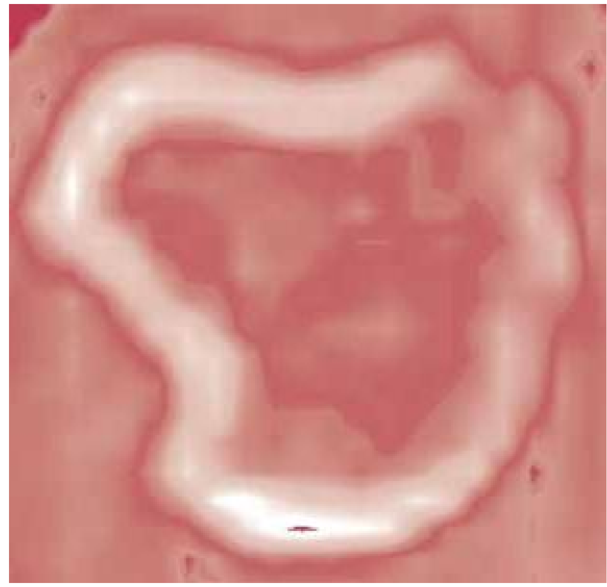
High spatial resolution depends upon *i)* a sufficient X-ray intensity, so that enough X rays reach the detector to provide good measurement statistics; *ii)* a detector with sufficient spatial resolution to discriminate between closely separated X-ray paths; and *iii)* monochromatic (single energy) radiation. Synchrotron radiation sources, because of their high brightness and natural collimation, have allowed the development of CT systems that have spatial resolutions approaching 1 μm. For this study we modified the X-ray tomographic microscope (XTM) developed at Lawrence Livermore National Laboratory in Livermore, California, for use on beam line 10–2 at the Stanford Synchrotron Radiation Laboratory (SSRL) at Stanford Linear Accelerator Center in order to image the three-dimensional structure and mineral density of bone in living animals. We wanted to demonstrate that the XTM with synchrotron radiation can detect microscopic changes in the spongy bone structure and connectivity in estrogen-deficient rats, an important animal model for osteoporosis. The improved resolution available with synchrotron radiation over the highest resolution CT scanners is shown in the two figures on the right.

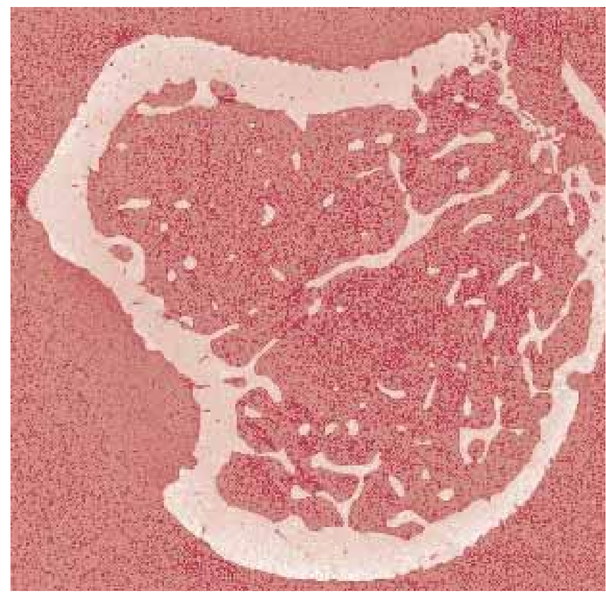
EXPERIMENTAL STUDY OF POST MENOPAUSAL BONE LOSS

In a recent study, the leg bones (tibias) of living female rats were imaged with the XTM at SSRL. Imaging times with the nearly monochromatic X-ray wiggler beam at 25 keV were less than 30 minutes per animal. Shuttering of the direct beam reduced actual exposure times to less than two-and-a-half minutes.

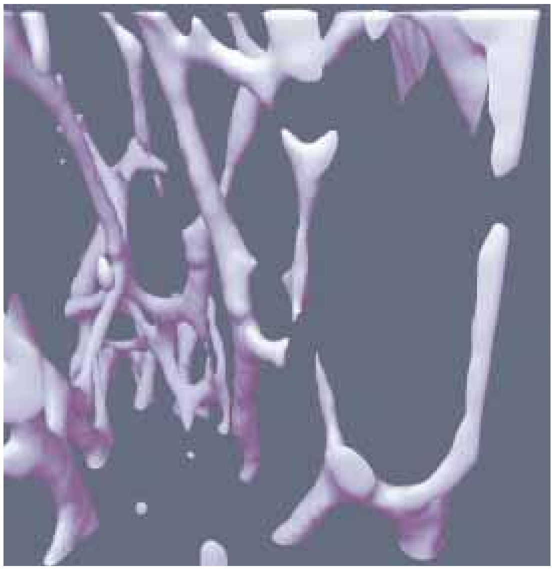
The rats were anesthetized, and while unconscious they were secured to a rotating platform with their right hind limbs elevated into the X-ray beam. On the day following the initial scans, rats were chosen at random and their ovaries were removed. Five weeks after removal of the ovaries, all animals were imaged a final time with the same imaging parameters.

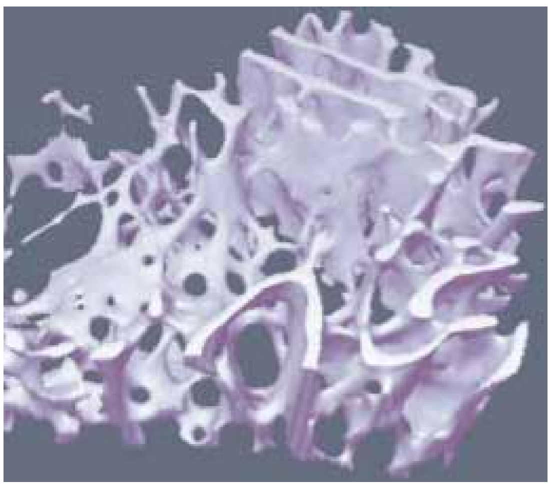
Once the data were acquired, the three-dimensional images of the tibias were reconstructed on a computer workstation. The volumetric data were analyzed by the following method. Cluster analysis was performed on the spongy bone structures in the three-dimensional images; it identified all of the spongy bone that was continuously interconnected, and also identified any isolated structures that were disconnected from the surrounding cortical bone and spongy structure. Cluster analysis provided a direct measure of the topological variables that quantify the number of isolated bone fragments and the number of imbedded pores. For the interconnected cluster, the connectivity was calculated from the three-dimensional image.

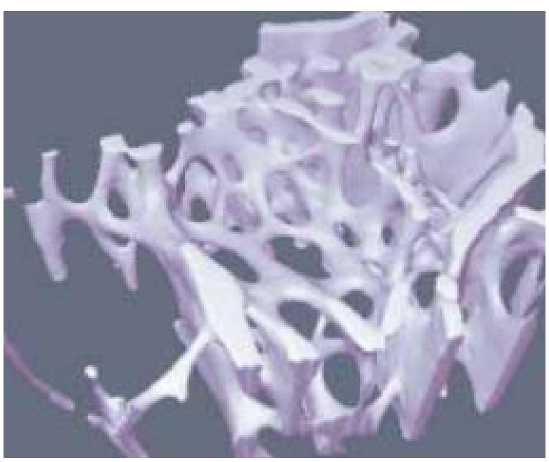




Conventional X-ray tomography instruments do not have the resolving power required to detect structural features within the spongy bone and cortex. Above is the highest resolution image of a rat leg bone with specialized commercial instrumentation. Below is the same bone imaged with the X-ray tomographic microscope and synchrotron radiation. Variations in the color of the bone correspond to small differences in the calcium concentration.







Top: An X-ray tomographic microscope image of a small region of spongy bone in the leg bone of an osteoporotic rat. The normal plate and strut-like structure of the bone has been greatly eroded, and several isolated bone fragments can be seen suspended in the marrow. Though contributing to the total bone mass, these isolated fragments do not contribute to the bones' strength and resistance to fracture.

Middle: The spongy bone in a rat leg at the earliest stages of osteporosis showing the beginning of perforations to the plate structures.

Bottom: The spongy bone of an osteoporotic rat given parathyroid hormone after osteoporosis has been established. New bone is formed, and the spongy bone is significantly thicker than the original bone; however, the original plate and strut-like structure of the bone is not reestablished.

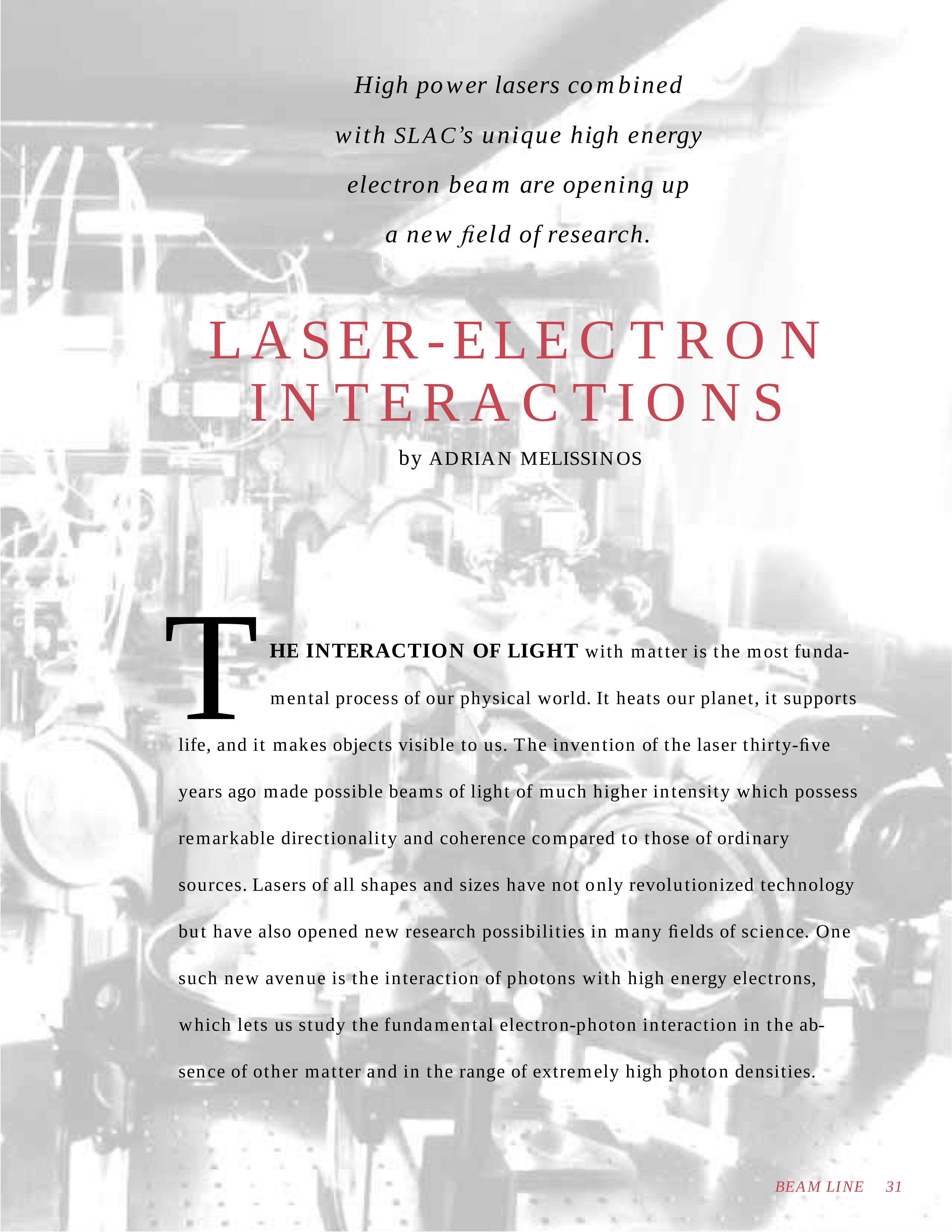
Three-dimensional images of the tibias just prior to removal of ovaries and five weeks after surgery showed that a 60 percent loss in bone volume occurred in the five weeks following estrogen loss (see "Biological Applications of Synchrotron Radiation" in the Fall/Winter 1994 *Beam Line*, Vol. 24, No. 3, page 21). In addition, the three-dimensional images demonstrated a significant change from an interconnected plate- and strut-like structure to one that is mostly disconnected struts. Also, dangling (or dead-end) elements are seen only in the estrogen-deficient animals. These dangling elements, although still contributing to the total bone mass, probably do not contribute to the strength of the bone.

A small region of spongy bone at higher magnification in a rat with ovaries removed is shown in the top figure on the left. Of particular interest is the small bone fragment that is isolated from the surrounding bone and supported only by marrow. We have only observed bone fragments such as this in animals with osteoporosis, where they account for about 1.5 percent of the total spongy bone volume. These isolated bone fragments, as well as the more significant fraction of dangling bone, may be responsible for the overlap in bone mass between individuals with osteoporotic fractures and individuals without fractures.

CAN WE REGROW LOST BONE?

Intermittent parathyroid hormone therapy has been shown to increase bone mass and improve biomechanical strength in osteoporotic rats. Also, intermittent parathyroid therapy both alone and in combination with estrogen therapy has been reported to preserve spongy bone connectivity. Because the reports of connectivity have been based on two-dimensional data, we have been using synchrotron radiation with X-ray tomographic microscopy to determine if intermittent parathyroid therapy actually does increase bone mass and connectivity. What we have found is that spongy bone volume and connectivity significantly decreased after 8 and 12 weeks of estrogen loss. Parathyroid treatment appears to increase bone mass by thickening existing bone, not by forming new connections (see middle and bottom figures on the left). From our results, we hypothesize that to re-establish connectivity in the spongy bone, treatment would have to be given before significant bone loss has developed, or treatment with a bone-forming agent such as parathyroid would be less effective. Further studies need to evaluate critical time points for the administration of bone-forming compounds and for assessing the effects of these treatments on improving bone strength.

New insights gained from these studies using synchrotron radiation are allowing us to develop more rapid screening of new clinical treatments for osteoporosis, a major public health problem responsible for over one million fractures a year in the United States alone.



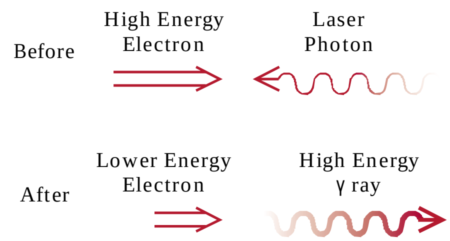
High power lasers combined with SLAC's unique high energy electron beam are opening up a new field of research.

LASER-ELECTRON INTERACTIONS

by ADRIAN MELISSINOS

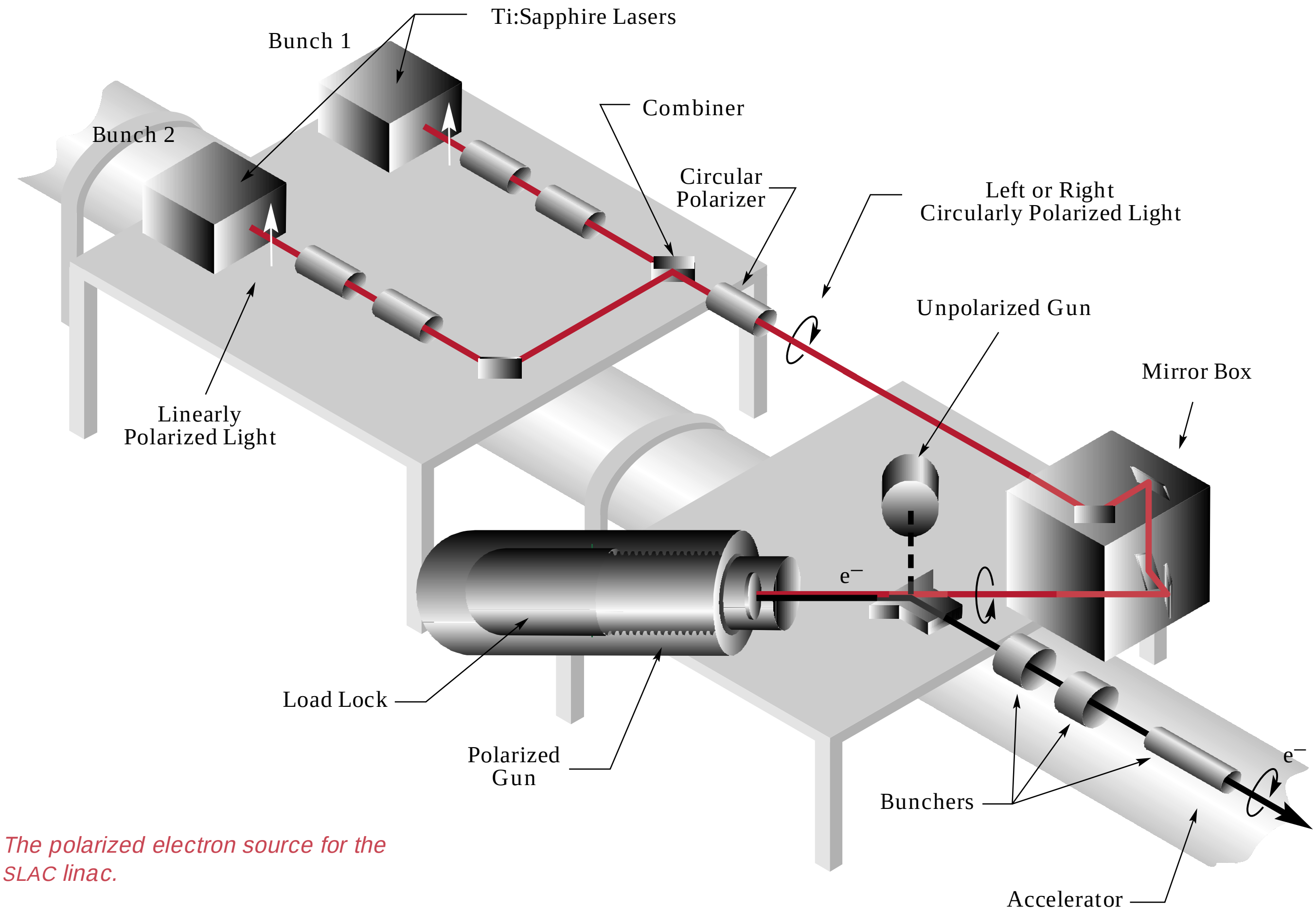
THE INTERACTION OF LIGHT with matter is the most fundamental process of our physical world. It heats our planet, it supports life, and it makes objects visible to us. The invention of the laser thirty-five years ago made possible beams of light of much higher intensity which possess remarkable directionality and coherence compared to those of ordinary sources. Lasers of all shapes and sizes have not only revolutionized technology but have also opened new research possibilities in many fields of science. One such new avenue is the interaction of photons with high energy electrons, which lets us study the fundamental electron-photon interaction in the absence of other matter and in the range of extremely high photon densities.

Right: Backscattering of a photon from a high energy electron.
Below: The 82-in. bubble chamber at SLAC in 1967. Top to bottom are Wolfgang Panofsky, Joseph Ballam, Robert Watt, and Louis Alvarez. This chamber was a modified version of the original 72-in. chamber built and operated by the Alvarez group at the Lawrence Radiation Laboratory.



That collisions will occur when a beam of electrons crosses through a counter-propagating beam of photons may seem obvious to some, but it could also be relegated to the domain of science fiction by others. The outcome of such an experiment depends on the density of the beams and on the duration of the crossing, as well as on the fundamental probability for the interaction to occur. If we compare the energy of an electron in the Stanford Linear Accelerator Center (SLAC) beam with that of a laser photon, a great disparity is evident. The electron energy is 50 billion electron volts, whereas the photon energy is typically 1 or 2 electron volts; the collision can thus be described by the proverbial analogy of a Mack truck colliding with a ping-pong ball. It is nevertheless true that under appropriate conditions the electron can transfer almost all its energy to the photon, as shown in the illustration above left. This process is referred to as Compton (or photon) backscattering.

BACKSCATTERING of a laser beam was first exploited at SLAC in 1969 to create high energy photons or gamma rays. The gamma rays were directed into the 82-inch bubble chamber, where their interactions in liquid hydrogen (on protons) were recorded and studied. An important aspect of high energy electron-photon collisions is that they depend on the state of polarization of the colliding beams. Electrons have spin that can point in one of two directions: along or against the direction of motion; the same is true for the photons. By measuring the rate of scattered events one can



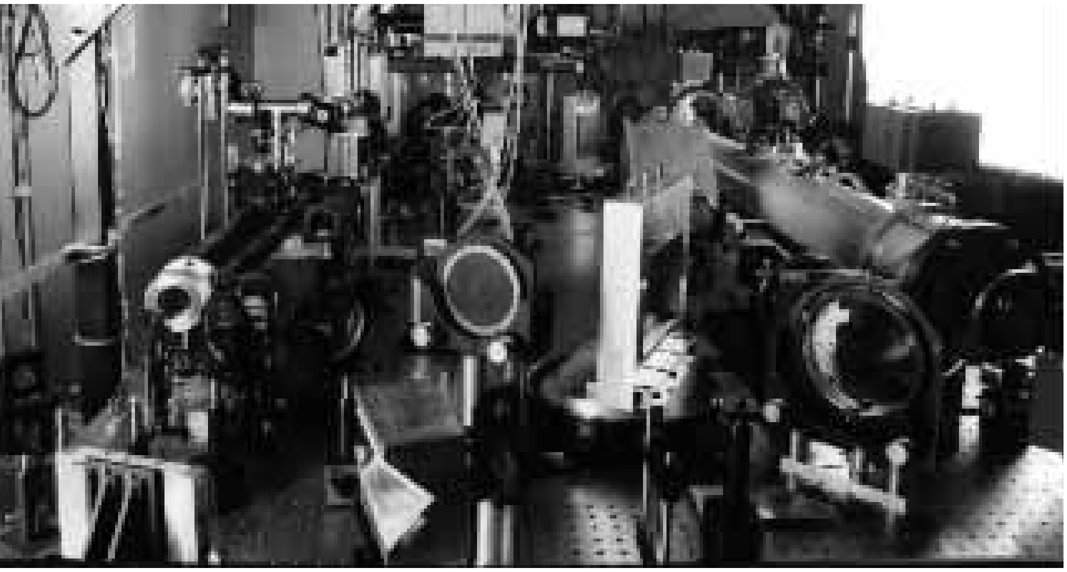
The polarized electron source for the SLAC linac.

determine the state of polarization of the electron beam, a technique that was pioneered at SLAC on the electron-positron ring SPEAR in the late 1970s.

An extension of the polarization-measurement technique, first used at Novosibirsk in Russia, allows the precise determination of the energy of the electrons in a storage ring. Three years ago such measurements revealed changes in the energy of the LEP electron-positron collider at CERN in Geneva, Switzerland, owing to the gravitational pull of the moon. The tidal force of the moon distorts the lattice of the 27 kilometer ring of magnets, resulting in a change of the beam energy at fixed radio-frequency and magnetic field values. What was first considered a puzzle was eventually resolved by the late Gerhard Fisher, a long-time SLAC accelerator physicist.

The energy spread of the photons in a laser beam is usually very small, and certain lasers can be tuned to deliver photons of a specific energy. This property in combination with the polarization dependence of the laser-electron interaction has made possible the highly successful polarized source that is now in use at the SLAC linac (see "The Heart of a New Machine" in the Summer 1994 issue of the *Beam Line*, Vol. 24, No. 2). In this case it is the laser photons that transfer energy to the electrons so that they can emerge from the semiconductor cathode and be accelerated in the electron gun and then injected into the linac. In the strained gallium arsenide crystal cathode, atomic levels corresponding to different polarization states have different energies and can be selectively excited by the laser. This has yielded polarizations as high as 85 percent. The same principle is used to achieve polarization in some of the targets for the electron-scattering experiments being carried out in End Station A at SLAC. Here a titanium sapphire laser operating at a wavelength of 790 nanometers excites rubidium atoms, which in turn collide with atoms of the helium isotope ^{3}He. This causes a significant polarization of the ^{3}He nuclei, and therefore of the two protons and neutron that form the nucleus.

Incidentally, Compton backscattering is not simply restricted to the laboratory but also plays an important role within our galaxy, and presumably in all of intergalactic space as well. Very high energy cosmic-ray protons scatter from the photons that form the microwave background radiation that permeates all of space. Although the density of the radiation is about 400 photons/cm^3, many orders of magnitude lower than that within a laser beam, the distances over which the interaction can occur are correspondingly enormous compared to terrestrial standards, so collisions do occur. In fact, it is believed that the highest energy of the cosmic rays is limited by their collision with the microwave background photons.



The T^3 laser facility used in SLAC Experiment 144.

AN EXPERIMENT currently in progress at SLAC (E-144) explores for the first time a different dimension of the electron-photon interaction—what happens if the photon density is extremely high? The experiment became possible because of recent advances in laser technology that can produce densities as high as 10^{28} photons/cm^3 at the focus of a short laser pulse. To suggest the scale of this number, we recall that the density of electrons in ordinary matter is in the range of 10^{24}/cm^3. High photon density corresponds to high electric field at the laser focus, approaching $E = 10^{11}$ volts/centimeter (V/cm). At such field strengths, atoms become completely ionized. More importantly, however, when an electron from the SLAC beam passes through the laser focus, it feels in its own rest frame an electric field multiplied by the ratio $\gamma = \varepsilon / mc^2$. This effect is a consequence of the special theory of relativity, which is applicable when the particle velocity approaches the speed of light. For the SLAC beam, the energy ε is about 50 GeV; since $mc^2 = 0.5$ MeV, the factor γ is of the order of 10^5. Thus the electric field seen by the electron is about $E = 10^{16}$ V/cm; this field strength is referred to as the critical field of quantum electrodynamics.

The interaction of electrons with such strong electric fields has hitherto been inaccessible to laboratory experiments (similar phenomena are thought to occur in very dense neutron stars). Just as atoms are torn apart in fields exceeding 10^9 V/cm, one can speculate that the electrons themselves may not withstand the critical field. What would be the manifestation of such a disruptive interaction? Presumably electron-positron pairs would be created out of the vacuum, the energy being supplied by the electric field. Experiment 144 has indeed observed positrons produced under such circumstances. Furthermore, the ordinary electron-photon scattering interaction is modified in the presence of strong electric fields by allowing for the simultaneous absorption of several laser photons. We will return to these experimental results.

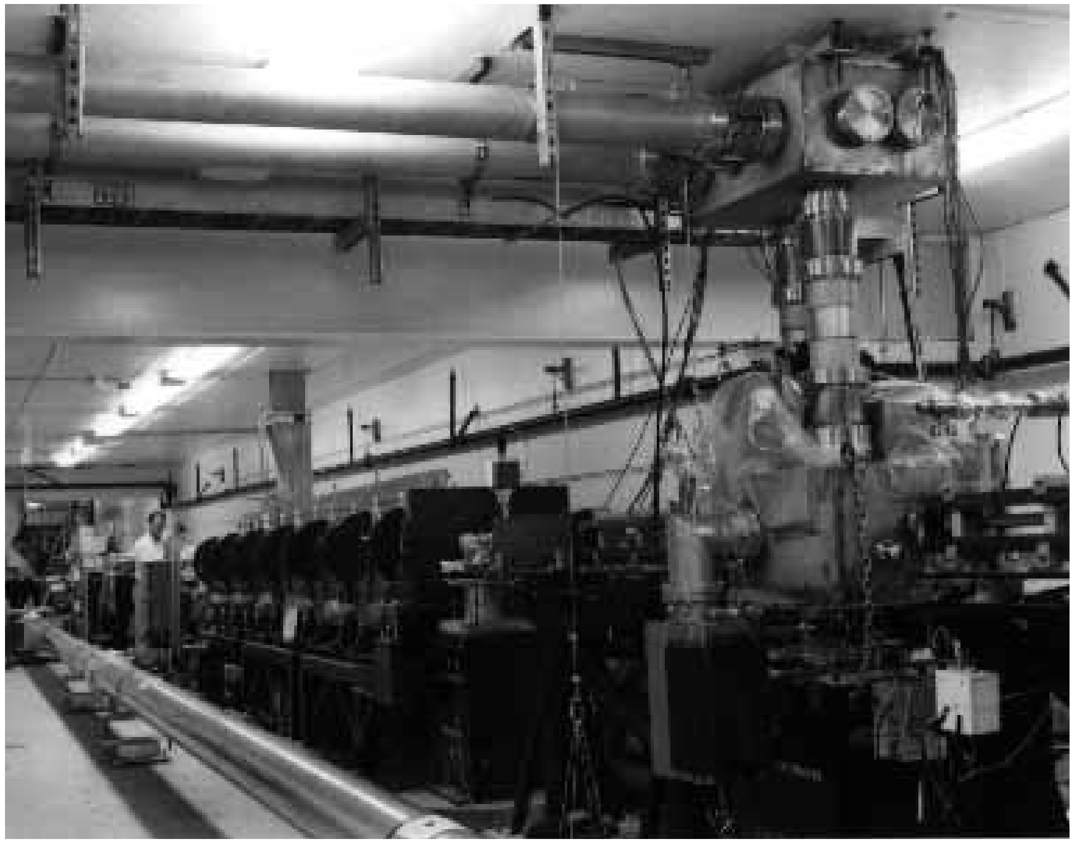
The laser system for E-144 is based on the experience gained at the Laboratory for Laser Energetics of the University of Rochester; it uses neodymium embedded in a yttrium-lithium-fluoride crystal matrix (Nd:YLF laser) followed by neodymium in a glass matrix (Nd: glass laser). It has the advantage of being highly compact as compared to lasers of similar power and is nicknamed T^3, for Table-Top-Terawatt laser.

Neodymium lases in the infrared at a wavelength of about 1060 nanometers; however, it is possible to double the frequency of the light with good efficiency to obtain beams in the green wavelength of about 530 nanometers. Typically the laser delivers 1–2 joules of energy in a single pulse, which is only 1.2 picoseconds (trillionths of a second) long. Thus the peak power is of the order of 10^{12} watts, to be contrasted with a common helium-neon laser that operates at a level of about 10^{-3} watts. Finally the laser pulse must be focused as tightly as possible. This implies the use of large beams and short focal length (to achieve a small f-number) and the absence of aberrations; nearly diffraction-limited spots of 20 mm^2 area have been achieved for green light using $f = 6$ optics.

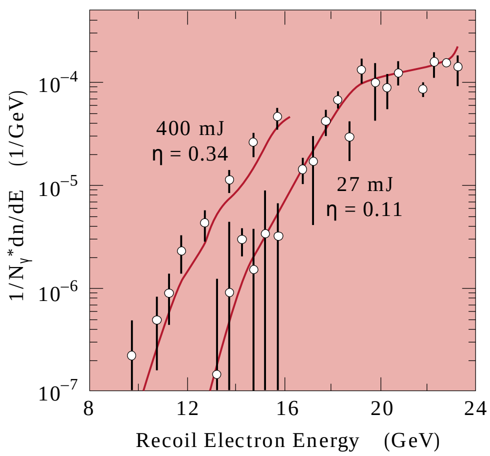
To reach joule energies in a single pulse, a chain of several laser amplifiers must be used. Initially a mode-locked oscillator produces a pulse train of short pulses, typically 50 picoseconds long. This is achieved by placing an acousto-optic switch that is driven by an external frequency with period equal to twice the time for one round trip of the pulse between the laser mirrors inside the laser cavity. As a result, the cavity can lase only for a short time when the switch is open and in phase with the external radio-frequency. This frequency has been chosen to be a sub multiple of the accelerator drive frequency, and in this way the pulses in the laser train are synchronized with the electron pulses in the linac. A single pulse is selected out of the pulse train by a Pockels cell, but the energy in the pulse is only a few nanojoules. The pulse is then stretched in time and chirped in frequency before being injected into a regenerative amplifier. After 100 round trips in the regenerative amplifier, the pulse energy is at the millijoule level, at which point the pulse is ejected from the regenerative amplifier and further amplified in two additional stages. The last stage is of special construction using a slab of lasing material instead of the usual rods to permit a repetition rate of 1 hertz. Finally, the pulse is compressed in time in a pair of diffraction gratings to achieve the desired short length.

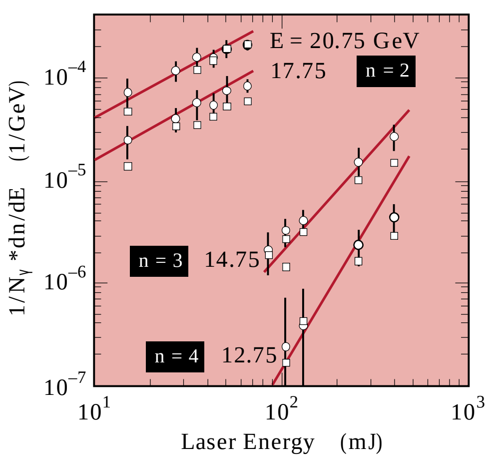
The experiment is installed in the Final Focus Test Beam (FFTB) line (See "The Final Focus Test Beam," in the Spring 1995 issue of the *Beam Line*, Vol. 25, No. 1), just downstream of the primary focus. This location is particularly advantageous because the tight focal area and short duration of the laser pulse must be matched by an electron pulse of corresponding quality. The laser beam is transported by high performance mirrors to the interaction point, where it crosses the electron-beam line at a 17 degree angle. Immediately after the interaction point, a string of six permanent magnets deflects the electron beam into a beam dump; these magnets also serve to disperse the electrons that have interacted and the positrons that have been produced in the interaction so that their momenta can be measured. Electrons and positrons are detected in silicon calorimeters placed below and above the original beam line. These detectors measure the total energy deposited in a narrow range of electron (positron) momenta. The high energy gamma rays continue in the forward direction and are detected in a separate calorimeter 40 meters downstream from the interaction point.

One of the concerns during the planning of the experiment was whether the synchronization of the laser pulses with the electron beam could be established and maintained. The length of the laser pulse is 300–600 micrometers, and the electron pulse is only slightly longer; furthermore, the two beams cross at an angle. Thus the timing and the path lengths traversed by these two pulses originating from very different sources must be kept to a tolerance of a fraction of a millimeter. This was successfully accomplished with a phase-locked loop between the laser mode locker and the linac radio-frequency, as well as by careful construction of the transport line. A computer-controlled delay inserted in the laser line was used to set and maintain optimal timing.



The laser-electron interaction point and the analyzing spectrometer for Experiment 144 inside the Final Focus Test Beam cave.





Top: The normalized cross section for multiphoton Compton scattering plotted as a function of momentum for laser energies of 27 and 400 millijoules. The laser wavelength was λ = 1054 nanometers and the electron energy ε = 46 GeV.

Bottom: The normalized cross sections for 2, 3,and 4 photon absorption as a function of laser energy (λ = 1054 nanometers and ε = 46 GeV). For linear processes the cross section is independent of laser energy. The open circles show the predictions of the theory.

NOT EVERY BEAM electron crosses through the laser focus, but at high laser density every electron that does cross through the laser focus interacts, giving rise to a backscattered gamma ray with energy between 0 and 21 GeV (for infrared light and for 46 GeV incident electrons). Some 5×10^7 gammas were produced by each electron pulse, corresponding to conversion of approximately 1 percent of the incident electron flux (as expected from the relative size of the two beams). Interactions that involve the absorption of two or more photons are much less common but still copious. In this case it is the recoil electrons that are being detected; if a single (infrared) photon is absorbed, the recoil electron energy is always greater than 25 GeV. Thus electrons with energy below 25 GeV are a measure of interactions where two or more photons were absorbed (there is also a finite probability that the electron scattered twice at different positions within the laser focus). The measured spectrum of recoil electrons for two different laser energies is shown in the top graph on the left. Recoil electrons in the range between 18 and 25 GeV result from the absorption of two photons, between 13 and 18 GeV from the absorption of three photons, and so on.

The absorption of a single photon is a linear process; this implies that if the laser intensity is doubled, the scattering rate also doubles. In contrast, the absorption of several photons is a nonlinear process. When the laser intensity is doubled the rate of 2-photon absorptions increases by a factor of four, the rate of 3-photon absorptions by a factor of eight, and in general the rate of n-photon absorptions increases as the nth power of the laser energy. That this is true can be seen in the bottom graph on this page where the observed rate for two-, three-, and four-photon absorption is plotted as a function of laser energy. The nonlinear behavior for these processes is clearly evident.

The rate for the production of electron-positron pairs is relatively low at present laser intensities; approximately one positron is detected in 1000 laser shots. The physical mechanism in this case is the following: an electron enters the laser focus and produces a high energy gamma ray; the gamma ray interacts simultaneously with several (at least four) laser photons to produce the pair. This result is the first demonstration of light-by-light scattering involving physical photons. There was little doubt that this process, which has been amply verified for virtual photons, would occur; however, the stage has now been set for further precision experiments that can probe quantum electrodynamics in the critical field regime.

IT SHOULD COME as no surprise that an understanding of the electromagnetic interaction in high electric fields is essential for the design of the next generation of linear colliders. To achieve the required luminosity, the beams at the collision point of these new machines must have dimensions of only a few nanometers. This results in an extremely high electric field inside the electron (or positron) bunch; the incoming positron (electron) that

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enters the oppositely moving bunch is affected by the field and can lose a significant amount of energy in the form of radiation and/or pair production. This effect is already observable in the collisions at the Stanford Linear Collider and has been given the name "beamstrahlung." It will be much more important for future linear colliders, and designers are making every effort to minimize its impact.

Finally, it is desired to include in future electron-positron colliders the option of operating them as gamma-gamma colliders. This has certain advantages in identifying the particles produced in the collision, especially scalar particles such as the hypothesized Higgs boson. The high energy electron and positron beams can be converted to gamma-ray beams by backscattering laser photons from each of the beams. In this respect E-144 has been the pilot experiment for future gamma-gamma colliders both in terms of the hardware involved and in measuring the fundamental processes that govern such collisions. There are still many unanswered questions and much work to be done before gamma-gamma colliders can be designed with certainty.

Investigation and exploitation of the electron-photon interaction has had a long tradition at SLAC. Higher energies, new technology, and new ideas have confirmed theoretical predictions that, in some cases were made decades ago. The recent experiments present an opportunity for probing this fundamental interaction in a new regime. No doubt the answers will continue to be important.

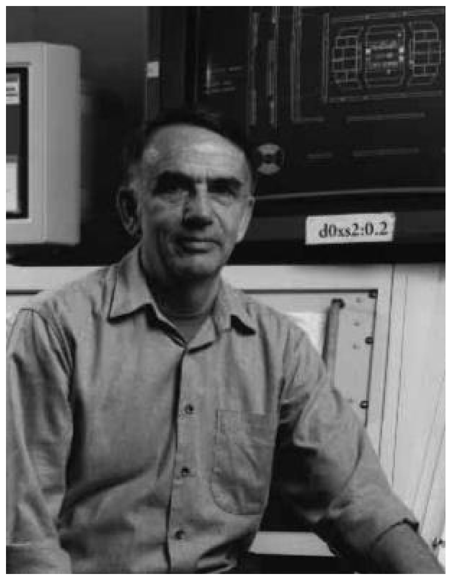
Experiment 144 group photograph. Pictured left to right are (kneeling) Glenn Horton-Smith, SLAC; Theofilos Kotseroglou, Wolfram Ragg, and Steve Boege, University of Rochester; (standing) Kostya Shmakov, University of Tennessee; David Meyerhofer and Charles Bamber, University of Rochester; Bill Bugg, University of Tennessee; Uli Haug, University of Rochester; Achim Weidemann, University of Tenessee; Dieter Walz, David Burke, and Jim Spencer, SLAC; Christian Bula and Kirk McDonald, Princeton; Adrian Melissinos, University of Rochester. Not pictured are Clive Field and Allen Odian, SLAC; Steve Berridge, University of Tennessee; Eric Prebys, Princeton; and Thomas Koffas, University of Rochester.

CONTRIBUTORS

BILL CARITHERS, senior staff physicist at Lawrence Berkeley National Laboratory (LBNL) and visiting scientist at Fermi National Accelerator Laboratory, currently serves, with Giorgio Bellettini, as spokesperson for CDF, the Collider Detector at Fermilab collaboration. He has held this position since January 1993.

Carithers did his undergraduate work at the Massachusetts Institute of Technology and earned his PhD in physics from Yale University in 1968. Since then he has held positions at Columbia University and Rochester University before making the move west to LBNL in 1975.

He was a Sloan Fellow from 1972 to 1974.



PAUL GRANNIS completed his bachelor's degree at Cornell University and received a doctorate from the University of California at Berkeley in 1965. Since 1966 he has been on the faculty of the State University of New York at Stony Brook, with visiting appointments at the Rutherford Laboratory, CERN, University College London, and Fermi National Accelerator Laboratory.

From its inception in 1983 until 1993, he was the spokesman for the DØ experiment at the Fermilab antiproton collider; since 1993, he has served as co-spokesman for DØ with Hugh Montgomery.

Grannis is a Fellow of the American Physical Society and vice-chairman of the Division of Particles and Fields of the American Physical Society and a Sloan Fellow from 1969 to 1971.

JOHN LEARNED has been at the University of Hawaii where he is Professor of Physics since 1980. He went there to get the DUMAND project started and thought he would leave in three or four years. Fifteen years later, a little wiser, and much more experienced at sea, he and his colleagues are still pushing to do high energy neutrino astronomy.

He has also been involved in the IMB nucleon decay experiment, of which he was a co-founder, and had his greatest scientific thrill leading the discovery of the neutrino burst from supernova 1987A. He also had a foray into high energy gamma-ray astronomy in the mid-1980s, building and operating a Cherenkov air shower telescope on Haleakala.

For obvious reasons he prefers to spend his holidays in the mountains rather than at sea.

MICHAEL RIORDAN has been associated with the *Beam Line* since he came to SLAC in 1988 first as editor now as contributing editor. During 1995 he was on leave from his position as Assistant to the Director at SLAC, writing his latest book, **Crystal Fire**, a history of the transistor to be published by W. W. Norton in 1997. He is the author of **The Hunting of the Quark** and co-author of **The Shadows of Creation** in case you can't tell from the above photograph.

He did his PhD research at SLAC on the famous MIT-SLAC deep inelastic electron scattering experiments.

JOHN H. KINNEY is a research scientist in the Chemistry and Materials Science Department at Lawrence Livermore National Laboratory. He received his BA degree in mathematics and physics from Whitman College and his PhD in materials science from the University of California at Davis in 1983.

In collaboration with researchers from the University of California, San Francisco, he has been applying synchrotron X-ray methods to the study of diseases in calcified tissues. Most recently, this work has been extended to the study of calcifications in coronary artery disease with researchers from Stanford University.

He has published over sixty articles in peer-reviewed journals.

ADRIAN MELISSINOS has been on the faculty of the University of Rochester since 1958, the year he earned his PhD from the Massachusetts Institute of Technology. He has served as department chairman and visiting scientist at CERN. His recent research efforts are in the application of high power lasers to particle physics and particle accelerators.

Over the years Melissinos has worked on experiments at the Cosmotron, AGS, Fermilab, SLAC, and Cornell. He has been involved in developing techniques for detecting gravitational interactions and in searches for cosmic axions.

He is the author of a widely used physics textbook. He is a Fellow of the American Physical Society and a corresponding member of the National Academy of Athens.

DATES TO REMEMBER

Jan 7–13	Aspen Winter Conference on Particle Physics: The Third Generation of Quarks and Leptons, Aspen, CO (Aspen Center for Physics, 600 W. Gillespie St., Aspen, CO 81611).
Jan 14–20	Aspen Winter Conference on Gravitational Waves and Their Detection: Data Analysis LIGO Research Community Space Based Detectors—LISA, Aspen, CO (Aspen Center for Physics, 600 W. Gillespie St., Aspen, CO 81611).
Jan 15–26	1996 US Particle Accelerator School (USPAS 96), San Diego, CA (US Particle Accelerator School, c/o Fermilab, MS 125, PO Box 500, Batavia, IL 60510 or USPAS@FNALV.FNAL.GOV).
Mar 18–22	General Meeting of the American Physical Society, St. Louis, MO (ASP Meetings Department, One Physics Ellipse, College Park, MD 20740-3844 or MEETINGS@APS.ORG).
Apr 1–3	Phenomenology Symposium 1996, Madison, WI (Linda Dolan, LDOLAN@PHENXD.PHYSICS.WISC.EDU).
Apr 9–12	International Magnetics Conference (INTERMAG 96), Seattle, Washington (Courtesy Associates, 655 15th Street, NW, Suite 300, Washington, DC 20005 or MAGNETISM@MCIMAIL.COM).
Apr 22–27	CERN Accelerator School, Course on Synchrotron Radiation and Free-Electron Lasers, Grenoble, France (Mrs. S. von Wartburg, CERN Accelerator School, AC Division, 1211 Geneva 23, Switzerland or CASGREN@CERNVM.CERN.CH).
May 26–Jun 9	Aspen Center for Physics Workshop on High Energy Neutrino Astrophysics, Aspen, CO (Aspen Center for Physics, 600 W. Gillespie, Aspen CO 81611).
Jun 10–14	5th European Particle Accelerator Conference (EPAC 96), Sitges, Spain (C. Petit-Jean Genaz, CERN-AC, 1211 Geneva 23, Switzerland or CHRISTIN@CERNVM.CERN.CH).
Jun 24–Jul 12	Division of Particles and Fields/DPB Snowmass Summer Study of Future Directions in US Particle Physics, Snowmass, CO (C. M. Sazama, Fermilab, MS 122, PO Box 500, Batavia, IL 60510 or SAZAMA@FNALV.GOV).
Jul 25–31	28th International Conference on High Energy Physics, Warsaw, Poland (A. K. Wroblewski, Institute of Experimental Physics, Warsaw University, ul. Hoza 69, PL-00-681, Warsaw, Poland or ICHEP96@FUW.EDU.PL).