Scientific and Technological Change (1983)

Bromley, D. Allan; Naval Studies Board; National Research Council

Pages
89

Size
7 x 10

ISBN
0309325579

The Charles H. Davis Lecture Series
Twelfth Lecture

SCIENTIFIC AND TECHNOLOGICAL CHANGE

by
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Yale University

Presented Before the Students and Faculty of
The Naval Postgraduate School
November 8, 1988

Organized by
The Naval Studies Board
of the
National Research Council

Sponsored by
The Office of Naval Research

NATIONAL ACADEMY PRESS
Washington, D.C. 1989

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THE CHARLES H. DAVIS LECTURE SERIES

At the close of that greatest of all contests of men and machines, World War II, Theodore von Karman could say, with deep personal conviction, that ". . . scientific results cannot be used efficiently by soldiers and sailors who have no understanding of them, and scientists cannot produce results useful for warfare without an understanding of the operations." With such simple truths fresh on their minds, von Karman and his civilian and military colleagues proceeded to forge institutional links—such as the Office of Naval Research—through which they hoped to encourage an enduring partnership between the scientific and military communities. Though the intensity of the bond has fluctuated with the ebb and flow of international relations and internal affairs, the partnership has endured to produce a military capability but dimly perceived by those who established it. But the partnership is not self-sustaining; it requires the constant vigilance of those who have not forgotten the bitter lessons of the past, the outspoken dedication of those whose vision extends beyond the next procurement cycle, and, above all, it requires open communication between the partners. It is to this latter task that the Charles H. Davis Lecture Series is dedicated.

The lecture series is named in honor of Rear Admiral Charles Henry Davis (1807–1877) whose distinguished career as a naval officer and as a scientist so epitomizes the objectives of the series, and whose clear vision of the proper role of science in human affairs redounded to the betterment of all men. The topics and the speakers in the series are chosen by a Search Committee operating under the National Research Council of the National Academy of Sciences, and two lectures are presented each year before the students and faculty of both the Naval Postgraduate School in Monterey, California, and The Naval War College at Newport, Rhode Island. The series is sponsored by the Office of Naval Research.

Rear Admiral Charles H. Davis

(1807–1877)

CHARLES HENRY DAVIS was born January 16, 1807, in Boston, Massachusetts. His education consisted of preparation at the Boston Latin School followed by two years at Harvard University (1821–1823). In 1823, Davis was appointed midshipman and sailed (1924) on the UNITED STATES to the West Coast of South America where he transferred to the DOLPHIN for a cruise of the Pacific. Returning to Harvard he continued to work on a degree in mathematics and is listed with the graduating class of 1825.

In 1829 Davis became passed midshipman and was ordered to the

ONTARIO (1829–1832) of the Mediterranean squadron. Later, while serving aboard the VINCENNES (1833–1835), he was promoted to lieutenant. Aboard the INDEPENDENCE (1837–1841) Davis made a cruise to Russia and then to Brazil. Throughout these early years at sea Davis continued to study mathematics, astronomy and hydrology. During this period one of his superiors would write of him, "C. H. Davis is devoted to the improvement of his mind; and his country may expect much from him."

From 1842 to 1856 Davis undertook a number of special tasks and served on several commissions and boards. Notable among these was his participation in a survey of the New England coastal waters (1846–1849) during which he discovered several shoals that may have been responsible for a number of unexplained wrecks in the area. It was during this period in his career that Davis published "A Memoir upon the Geological Action of the Tidal and Other Currents of the Ocean" (1849) and "The Law of Deposit of the Flood Tide" (1852). He was also a prime mover in establishing the "America Ephemeris and Nautical Almanac" (1849) and supervising its publication at Cambridge, Massachusetts until 1855 and again from 1859 to 1862.

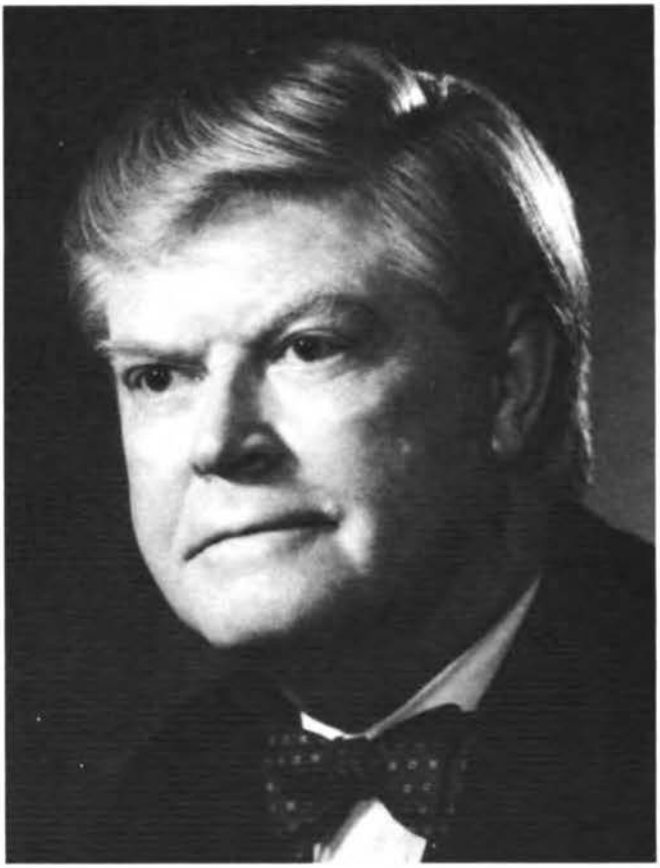
Promoted to commander in 1854, Davis resumed sea duty in command of the ST. MARYS in the Pacific (1856–1859). While he was captain of the ST. MARYS he was instrumental in securing the release of the adventurer William Walker and his followers who were besieged at Rivas, Nicaragua.

With the outbreak of the Civil War Davis was immediately appointed to a number of important positions. He became the executive head of the new Bureau of Detail for selecting and assigning officers. He was one of three officers appointed by Secretary Gideon Welles to the Ironclad Board which passed judgment on the plans and specifications for the MONITOR and other ironclads. Promoted to captain in November 1861, Davis participated in the development of plans for blockading the Atlantic Coast, planning the operation against Hatteras Inlet and Port Royal Channel, and the early naval strategy of the war.

During the operations against Port Royal, Davis served as captain of the fleet and Chief of Staff to Admiral Samuel F. Du Pont. He shares with Du Pont a great deal of the credit for the excellent plan of attack carried out on November 7, 1861. Later, as flag officer of the Mississippi Flotilla, Davis led successful engagements against the Confederate fleet which contributed to the abandonment of Fort Pillow and the surrender of Memphis. He was promoted to commodore in July 1862, and to rear admiral on February 7, 1863.

In late 1862 Davis returned to Washington to head the newly established Bureau of Navigation. From this position he worked closely with such distinguished scientists as Joseph Henry and Alexander Bache to establish a "Permanent Commission" to advise the government on inventions and other scientific proposals which were being stimulated by the war. The Permanent Commission was established by the Secretary of the Navy on February 11, 1863 with Davis, Bache and Henry as members. However, Davis and his colleagues saw a wider need for cooperation between science and government and worked diligently for the establishment of the National Academy of Sciences. Their efforts were successful; President Abraham Lincoln signed a bill authorizing the establishment of the Academy on March 3, 1863.

In 1865, Admiral Davis was appointed superintendent of the Naval Observatory in Washington. In 1867 he returned to sea in command of the South Atlantic Squadron. Back in Washington in 1869 he was made a member of the Lighthouse Board and commander of the Norfolk Navy Yard. He later resumed his post as superintendent of the Naval Observatory where he served until his death on February 18, 1877.



D. ALLAN BROMLEY

SCIENTIFIC AND TECHNOLOGICAL CHANGE

D. ALLAN BROMLEY
Yale University

Just about ten years ago an old friend of mine, Dr. Philip Handler, then president of the National Academy of Sciences, delivered the first Charles H. Davis Lecture, titled *The Future of American Science*. It is then doubly a pleasure and privilege to have been asked to join the distinguished list of speakers who have followed him in this series and to be able to return on this tenth anniversary of its inauguration.

In speaking on scientific and technological change, I am very much mindful of the fact that change—and rapidly accelerating change—is what more than anything else characterizes our age. Particularly is this the case in scientific and technological matters; it has recently been estimated that the useful half-life of what an undergraduate learns in either science or engineering is at most some five years. Obviously this poses enormous problems for us as a nation—both in providing opportunities and incentives for the continuing education of our key personnel and in attempting to improve the flow of talented young people into scientific and technical careers. In neither case have we been at all successful, and the challenge to do better underlies everything else that we, as a nation, hope to accomplish in our future.

Clearly the Department of Defense is no stranger to these problems or to the need to keep pace with the staggering rate at which new science and new technology open up new tactical and strategic windows, and equally rapidly, close old ones.

THE DEPARTMENT OF DEFENSE AND THE RESEARCH COMMUNITY

In the period immediately following World War II, the Department of Defense, in particular the Navy, was responsible for developing the techniques—uniquely American—for the federal support of both fundamental and applied research in the nation's universities and in the private sector, as well as in federal laboratories. This system was based on the identification of excellence, wherever it could be found, and the support of that excellence with a minimum of red tape. The entire nation owes an enormous and usually unrecognized debt of gratitude to Captain Robert Conrad and Dr. Emanuel Piore, who, in the immediate postwar period in the Office of Naval Research, put together the mechanism and principles of federal support of research and development that remain the envy of the world.

During the 1950s and early 1960s, the Department of Defense was, by a large measure, the dominant supporter of fundamental research in the nation's universities and was responsible for building and supporting a scientific and technical enterprise that was unmatched anywhere. Unfortunately, during the latter part of the 1960s and early 1970s—during and after the Vietnam conflict—many of the bridges that had been carefully built between the Department of Defense and the academic community were destroyed, to the great loss of both academia and the Department of Defense. In my view, academia must share most of the responsibility for this very unfortunate development—unfortunate in a great many ways but most particularly in that the communication channels between the nation's military leaders and some of its brightest scientists and engineers, both young and old, began to close up. I am convinced that these are exceedingly important channels and that one of the challenges now facing us is that of rebuilding them and reestablishing the easy flow of ideas and people between our military and our academic establishments. I believe that both have much to gain.

The contact between the Navy and the universities goes back to the early days of the nineteenth century. I am reminded that during much of Admiral Davis's career the Navy had a rather remarkable one-man Office of Naval Research, from 1839 through 1879, in the person of John Ericson. Early in his career Ericson designed the USS PRINCETON, the first man-of-war in the world to be driven by a screw propeller. Why he called it the PRINCETON I have been unable to determine. In any case a warship of this importance clearly required appropriate armament, and so Ericson went to some seven of the nation's universities, including Yale, and asked them to design 12-inch guns on the understanding that the resulting designs would be constructed and tested by the Navy, with the winning institution then receiving an appropriate reward and further contracts. This represents the first specific case of our federal government contracting with the nation's universities.

On a spring morning in 1845, the USS PRINCETON steamed out into the Chesapeake Bay for the initial tests. The first test was of a gun designed by Captain R.F. Stockton of the Navy—fortunately for the universities—because when it exploded, as it did, it killed the secretary of state, the secretary of the Navy, a naval captain, a congressman from Maryland, and as the newspaper reports of the day have it, "sundry other dignitaries." This is clearly the sort of thing that gives technology a bad name—but it did establish a working relationship between the Navy and the universities that was to flourish in the years ahead.

The Impact of Science and Technology on Society

But now let me return to this question of change. Figure 1 is intended simply as a reminder of how very recent are a few selected discoveries in physics that have changed, irretrievably, the character of our society and even how we as a nation view ourselves and our future. The discovery that electromagnetic waves were in fact real, and not simply a figment of Maxwell's imagination, has led to the explosion in information, communication, computation, entertainment, medical care, and other areas far too numerous to mention. All of this has developed within the last 100 years. Only 75 years ago Rutherford discovered the atomic nucleus and opened the gateway to the atomic age, an age with which our society has not yet come to terms. In that same year Onnes discovered superconductivity, a solution that has been looking for appropriate problems since 1911, and which during the past two years may finally have taken off in terms of major impact on our society. I shall return to it below.

Figure 1.

PHYSICS

100 YEARS AGO

Hertz discovers electromagnetic waves.

75 YEARS AGO

Rutherford discovers the atomic nucleus.
Onnes discovers superconductivity.

50 YEARS AGO

Whittle invents the jet engine.
Aitken begins work on a digital computer.
Anderson discovers mesons in cosmic radiation.
Public television is introduced in the United Kingdom.

Only 50 years ago, Whittle invented the jet engine, which not only increased our speed of travel by an order of magnitude but also brought about a complete, qualitative difference in the way we conduct our affairs. Prior to the jet engine the idea of making a transoceanic or a transcontinental flight to conduct a single day's business was simply out of the question; now it is standard, and the impact of this change, particularly in the establishment of a world marketplace, has not yet been fully appreciated. Aitken, in this same year, began work on the first digital computer at Harvard, giving us the first glimpse of the computer revolution, which is still only in its infancy despite its already enormous impact on all of us. Anderson's discovery of mesons in cosmic radiation gave us a beginning of an insight as to where we fit in the much grander scale of things in our universe and at the same time gave us vital clues concerning the structure of matter at its most fundamental level. Here, truly, was a first hint at the joining of the ultrasmall with the ultralarge that has become a hallmark of modern science.

And finally, 50 years ago, public television was introduced in the United Kingdom. It, too, has had a dramatic impact on the world's society. On the one hand the availability of peddle-driven television sets in even the remotest native villages in the Third World has for the first time given the inhabitants of those villages some concept of the vast difference in the quality of life that we and they enjoy. Unless we act—and unless we are perceived to be acting—in a way to reduce that difference, we will inevitably face a world in turmoil. On the other hand, within our own society, as has been demonstrated all too vividly in the just completed presidential campaign, television has not only come to dominate both information transfer and entertainment for our public but also has tended to trivialize much of both.

Ten years ago Phil Handler recognized that we were entering a decade of profound change—change that would in a great many areas be led by science and by technology. However, even he, a confirmed scientific optimist, did not begin to see more than a very small fraction of the surprises that awaited us during this decade of the 1980s; and even he could never have anticipated a year like the one that has just passed—truly a year of supers!

A YEAR OF SUPERS

I list some of these developments in Figure 2. High-temperature superconductivity, first announced publicly in December 1986, is clearly one of the most exciting and potentially far-reaching discoveries of the entire decade. Supernova 1987 A—in the larger Magellanic Cloud—was the first supernova to be visible to the naked eye from the earth's surface in more than 400 years, and observations on it have given us entirely new confidence in our fundamental understanding of this most cataclysmic of all natural events. The Superconducting Supercollider (SSC), the largest single experimental piece of apparatus ever conceived for human experiment, a magnetic ring some 52 miles in circumference, has received presidential approval, although the funding required to implement that approval is as yet far from at hand. Supercomputers have moved from computer science curiosities to workhorses in field after field where, above all else, their ability to present enormous bodies of information in graphic form—enabling the human eye and brain to work their often miraculous synthetic and pattern recognition abilities—has revolutionized fields from cosmology to fluid physics and from weapons design to meteorology. The concept of supersymmetry has opened up new doorways beyond the grand unified theories of fundamental physics and holds promise, at long last, of providing not only an answer to Einstein's dream of the unification of the natural forces but also, and unexpectedly, the marvelous bonus of an understanding of the origin of all the matter upon which these forces operate. And finally, the concept of superstrings, wherein the elementary particles are no longer considered as points but rather as infinitesimal snippets of the fundamental fabric of space-time itself, holds the promise, at long last, of letting us understand where mass, that most common but still most mysterious of physical properties, originates and how our entire universe was born, how it grew, and what its future holds.

Figure 2.

A YEAR OF SUPERS

SUPERCONDUCTIVITY - high temperature

SUPERNOVA - 1987 A - Magellanic Cloud

SUPERCONDUCTING SUPERCOLLIDER - Presidential approval

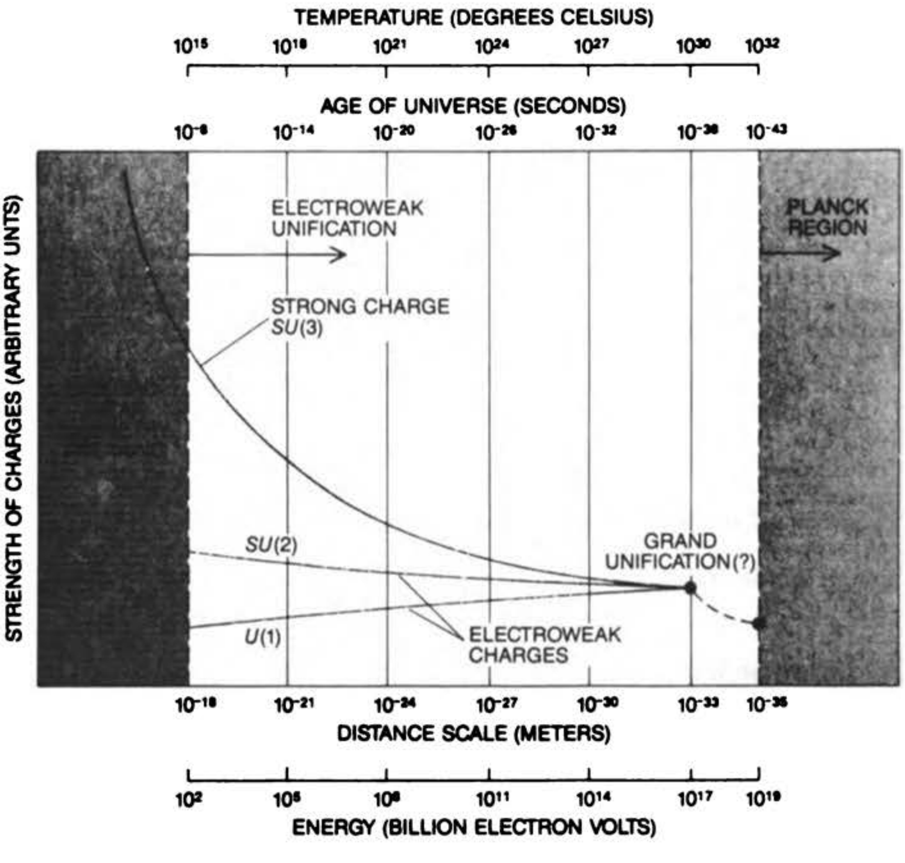
SUPERCOMPUTERS - keys to understanding

SUPERSYMMETRY - beyond the Grand Unified Theories

SUPERSTRINGS - the way to unification?

All of these developments have their roots in physics, the most fundamental of the sciences and the one most closely related to the widest spectrum of technologies and applications. As a professional physicist, I want to illustrate this matter of change by drawing on some of the recent developments in physics, but not for a moment do I wish to imply that there have not been dramatic developments elsewhere in the sciences and in technology. But what is becoming increasingly evident in recent years is that fundamental science, which for several decades was felt by many to be fragmenting into ever narrower specialties—each the province of a priesthood that communicated very poorly, if at all, either with other scientists or with the broader public—has, in fact, an underlying cohesion and unity that are becoming increasingly evident. It is not accidental that the recent discoveries on the smallest entities in our universe bring immediate new insight into the behavior of the very large, that discoveries in the theory of condensed matter and of metals illuminate the structure of

Figure 3.



atomic nuclei, or that the remarkable precision being developed in modern atomic physics is finding application in field after field.

THE FORCES OF NATURE

Let me begin with a rather global view of space-time and the natural forces. Figure 3 shows how the relative strength of the strong force that gives us nuclear energy and of the electroweak force that now combines electromagnetism, the basis for chemistry, biology, and for life itself, and the weak nuclear force responsible for radioactivity come together as the temperature is increased, as we go back in time toward the beginning of our universe, as we go down in scale to the distances that were relevant immediately after creation, and as we go up in the energy of the probe that we require if we are to study these phenomena in the region where they come together. This is what is known as grand unification. You will have noted, however, that I have not yet included gravitation, the fourth of the natural forces. We realize now that gravitation very probably merges with the other three forces as we move into the shaded region on the right—the so-called Planck region—with dimensions less than 10^{-35} m and with temperatures greater than 10^{32} degrees, conditions that were in existence some 10^{-43} s after the beginning of our universe some 20 billion years ago.

These are some of the most fundamental questions being addressed in the world of science at the present time; but at first sight they may seem to have very little if any relevance to any public concern or to any individual citizen. But there are two very important linkages. In order to reach these frontiers of understanding, fundamental research continues to push technology to its limits, and as technology responds with new concepts and new devices, use of them permits us to push the frontiers farther back and rapidly fans out throughout all of science and technology. The relation is a symbiotic and synergistic one, and we as a nation are critically dependent on it. And there is more. Fundamental understanding of such matters changes the way we think, how we view the human race itself, and how it—and we—fit into the grand design of our universe.

THE TOOLS OF FUNDAMENTAL SCIENCE

Let me illustrate some of the devices used in the study of elementary particle physics and the fundamental forces and matter of the universe. Figure 4 shows the two-mile-long Stanford linear accelerator (SLAC) (we will pass for the moment the question of why this accelerator happens to lie across the San Andreas fault!), and the inset figure shows the project that is just now reaching completion, the Stanford Linear Collider (SLC), wherein this accelerator produces beams of electrons and of anti-electrons (positrons) and collides them, head-on, at extremely high energies. The goal here is simply that of providing ever larger energies to ever smaller volumes in the hope that some, at least, of that energy will materialize—as a consequence of Einstein's familiar equation, $M = E/c^2$—into entirely new particles, into entirely new kinds of matter. Around the collision points are placed enormous detectors that isolate and identify the equally enormous numbers of subatomic particles and fragments that emerge from such microscopic collisions. Figure 5 is an illustration of one such event in which the electron and the positron collide, annihilating one another, to create a single very high energy photon, a particle of light, which in turn creates a quark and an anti-quark, and these give rise to two jets of particles, which appear in the computer output from the detector shown here. Such experiments provide one of the clearest signatures for the reality of the quarks, the fundamental entities that we believe to be the building blocks of the universe.

Figure 6 shows some exciting new data from the DESY accelerator in Hamburg, where it has been found that there is an amazingly large mixing between a new bottom flavored B^0 meson—first discovered at Cornell in 1983—and its antiparticle, $\overline{B^0}$. Previously, the only known

Figure 4.

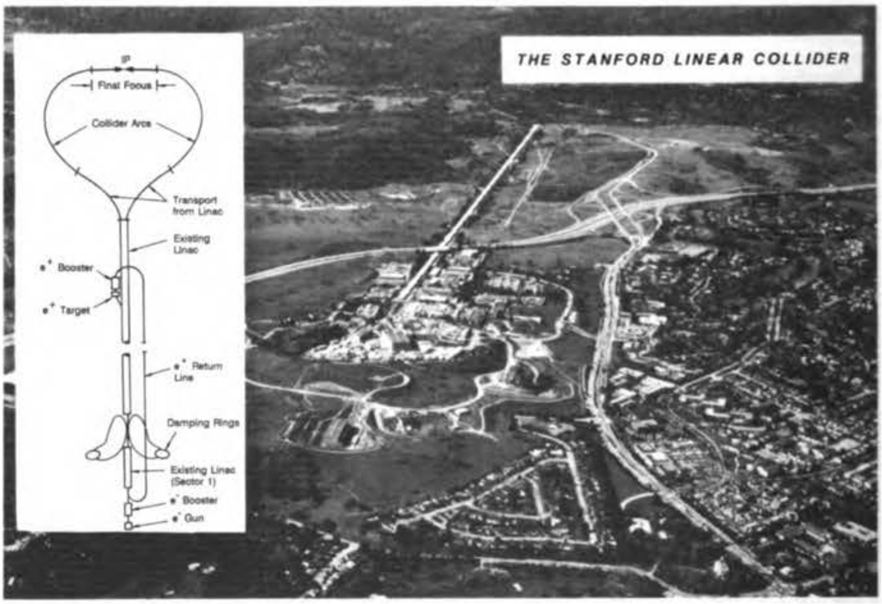
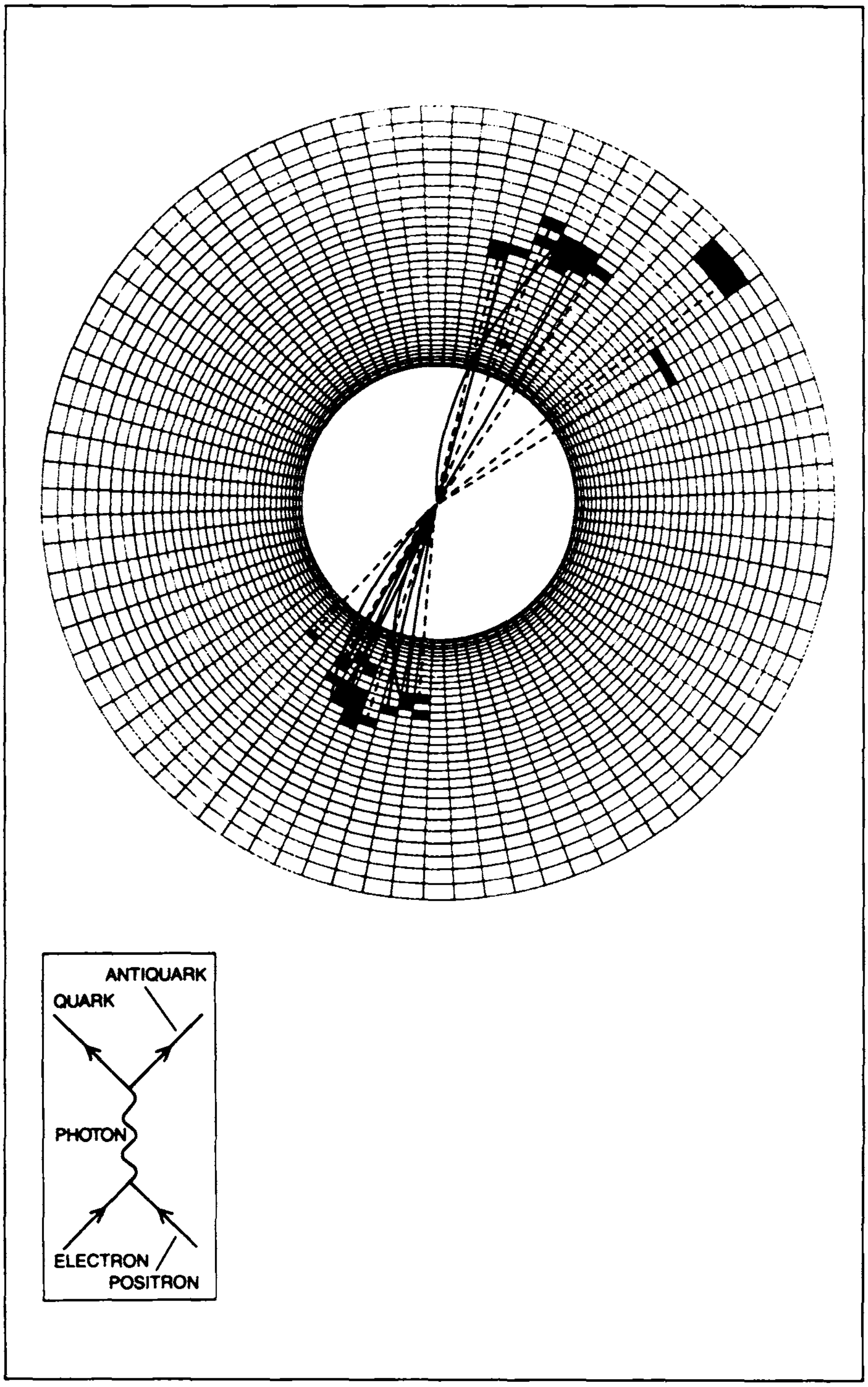


Figure 5.

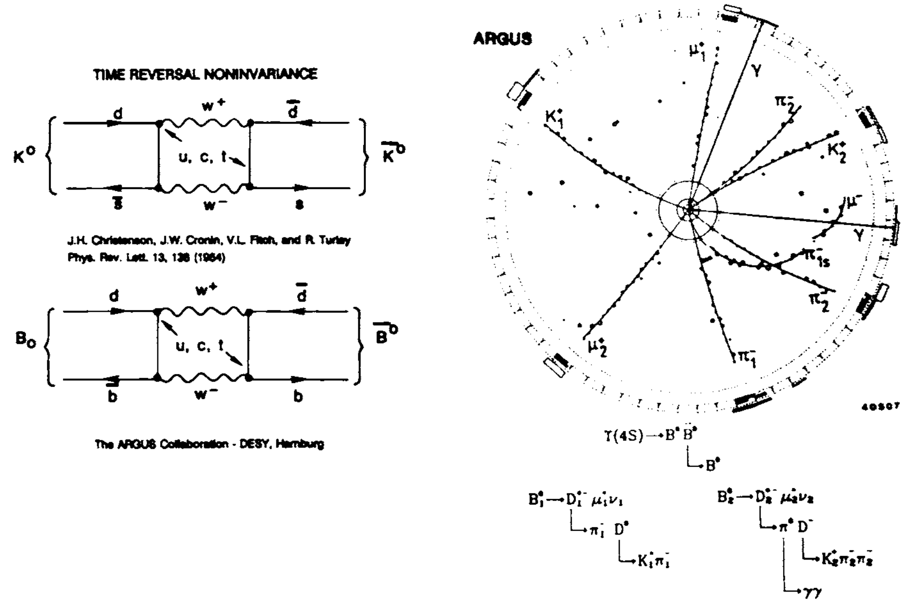


mixing of this kind was that of the more than ten times lighter K_0 meson with its antiparticle, from whose study Fitch and Cronin first deduced clear-cut evidence for time reversal noninvariance and for which they were awarded the 1980 Nobel Prize in physics. This is an exceedingly fundamental discovery that in its crudest sense implies that, at the creation, a tiny part of a mirror universe in which time runs in the opposite sense was trapped forever in our universe and a tiny fraction of our universe was similarly trapped in it.

The mixing, as shown in the box diagrams on the left of Figure 6, illustrates that the quark and anti-quark mixing is mediated by the three quarks, up, charmed, and top, together with their corresponding anti-quarks—all of which have two-thirds of the electrical charge of the electron—and by two of the heavy intermediate vector bosons, $W^{\pm}$. On the right of Figure 6 is shown what the detector surrounding the electron-positron collision point actually sees in one of these critical events. In the collision, an upsilon particle Y materializes from the delivered energy, which subsequently decays into a B^0, $\overline{B}^0$ pair, and the $\overline{B}^0$, as a consequence of mixing, converts into a second B^0. These two B^0 mesons then decay, as shown schematically below the detector figure and as identified in the figure itself, with the charged particles appearing as tracks of open circles and the gamma-ray photons as straight lines.

For 24 years since the original Cronin, Fitch, and Turlay discovery, time reversal noninvariance has remained tantalizingly beyond the reach

Figure 6.



J.H. Christenson, J.W. Cronin, V.L. Fitch, and R. Turlay Phys. Rev. Lett. 13, 138 (1964)

The ARGUS Collaboration - DESY, Hamburg

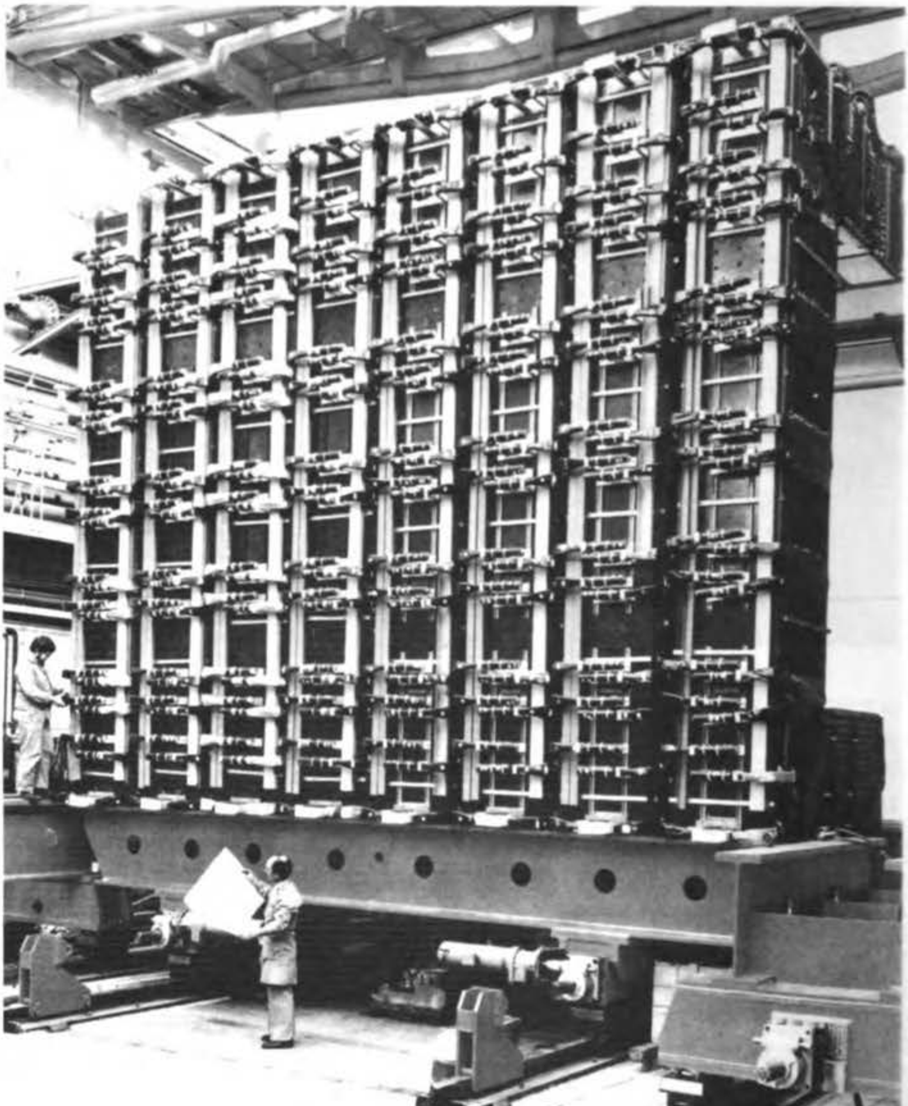
Figure 7.

of any new experimental probe. These new results on the B^0 meson not only confirm the original results but also provide important new insight into the mechanisms of time reversal invariance itself.

Some idea of the size of modern elementary particle physics facilities is provided by an aerial view of the CERN Laboratory in Geneva, shown in Figure 7 with the Geneva airport in the foreground. The superimposed white ring shows the current Large Electron-Positron Collider (LEP) ring, which would also house the proposed Large Hadron Collider (LHC) at 8 TeV currently under discussion at CERN. Detector instrumentation in this high-energy regime is also physically large and monetarily daunting. Figure 8 is a view of the UA1 detector used by Carlo Rubbia and his collaborators in the discovery of the $W^{\pm}$ and Z^0 intermediate vector bosons for which he and Van der Meer were awarded the 1984 Nobel Prize in physics.

Currently, the highest energies available anywhere in the world are those from the 6.3-km circumference Fermi National Accelerator Laboratory (FNAL) in Illinois. A recent upgrading of this facility with superconducting magnets has resulted in a total collision energy of 2 TeV, and experiments are now under way at that energy. Figure 9 is an aerial view of the FNAL, and Figure 10 shows the so-called Colliding Detector Fermilab (CDF) detector system during assembly.

Figure 8.



The upper panel of Figure 10 also shows the Italian, Japanese, and U.S. flags as a reminder of the truly international flavor of these activities. Not only does this work take fundamental physics into an entirely new energy domain and into a new scale of experimental apparatus, but it also makes a qualitative change in the way that fundamental discoveries on the frontiers of human knowledge are now being made. In the past, the traditional picture of fundamental discoveries was of those coming from the dedicated and often lonely efforts of the single investigator—as many still do. But in elementary particle physics, and increasingly in all the major fields of science, the voyage to the frontiers where new discoveries can be made is forever denied to the individual. Individuals still can, and must, play leadership roles in major new discoveries, but without the dedicated participation of literally hundreds of other able scientists and engineers, the work would be quite impossible and the discoveries would be forever denied to us. Such cooperation on the frontiers of knowledge is both new and important. New discoveries still come from the individual flash of genius, but increasingly they come from the close collaborative efforts of very large groups of scientists and engineers who conceive, design, build, and operate the major instrumentation needed to reach the frontiers. Figure 11 reproduces the title page of a recent CDF report that includes 229 participant scientists, 10 U.S. universities, and 3 U.S. National Laboratories, as well as 2 Japanese and 2 Italian groups, among the authors and institutions involved.

Figure 9.

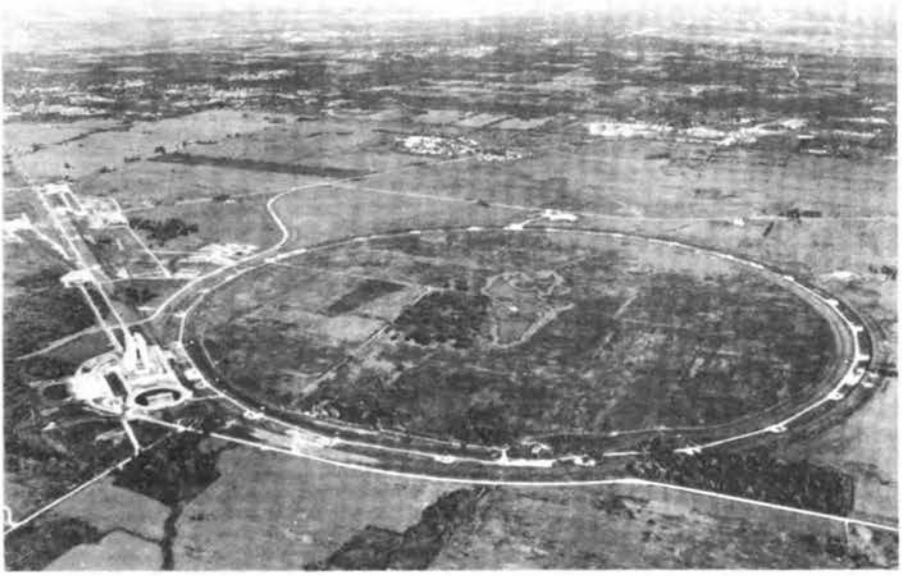
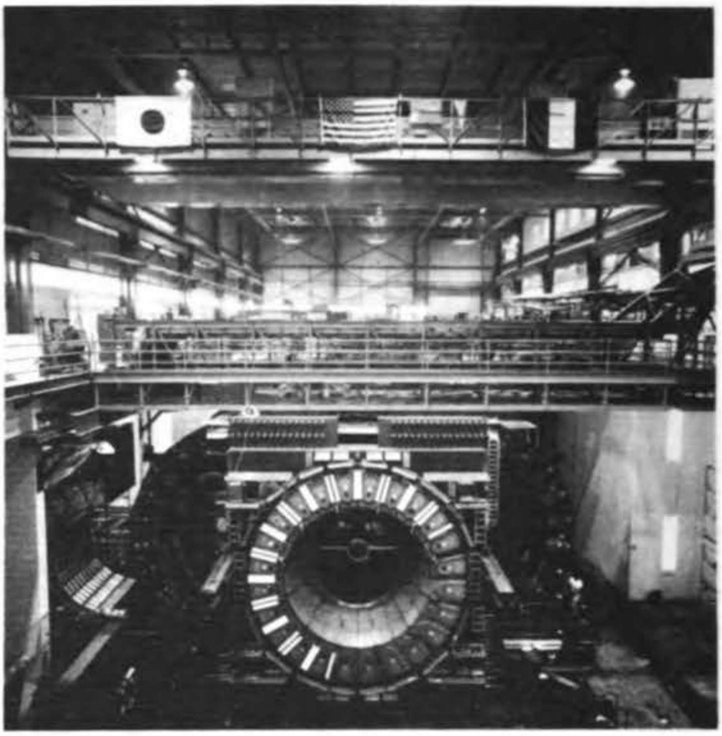


Figure 10.



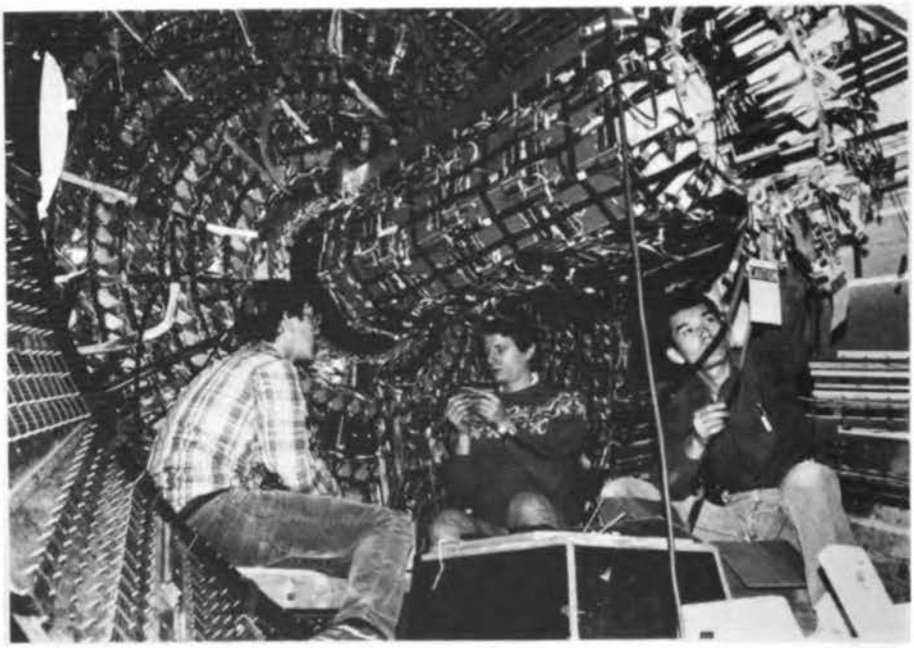


Figure 11.

CDF Collaboration - June, 1987

F.Abe[p], D.Amidei[c], G.Apollinari[k], G.Ascoli[g], M.Atac[d], P.Auchincloss[n],
A.R.Baden[f], A. Barbaro-Galtieri[i], V.Barnes[l], E.Barsotti[d], F.Bedeschi[k],
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G.Brandenburg[f], A.Brenner[d], D.Brown[f], A.Byon[l], K.L.Byrum[q], M.Campbell[c], R.Carey[f],
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M. Contreras[b], J.Cooper[d], M.Cordelli[e], M.Curatolo[e], C.Day[d], R.DelFabbro[k], M.Dell'Orso[k],
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A.Murakami[3], Y.Muraki[4], C.Nelson[d], C.Newman-Holmes[d], J.S.T.Ng[f], L.Nodulman[a],
J.O'Meara[d], G.Ott[q], T.Ozaki[p], S.Palanque[d], R.Paoletti[k], A.Para[d], J.Patrick[d], R.Perchonok[d],
T.J.Phillips[f], H.Piekarz[b], R.Plunkett[m], L.Pondrom[q], J.Proudfoot[a], G.Punzi[k], D.Quarrie[d],
K.Ragan[j], G.Redlinger[c], R.Rezmer[a], J.Rhoades[q], L.Ristori[k], T.Rohaly[j], A.Roodman[c],
H.Sanders[c], A.Sansoni[e], R.Sard[g], V.Scarpine[g], P.Schlabach[g], E.E.Schmidt[d], P.Schoessow[a],
M.Schub[j], R.Schwitters[f], A.Scribano[k], S.Segler[d], M.Sekiguchi[p], P.Sestini[k], M.Shapiro[f],
M.Sheaff[q], M.Shibata[p], M.Shochet[c], J.Siegrist[i], V.Simaitis[g], J.Simmons[l], P.Sinervo[j],
M.Siverts[5], J.Skarha[q], D.A.Smith[g], R.Snider[c], L.Spencer[b], R.St.Denis[f], A.Stefanini[k],
Y.Takaiwa[p], K.Takikawa[p], S.Tarem[b], D.Theriot[d], J.Ting[c], A.Tollestrup[d], G.Tonelli[k],
W.Trischuk[f], Y.Tsay[c], K.Turner[d], F.Ukegawa[p], D.Underwood[a], C.vanIngen[d], R.VanBerg[j],
R.Vidal[d], R.G.Wagner[a], R.L.Wagner[d], J.Walsh[j], T.Watts[n], R.Webb[o], T.Westhusing[g],
S.White[m], V.White[d], A.Wicklund[a], H.H.Williams[j], T.Winch[q], R.Yamada[d],
T.Yamanouchi[d], A.Yamashita[p], K.Yasuoka[p], G.P.Yeh[d], J.Yoh[d], F.Zetti[k]

CDF Member Institutions

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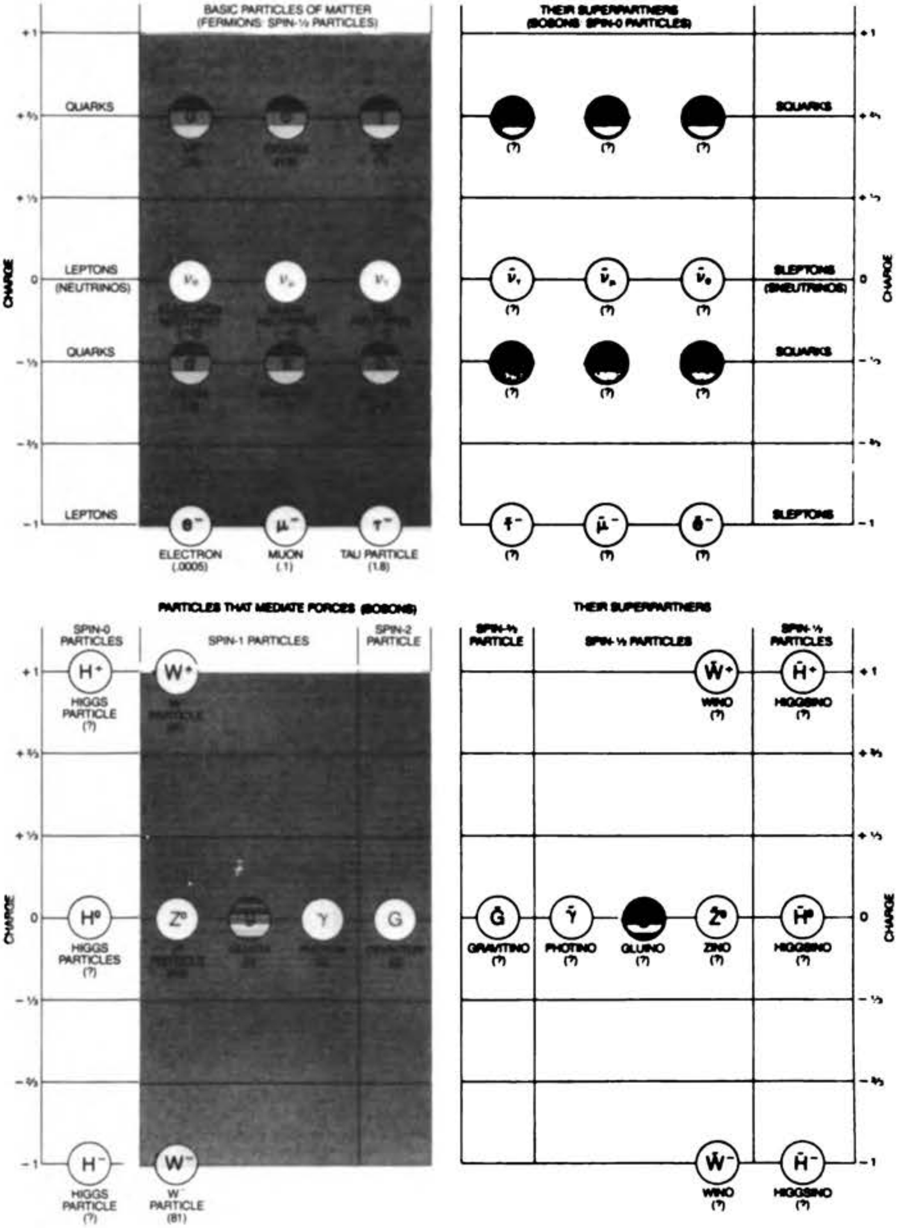
[d] Fermi National Accelerator Laboratory- [e] INFN, Frascati, Italy
[f] Harvard University-[g] University of Illinois-[h] KEK, Japan
[i] Lawrence Berkeley Laboratory-[j] University of Pennsylvania
[k] INFN, University of Pisa, Italy-[l] Purdue University
[m] Rockefeller University- [n] Rutgers University-[o] Texas A&M University
[p] University of Tsukuba, Japan-[q] University of Wisconsin

Visitors

[1] Oxford University, England- [2] INFN Trieste, Italy- [3] Saga University, Japan
[4] ICRR, Tokyo University, Japan- [5] Haverford College, Haverford, PA.

Figure 12.


BASIC PARTICLES OF MATTER (FERMIONS: SPIN-½ PARTICLES)
THEIR SUPERPARTNERS (BOSONS: SPIN-0 PARTICLES)
+1
+⅔
+⅓
0
−⅓
−⅔
−1
CHARGE
QUARKS
LEPTONS (NEUTRINOS)
QUARKS
LEPTONS
SQUARKS
SLEPTONS (SNEUTRINOS)
SQUARKS
SLEPTONS
ELECTRON (.0005)
MUON (.1)
TAU PARTICLE (1.8)
(?)
PARTICLES THAT MEDIATE FORCES (BOSONS)
THEIR SUPERPARTNERS
SPIN-0 PARTICLES
SPIN-1 PARTICLES
SPIN-2 PARTICLE
SPIN-3/2 PARTICLE
SPIN-½ PARTICLES
SPIN-½ PARTICLES
HIGGS PARTICLE (?)
HIGGS PARTICLES (?)
HIGGS PARTICLE (?)
W⁻ PARTICLE (81)
WINO (?)
HIGGSINO (?)
GRAVITINO (?)
PHOTINO (?)
GLUINO (?)
ZINO (?)
HIGGSINO (?)
WINO (?)
HIGGSINO (?)

From all such work—both experimental and theoretical—has emerged what is now known as the standard model of matter and its behavior. This is illustrated in Figure 12; in this model all matter is composed of quarks and leptons whose interactions are mediated by the exchange of so-called gauge particles that carry the forces of nature.

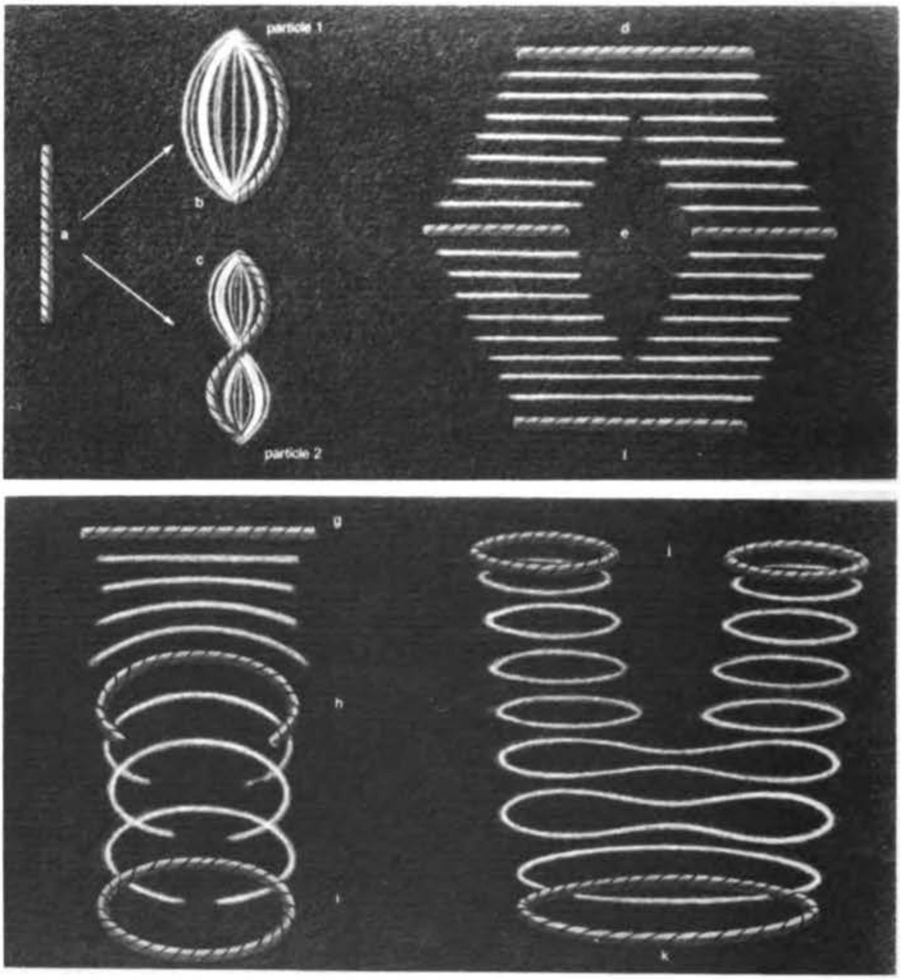
The standard model also assumes the existence of four, and only four, such forces—electromagnetic, strong, weak, and gravitational—and it assumes only three generations of quarks and leptons, although the evidence against a fourth and more generations is far from complete as yet. All the matter familiar to us in the physical universe is constructed of first-generation quarks and leptons; those in the higher generations are produced and studied only with our large accelerators. (I.I. Rabi at Columbia University once asked, "Who ordered them?") This standard model, however, has been remarkably successful in reproducing experimental observations and in suggesting new and challenging experiments. But open and very puzzling questions remain.

Perhaps the most challenging of these questions concerns the origin of mass itself. In the simplest version of the electroweak dynamics (the synthesis of electromagnetism and the weak nuclear interaction), it is postulated that the spontaneous symmetry breaking in the electroweak interaction, leading to the observed great mass difference between the photon and the heavy intermediate vector bosons—all of which in a symmetric theory would have zero mass—arises from an interaction with an electrically neutral field, the Higgs field, which, if it exists, permeates the entire universe and assumes a nonzero background value even in a perfect vacuum. This is no longer as distressing as it once might have been, given the rapidly increasing indications that the vacuum itself is a highly sophisticated medium capable of a wide variety of interesting fluctuation and other phenomena.

The interaction of the particles of nature with the Higgs field gives them an energy and thus a mass with respect to the vacuum. In this simplest of models, the Higgs field would be represented by a single Higgs particle as suggested in Figure 12. Unfortunately, existing theory does little to constrain the mass of the Higgs particle itself; if the mass were less than 50 GeV/c^2, it should be found in existing or planned electron-positron colliders, and if between 50 and 200 GeV/c^2, it should be detectable at the new Fermilab accelerator. For masses above 200 GeV/c^2, its lifetime for decay into two vector bosons will be so short and thus its energy width so great that it may not make any sense to discuss it as a single particle. In any event, if the Higgs particle is as heavy as 1 TeV/c^2, then electroweak theory predicts a whole series of quite new phenomena in that energy regime. This, however, may also reflect a fundamental problem with electroweak theories. If they are simply extrapolated to energies above 1 TeV, they characteristically predict probabilities for certain interactions—as for one W boson with another—that exceed unity. The theories as they stand must therefore be incomplete.

In the absence of any experimental evidence for the existence of a Higgs particle, a totally different approach to the origin of mass that is under widespread study involves supersymmetry. In a supersymmetric world, as shown in the right part of Figure 12, every particle, including the Higgs boson if it exists, would have a partner identical to it in every aspect except spin; to every ordinary fermion there would correspond a supersymmetric boson and to every ordinary boson, a supersymmetric

Figure 13.



fermion. The supersymmetry field thus is different from all others in that it treats fermions and bosons on an equal footing and can transform one into the other.

But if the supersymmetric partners of this theory differed only in spin and if they in fact exist, many already would have been discovered. Since none have been, this leads naturally to the suggestion that, as in the case of the electroweak symmetry, supersymmetry is also broken in such a way as to give all the supersymmetric partners masses that are beyond current experimental reach. This constitutes one of the arguments for new, higher-energy facilities.

Despite all its successes, the standard model also fails in one very glaring respect. It is unable to incorporate gravitation with the other natural interactions.

In an effort to remedy this problem, Green and Schwartz and now many other theorists have turned in recent years to the development of so-called superstring theories. Ab initio, these theories postulate the validity of special relativity, of quantum mechanics, and of supersymmetry, and they also insist that all the forces of nature be included.

Within the theory, which is cast in a ten-dimensional universe—six dimensions having been compactified in the earliest instants of the universe to leave our familiar one temporal and three spatial dimensions—the elementary particles are thought of as one-dimensional segments rather than as points, with characteristic segment lengths equal to 1.6×10^{-33} cm (the Planck length) and characteristic masses of 1.2×10^{19} GeV/c^2 (the Planck mass). It is clear, returning to Figure 3, that there is a logical appeal to this idea, because in that figure it is shown that the Planck region is necessarily the one relevant to a unified theory containing gravitation.

Figure 13 is a highly schematic representation of some aspects of modern string theory. An elementary string (a) can vibrate in a number of different ways to represent different particles, as shown here for cases (b) and (c); a single string (d) can also divide (e) to represent a decay process or join (e) → (f) to represent a fusion process. An open string (g) can bend (h) and finally join its ends to form a closed loop (i); two such loops (j) can then join to represent a fusion process (k) or separate to represent a decay.

Thus far, unfortunately, although string theory has enormous aesthetic appeal, it remains completely impregnable to experimental tests; beyond that, we have no idea whatsoever how compactification occurs or why. If we are to make progress in obtaining answers to this kind of fundamental question, we must search for Higgs boson and for possible supersymmetric particles, and we need to understand what goes wrong with our standard models at energies above 1 TeV.

For all of this work, we need to be able to deliver more energy into ever smaller volumes. We must also remember that the 2-TeV energies at Fermilab permit detailed study of phenomena only up to about 0.3 TeV, and if we want to study in the range of 1 to 5 TeV, we need accelerator energies that are at least equal to or greater than 20 TeV.

It was thus with great enthusiasm that the elementary particle physics community learned last year that President Reagan had formally approved construction of the proposed Superconducting Supercollider Accelerator (SSC); Congress has not yet added its approval, and therefore the necessary funding is not yet in sight. As designed, this facility would have colliding 20-TeV proton beams to yield effective 40-GeV energies for experimental purposes.

Figure 14.

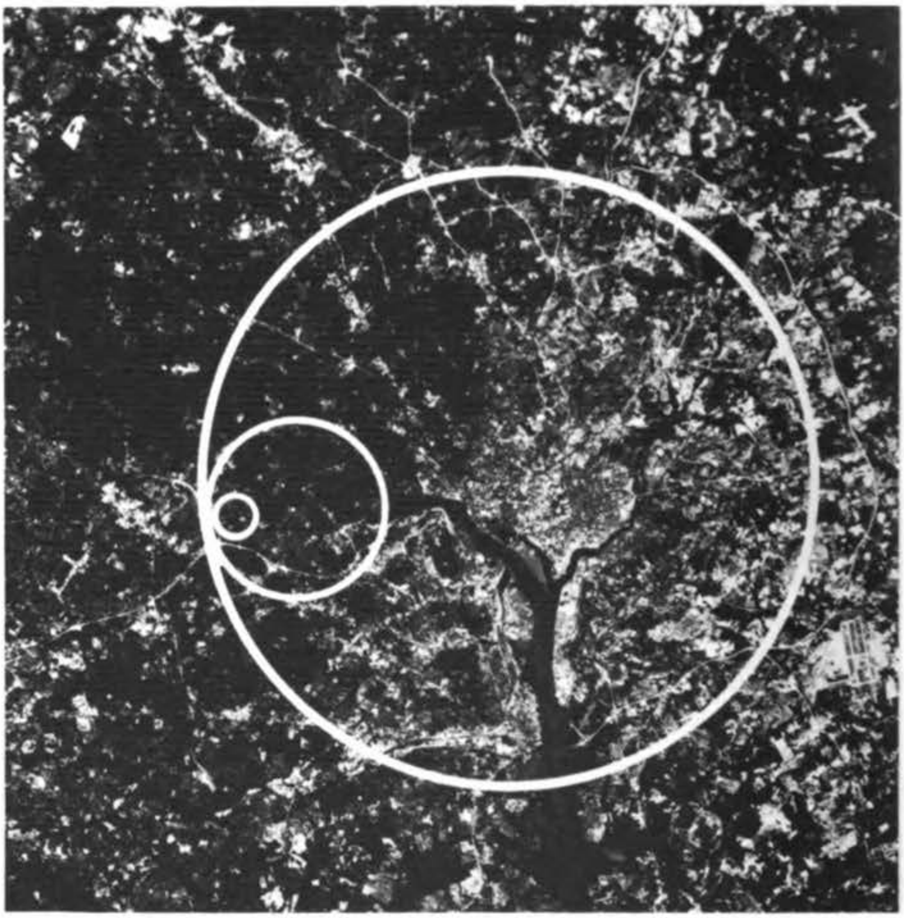


Figure 14 provides some concept of the size of this proposed facility. Here it is shown superimposed on a Landsat photograph of Washington, D.C., with National Airport just below the center of the photograph. Depending on design details, it will have a ring circumference of about 52 miles, compared to the 16-mile circumference of the LEP (or LHC) ring at CERN in Geneva.

This new machine will require about 2000 tons of actual superconductor for the windings in the magnets that keep the protons on their circular path, and it bears emphasis that the particle physics community has been largely responsible for the development of superconducting technology on a large scale and for its transfer to the industrial sector. It has also played a central role in the development of modern information-handling hardware and software and continues to push the frontiers of technology in almost every field.

HIGH-PRECISION ACCELERATORS

It should not be thought, however, that only these huge accelerators are important in fundamental physics. As the proud owner of one of the most powerful of the ultraprecise accelerators that complement the very large ones, I show in Figure 15 a photograph taken inside the pressure tank of the first of the ESTU class Van de Graaff electrostatic accelerators installed in the A.W. Wright Laboratory at Yale University. The high-voltage terminal of this machine, whose edge appears just below the top of the figure, has already been operated at voltages of up to 22.5 MV, and it is our expectation that we will soon reach 25 MV, making this one of the most powerful, if not *the* most powerful, precision accelerators anywhere in the world.

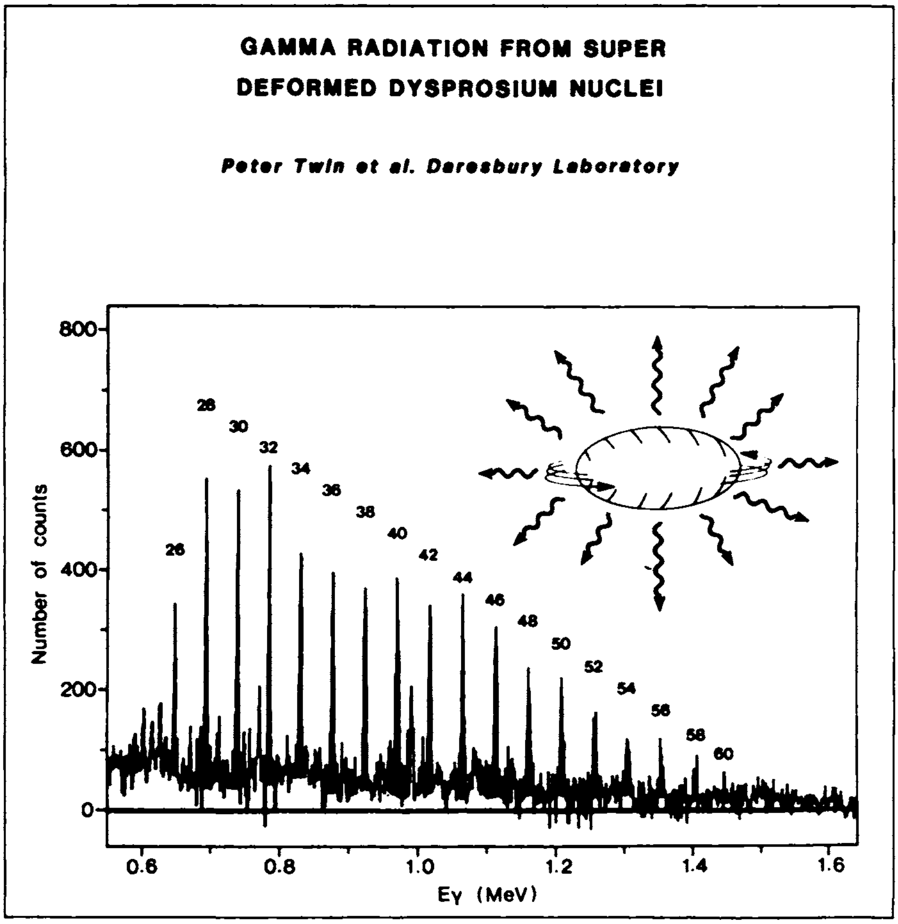
Whereas the large accelerators at Stanford and Fermilab and the proposed supercollider probe deep inside the protons and neutrons, which are the building blocks of nuclei, accelerators like this one at Yale allow us to do microsurgery on individual atomic nuclei to understand how they are constructed, how they interact, how we can obtain energy from them, and how we can use them in a very wide range of technologies. Such accelerators also allow us to use individual nuclei as microscopic laboratories wherein we can examine the fundamental forces and symmetries of nature.

Figure 16 is typical of the exciting new results that such machines have made possible in the recent past. If, instead of using protons as projectiles, we use much heavier nuclei, as we can in the electrostatic machines, it becomes possible to carry very large amounts of spin or angular momentum into the collision without, at the same time, bringing so much

Figure 15.

energy that the nuclei involved are shattered beyond recognition. By spinning nuclear systems ever faster and indeed until the centrifugal forces rip them apart, we can study in a very delicate way the strong nuclear forces that normally hold the nucleus together and that are the source of nuclear energy. We can begin to understand how the shapes of nuclei change with increasing temperature and with increasing spin, and we can begin to search for the phase transitions—analogous to those that occur when water freezes or boils—that our modern theories predict should occur in the matter of which the nuclei are constructed. Up until a few years ago no one had succeeded in spinning nuclei to values exceeding some 30 units of angular momentum. Figure 16 is a dramatic one from the Daresbury Laboratory in England showing how, with new detection systems, it has been possible to spin a football-shaped nucleus of the rare earth element dysprosium and then detect the gamma rays

Figure 16.



GAMMA RADIATION FROM SUPER DEFORMED DYSPROSIUM NUCLEI

Peter Twin et al. Daresbury Laboratory

that are emitted as it spins down, emitting 2 units of angular momentum with each photon from an initial spin value of 60 units down to 26 units in this particular figure.

One of the most exciting areas in modern nuclear physics is the search for previously unrecognized dynamic symmetries that underlie both the structure and dynamic properties of nuclei and that provide a framework within which a vast amount of previously uncorrelated data now fit comfortably. For the first time in the 75 years since the nucleus was discovered, we have theoretical models that can reproduce essentially all that we have measured concerning the structure of nuclei, and we appear to be on the threshold of a corresponding unification of what we know about how nuclei interact with one another.

It bears emphasis that the new technologies, new accelerators, new detector systems, and new information handling systems that have made these results possible have sparked a renaissance in the spectroscopy of the nuclear quantum system that is analogous to and as broad ranging as that which occurred in atomic physics with the development of the laser.

RARE PROCESSES

Nuclear Double Beta Decay

And lest it be thought that work on these microscopic systems can be carried out only with accelerators, I list in Figure 17 the results of a decade-long experiment carried out at the University of California at Irvine by Michael Moe and his collaborators that in 1987 resulted in observing, for the first time in a laboratory, a process known as nuclear double beta decay, in which two protons are converted simultaneously to neutrons by the weak interaction in what is, by a very large margin, the rarest physical process that has ever been observed. The measured half-life of 10^{20} years is about 10 billion times longer than the lifetime of our universe!

These data were obtained with an extremely sophisticated detector system used to study a tiny radioactive sample under conditions in which background radiations had been reduced to the maximum degree possible so that the extremely rare, double beta decay events could be isolated and identified. Not only does this work provide an extraordinarily sensitive test of our knowledge of the structure of the nuclei involved, but it also holds the promise of providing fundamental new information on the nature of the fundamental weak interaction and of providing either a measurement of, or a very stringent limit on, the mass of the elusive neutrino. I shall return to these questions below.

Figure 17.

NUCLEAR DOUBLE BETA DECAY

- **Observed first in 1987 by Elliott, Hahn, and Moe at the University of California, Irvine**

- **The rarest process, by a large margin, ever observed in a laboratory**

- **The two-neutrino mode:**

  $^{82}Se \longrightarrow {}^{82}Kr + 2e^- + 2\bar{\nu}$

  Half-life: $(1.1^{+0.8}_{-0.3}) \times 10^{20}$ **years**

  Phys. Rev. Lett. 59, 2020 (1987)

- **The zero-neutrino mode:**

  $^{82}Se \longrightarrow {}^{82}Kr + 2e$

  not yet observed

  $^{76}Ge \longrightarrow {}^{76}Se + 2e$

  Half-life $> 6 \times 10^{23}$ **years**

  University of California, Santa Barbara
  Lawrence Berkeley Laboratory - unpublished

Proton Decay

A second example of important subnuclear processes that do not involve use of an accelerator is a process that is predicted by every one of the standard models—the decay of the proton, a fundamental particle that until very recently was considered absolutely stable, indeed the most stable particle in our universe. In Figure 18 I list seven major detection systems now in operation, or under construction, around the world that are used in searching for this decay. Three of the experiments employ water Cerenkov detectors. The other four experiments are based on detectors in which iron plates are interleaved with particle counters. All are installed underground to shield against cosmic radiation coming from outer space.

While the simplest version of the standard model a few years ago predicted a proton half-life of roughly 2.5 × 10^{31} years (1000 billion, billion times the lifetime of the universe!), the experimental data, thus far, set a lower limit of 1.7 × 10^{32} years, but there are much more complex versions of the model available even if this would appear to rule out the simplest one. At the current limit of 1.7 × 10^{32} years, a human would have to live about 2500 years before a single one of his body protons would decay, so the instability is anything but large.

The search for proton decay continues, however, because the standard

Figure 18.

	SPONSORING INSTITUTIONS	LOCATION	DEPTH (EQUIVALENT METERS OF WATER)	DETECTOR MASS (METRIC TONS)	DETECTION METHOD
WATER CERENKOV DETECTORS	University of California at Irvine, University of Michigan, Brookhaven National Laboratory, Cleveland State University, University of Hawaii, California Institute of Technology, University College Warsaw	Morton Thiokol salt mine, Painesville, Ohio	600 (1,600)	8,000 TOTAL 3,300 FIDUCIAL	2,048 FIVE-INCH PHOTOMULTIPLIERS ON ONE-METER SURFACE GRID
	KEK, University of Tokyo, University of Tsukuba	Kamioka metal mine	825 (2,400)	3,000 TOTAL 1,000 FIDUCIAL	1,000 20-INCH PHOTOMULTIPLIERS ON ONE-METER SURFACE GRID
	Harvard University, Purdue University, University of Wisconsin	Silver King mine, Park City, Utah	525 (1,500)	700 TOTAL 420 FIDUCIAL	704 FIVE-INCH PHOTOMULTIPLIERS ON ONE-METER LATTICE, MIRRORED WALLS
LAYERED TRACKING DETECTORS	Tata Institute, Osaka City University, University of Tokyo	Kolar gold fields, South India	2.500 (7,600)	140 TOTAL 100 FIDUCIAL	1.600 PROPORTIONAL GAS COUNTER TUBES
	CERN, Frascati Laboratory, University of Milan, University of Turin	Mont Blanc tunnel, French-Italian border	1,850 (5,000)	150 TOTAL 100 FIDUCIAL	47,000 LIMITED STREAMER TUBES
	Orsay, École Polytechnique, Saclay, Wuppertal University, Tufts University	Fréjus tunnel, French-Italian border	1,550 (4,200)	160 TOTAL	1.500 PLASTIC FLASH-TUBE PLANES; 200 GEIGER TUBES
	Argonne National Laboratory, University of Minnesota, University of Oxford, Rutherford Laboratory	Soudan iron mine, Soudan, Minn.	675 (1,800)	30 (PROTOTYPE)	HEXAGONAL DRIFT TUBES

model versions all require that it occur; if, as we push the measurement limits to longer and longer lifetimes, we continue to find no evidence at all for proton decay, it will indicate that something is fundamentally wrong with our standard models.

Neutrinos from Supernova 1987 A

Fortunately, although these detectors were all established to search for decay of the proton, they are also sensitive—at an extraordinarily low level of efficiency—to neutrinos coming from outside the solar system or from our sun. As shown in Figure 19, once Supernova 1987 A had been observed with the naked eye, in South America, the groups operating the first two of the detectors listed in Figure 18 searched their computer tapes from their detectors and found that they had, indeed, detected neutrinos coming from the supernova. Despite the fact that 10 million billion of these neutrinos passed through the particular detector whose data are shown here, only 12 were detected. But these 12, in terms of their energies and their arrival time, provided the first experimental proof that stars do actually undergo gravitational collapse into neutron stars and into black holes. Moreover, these data securely anchored theories—developed over decades to describe supernova events—that prior to this observation had had large speculative components but that these data demonstrated to be remarkably correct. Finally, the arrival time of these neutrinos from the collapsing star, when compared to the arrival time of the light from the collapse, makes it possible to put an upper limit of 15 eV on the neutrino mass. This is already too small a value for the neutrinos to provide the missing mass in our universe that would be required to bring its current expansion to an end and perhaps cause it to collapse in on itself in an ultimate Big Crunch some 20 billion years in the future. Again, measurements with small detection systems in laboratories on the earth's surface—as in the case of nuclear double beta decay—and measurements on catastrophic events occurring far beyond the boundaries of our Milky Way galaxy provide complementary evidence on the neutrino mass and, again, illustrate the remarkable unity that exists throughout science.

THE BEHAVIOR OF NUCLEAR MATTER

Because more than 98 percent of all the matter in the known universe is nuclear matter and because there are the possibilities of totally new kinds of nuclear matter that we have not yet encountered and of new methods of releasing nuclear energies still unknown to us, the study of this nuclear matter remains one of very high priority. It bears emphasis that in our present most efficient reactors, less than 0.1 percent of the energy present in the fuel is being released; a factor in excess of 1000 awaits us in terms of potentially available energy.

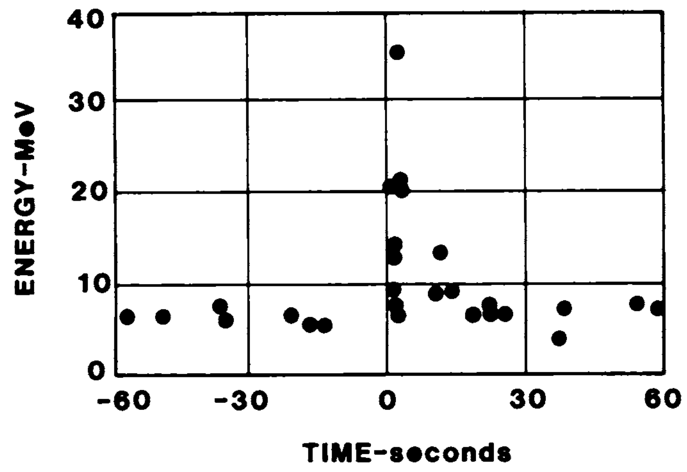
The Continuous Electron Beam Accelerator Facility

We are currently following two complementary paths toward exploring this nuclear matter. On the one hand, because we believe that we

Figure 19.

NEUTRINOS FROM SUPERNOVA 1987A

Data from Tokyo-Pennsylvania Collaboration
Kamiokande Detector

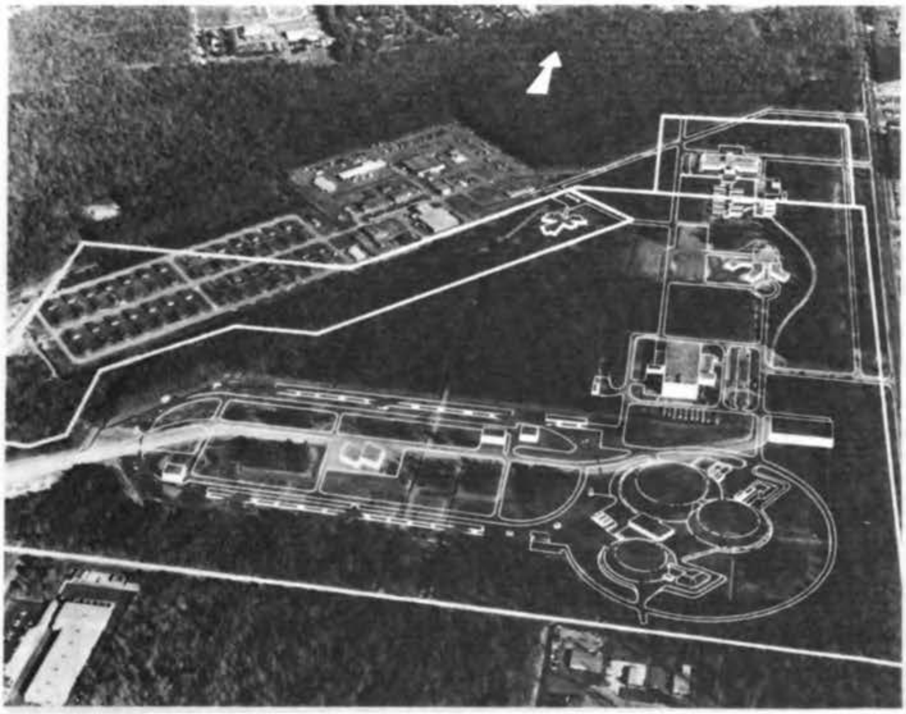


- Supernova emitted 10^{57} neutrinos in a few seconds –10 times the total number of neutrons and protons in the sun
- Of these, about 10^{16} passed through the detector and 12 were detected
- Provides first experimental proof of stellar collapse
- Pulse shape remarkably well reproduced by Bethe-Brown theoretical model based on nuclear phenomena
- Pulse duration sets upper limit of 15 eV on the neutrino mass

understand electromagnetic forces much better than we do any of the other natural ones, we have continued to focus our attention on the interaction of high-energy electrons with nuclei because, as projectiles, the electrons interact only through the electromagnetic force and in doing so illuminate the entire nuclear interior. Figure 20 is an overview of the major Colliding Electron Beam Accelerator Facility (CEBAF) now under construction at Newport News, Virginia. When completed, it will be, by a large margin, the most powerful such facility anywhere in the world. It consists of an oval racetrack, on each side of which is a 500-MeV linear accelerator, and the beam of electrons is passed four times around the racetrack before being directed to targets in one of the three circular areas shown at the lower right. If and when the research program demands it, the linacs can be extended to cover a larger fraction of the racetrack, and the maximum energy can be increased from its initial 4-GeV value to about 16 GeV while retaining very high intensity.

This facility is designed to study the transition that occurs in nuclei as their temperature is systematically raised. At low temperatures, as in normal matter, the constituent neutrons and protons simply move with higher kinetic energy, but as the energy is increased, the neutrons and

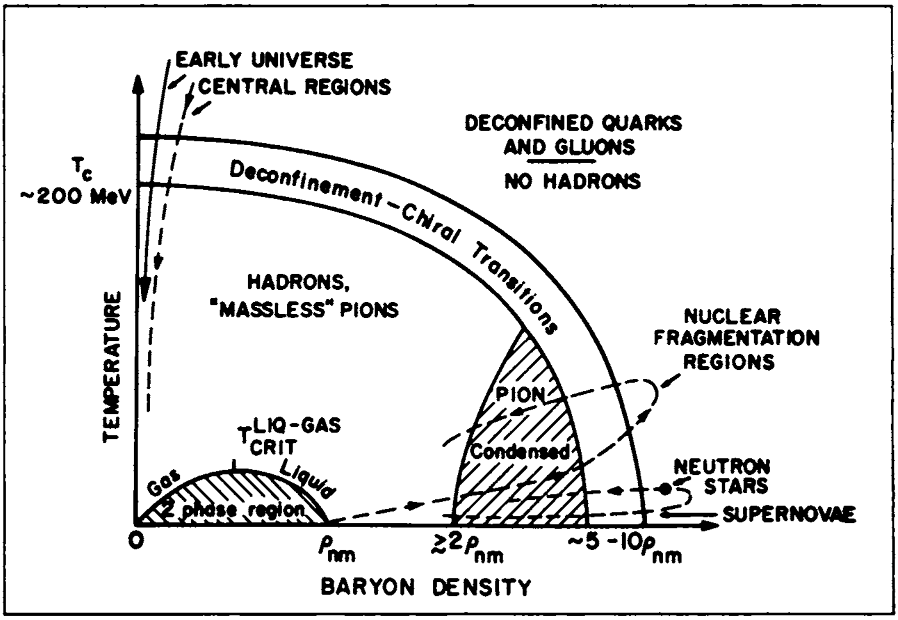
Figure 20.



protons themselves absorb energy, become excited to higher quantum states, and finally begin to melt so that their constituent quarks, and the gluons that bind these quarks, begin to be liberated and to move about the nucleus independent of their parent neutrons and protons. This marks the vital transition from hadronic matter, the kind of matter with which we are familiar and in which neutrons and protons play the dominant roles, into quark matter, in which the neutrons and protons have disappeared. The CEBAF facility, which will be completed in the early 1990s, will allow physicists from around the world to explore this vitally important transition.

As shown in Figure 21, this hadronic-to-quark-matter transition is one that has occurred at other times and in other places in the universe. In this figure, which is a schematic illustration of the equation of state for nuclear matter in which the temperature is plotted against the density, hadronic matter occurs inside the indicated transition zone, and quark matter, outside. In the earliest moments after the creation of our universe, when the enormously hot primordial plasma—still at very low density—had cooled down to about 200 MeV, which corresponds to a temperature of 2.5 × 10^{12} K, the quark matter began to condense and to transform into familiar hadronic matter. In supernova explosions, on the other hand, the density in the shock wave, which is characteristic of those explosions, rapidly rises to more than ten times that normal in nuclei, and the neutrons and protons are forced together so that once again they lose their

Figure 21.



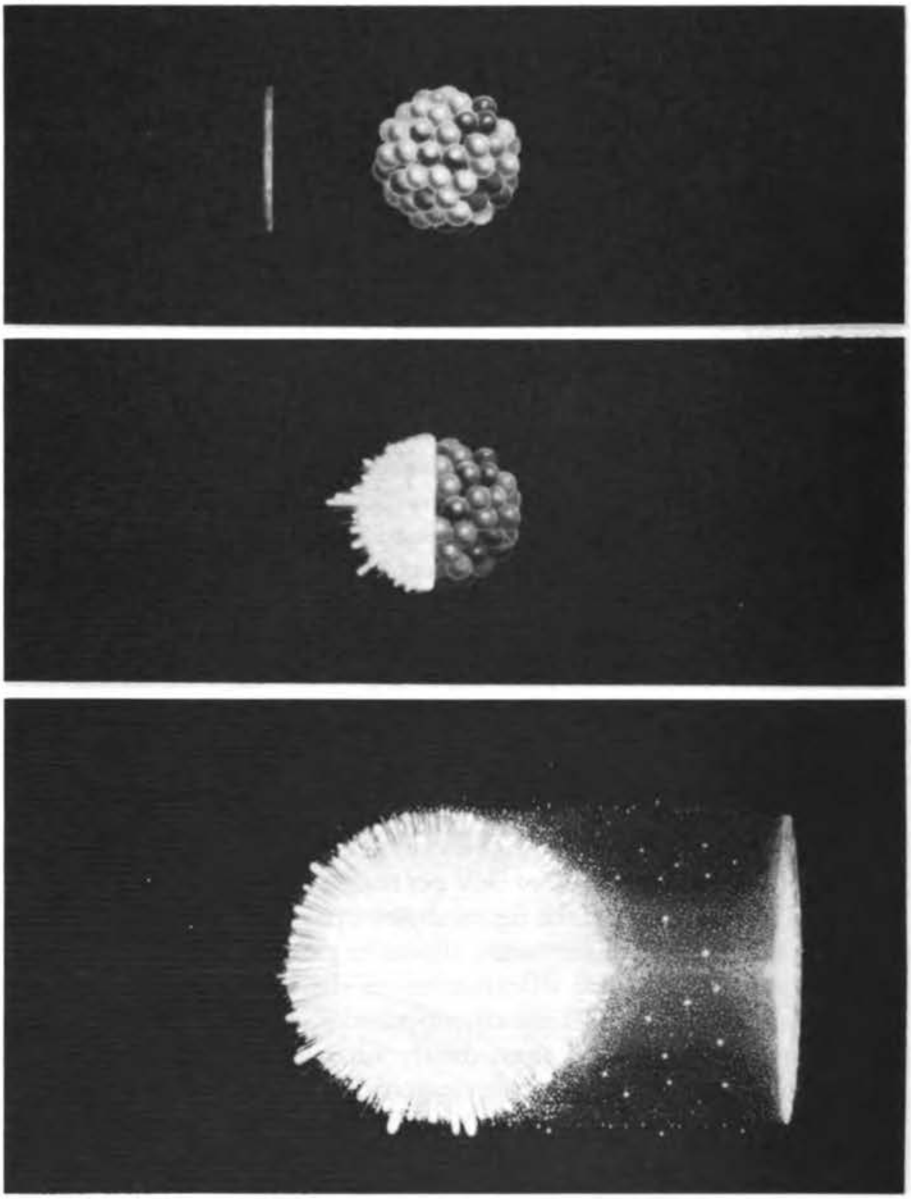
identity and merge into quark matter. Our goal in our planned studies is to traverse the transition region in controlled fashion to search for possible new forms of matter that might be created during this transition and to search for hints of new ways in which some of the enormous energies bound up in nuclear matter could be released.

The Relativistic Heavy-Ion Collider

But high-energy electrons are not the only probes that can be used in such work. Figure 22 is an artist's conception of the collision of a uranium projectile, traveling at relativistic velocities, with a uranium target nucleus at rest. In the upper panel, because of relativistic length contraction, the projectile appears as a disc about to impact on the target. As it passes through the target, as shown in the center panel, both the projectile and target are raised to enormously high temperatures, far above those necessary to liberate the quarks and gluons from the constituent neutrons and protons. After the projectile has passed completely through the target nucleus, as shown in the bottom panel, we have two regions heavily populated with fragments of the original target and projectile, and in between them an exceedingly hot region known as the firetube, which we believe is composed of almost pure quark-gluon plasma—the purest form of quark matter and indeed an entirely new, fifth state of matter.

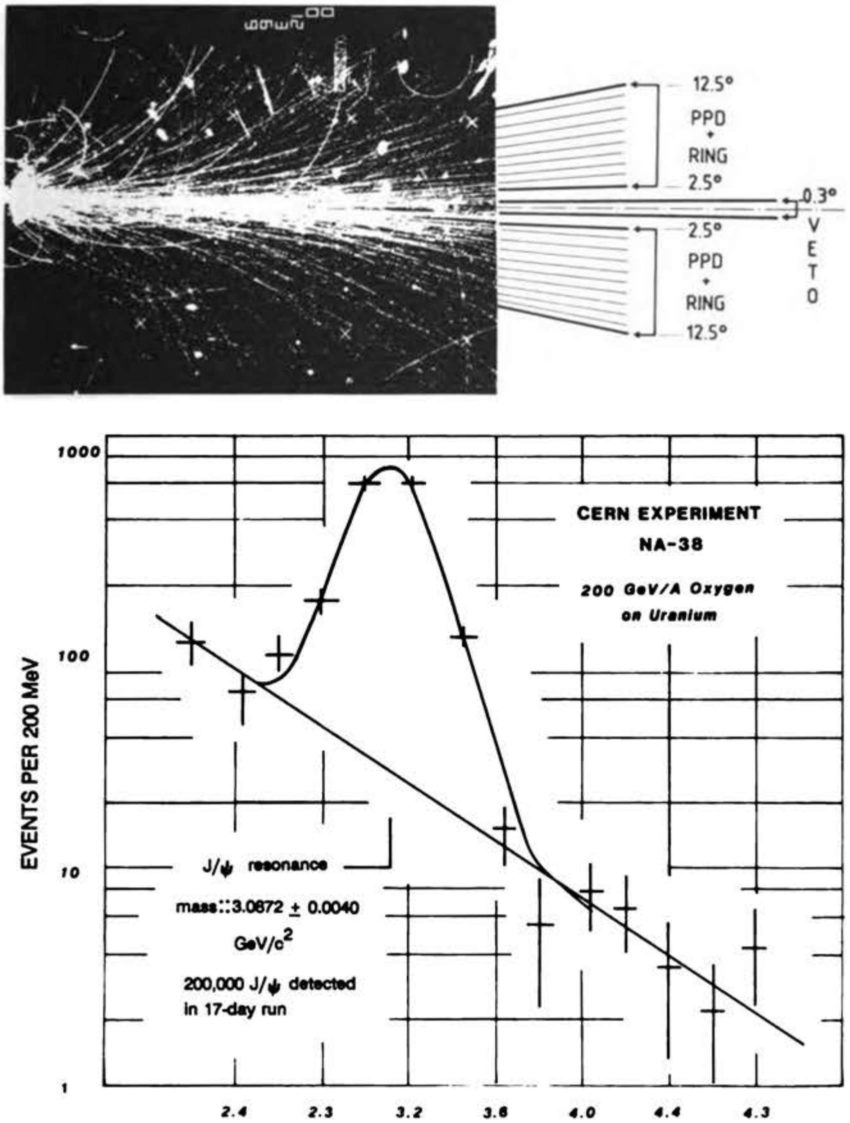
During this past year, for the first time, projectile beams having relativistic velocities, although still much lighter than uranium, have become available both at CERN in Geneva and at the Brookhaven National Laboratory on Long Island. Figure 23 is typical of the results obtained when oxygen projectiles carrying 200 GeV per nucleon strike lead and uranium targets. The upper part of the figure shows a photograph of the streamer chamber that surrounds the target, illustrating the enormous number of charged particles that are characteristic of these relativistic heavy-ion collisions. While these streamer chambers show the characteristics of the charged particle fragments immediately surrounding the target, additional detectors are mounted many meters downstream to pick up those particles traveling precisely along the original beam direction and those traveling in a cone about that direction. From the number of particles detected in these various systems, it becomes possible to measure many of the characteristics of the collision. One of the very important discoveries has been that at the relatively low energies of about 15 GeV per nucleon available at Brookhaven, the projectile is completely stopped in the target, whereas at the higher energies available at CERN, the targets are beginning to become partially transparent. In neither case, however, is there adequate energy to give us access to the firetube or to the pure quark-gluon plasma. Further evidence that we are still not seeing the

Figure 22.



desired plasma is shown in the lower part of Figure 23 where, in looking for pairs of heavy electrons from the collisions, we find a characteristic peak—the so-called J/Ψ resonance—discovered simultaneously many years ago at Brookhaven and at Stanford. This resonance is the signature for the presence of bound systems of charmed and anti-charmed quarks that could not exist in a fully developed quark-gluon plasma.

Figure 23.



ULTRA RELATIVISTIC HEAVY ION COLLISIONS

CERN EXPERIMENT NA-35 ***200 GeV/A oxygen on lead***

Figure 24.

Although these results are extremely interesting and tantalizing, they indicate quite clearly that if we are to really traverse the hadronic-quark transition region and be in a position to study quark matter, we again need heavy-projectile energies higher than any now available.

Fortunately, we already have in place at Brookhaven the remains of an accelerator that was initiated in the early 1980s, the so-called ISABELLE accelerator, whose construction was terminated in 1984 in favor of moving forward to the supercollider, but only after some $250 million had already been spent on civil engineering and on the development of refrigeration, magnets, and other components. Figure 24 is an aerial view of the Brookhaven site where, at the present time, beams of heavy ions up to those as heavy as sulfur ions are accelerated in the tandem accelerators in the lower right and then taken through a 1000-m transfer line to the old Alternating Gradient Synchrotron (AGS), where they are accelerated to energies of 15 GeV per nucleon for use in the present experiments. At the present time, the synchrotron booster shown to the left of the AGS is under construction. It will make it possible to accelerate much heavier projectiles—from sulfur up to gold—to similar energies in the AGS. The American nuclear physics community has now given its highest priority rating to the coupling of this system to a renaissance of the old

ISABELLE accelerator, which would then be called the Relativistic Heavy Ion Collider (RHIC). This would involve beams of all nuclear species, up to and including gold, counter-rotating at energies up to 100 GeV per nucleon so that, at six places around the ring where the beams are brought into head-on collision, 200 MeV per nucleon would be available. This would clearly be enough to give us full access to the firetube and the quark-gluon plasma and to whatever new phenomena lie in wait in and beyond the hadronic-quark transition region.

Fortunately, fully half of the hardware required to make this RHIC facility a reality is already paid for and in place at Brookhaven so that it is possible to make this a remarkably cost-effective proposal. This facility will be included in the Department of Energy request for construction funding in FY1990 and, if approved, will be operational in 1995, again as an absolutely unique facility in the world accelerator complement.

ATOMIC PHYSICS

In turning to a different area entirely, atomic physics, I am reminded of another of I.I. Rabi's comments: "The 20th century started in 1897 with Thompson's discovery of the electron."

To a remarkable degree, twentieth century technology has been based on our ability to manipulate electrons and atomic structure. I would also quote Alvin Trivelpiece, who, in making his presentation on behalf of the supercollider last year to President Reagan and the cabinet, noted that more than one-third of the U.S. gross national product can be traced directly to our understanding of the structure of the atom and its constituents. Here, too, the pace of change in recent years has been astonishing.

The fact that the laser worked a renaissance in atomic physics is now generally recognized, but only now are we beginning to understand how to fully use the unique characteristics of the coherent electromagnetic radiation that the laser provides.

Trapped Atoms

One of the most interesting recent discoveries—originally suggested by Haensch and Schalow and independently by Wineland and Dehmelt at the University of Washington—is that the mechanical forces exerted by laser light can dramatically lower the temperature of a sample of atoms or ions, allowing very high resolution, atomic spectroscopy, and ultralow temperature atomic studies. Once cooled, slowly moving ions and atoms can be trapped for indefinite periods in magnetic bottles and held for ultraprecise measurement. Figure 25 is a photograph of the intersection of a laser beam from the left and one of sodium atoms from the right. The slowed atoms, virtually at rest at the end of a magnetic solenoid, fan out into the skirt about the laser beam. The trapping limitation is currently set by the levels of residual vacua attainable and thus the collision rate with residual atoms. Trapping periods of many hours appear attainable in the near future.

By using a number of converging laser beams, it is possible to obtain what is now known as optical molasses at the intersection and to trap hundreds of thousands of atoms in the intersection at temperatures of about 100 micro Kelvin. Figure 26 shows six mercury ions that, after being slowed down, have been trapped in a so-called Paul trap. Each ion is fixed at a point where the Coulomb forces pushing it out are just balanced by the magnetic trap forces pulling it inward. The spacing

Figure 25.

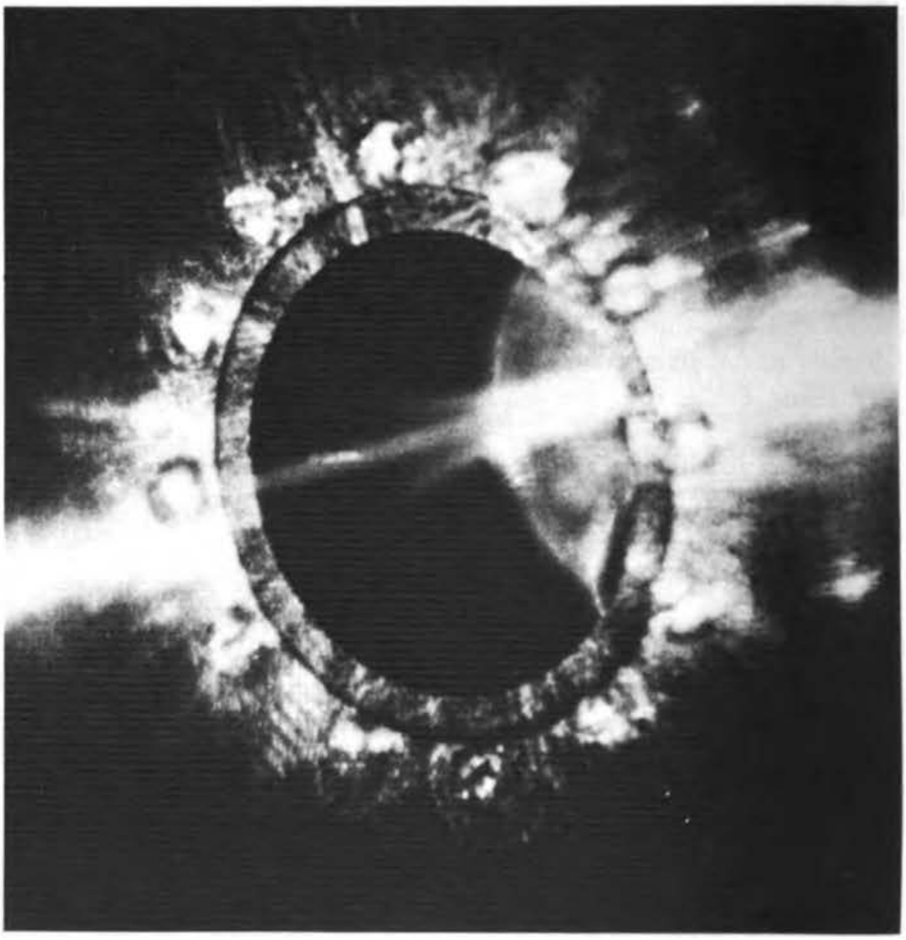
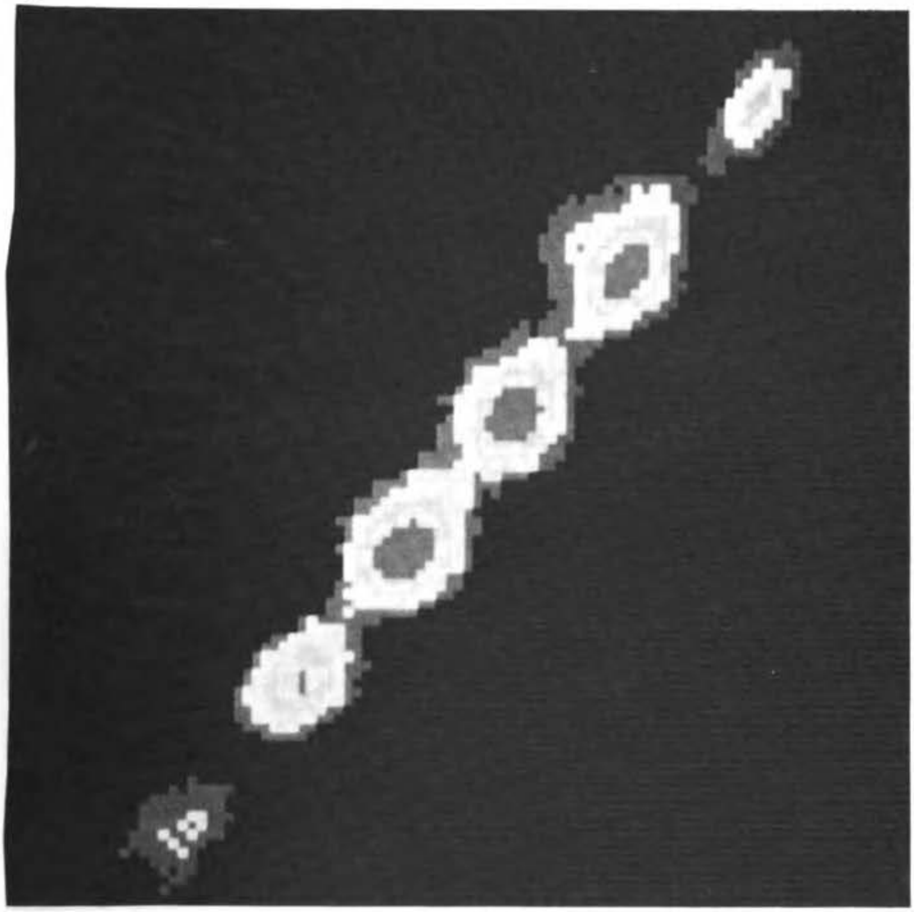


Figure 26.



between neighboring ions here is several microns. The ability to isolate individual atoms in this fashion makes possible, for the first time, whole ranges of new experiments on the details of quantum jumps by atomic electrons, and on how the atoms respond to external forces. Under appropriate conditions, the cold trapped atoms can indeed condense into crystals that remain suspended in the optical molasses. The National Bureau of Standards group headed by Wineland, which produces arrays such as that shown in Figure 26, refers to them as pseudomolecules, although the interatomic spacings are vastly greater than those in normal molecules. Such pseudomolecules again open up entirely new domains of molecular physics to studies of unprecedented precision.

Atomic and Molecular Spectroscopy

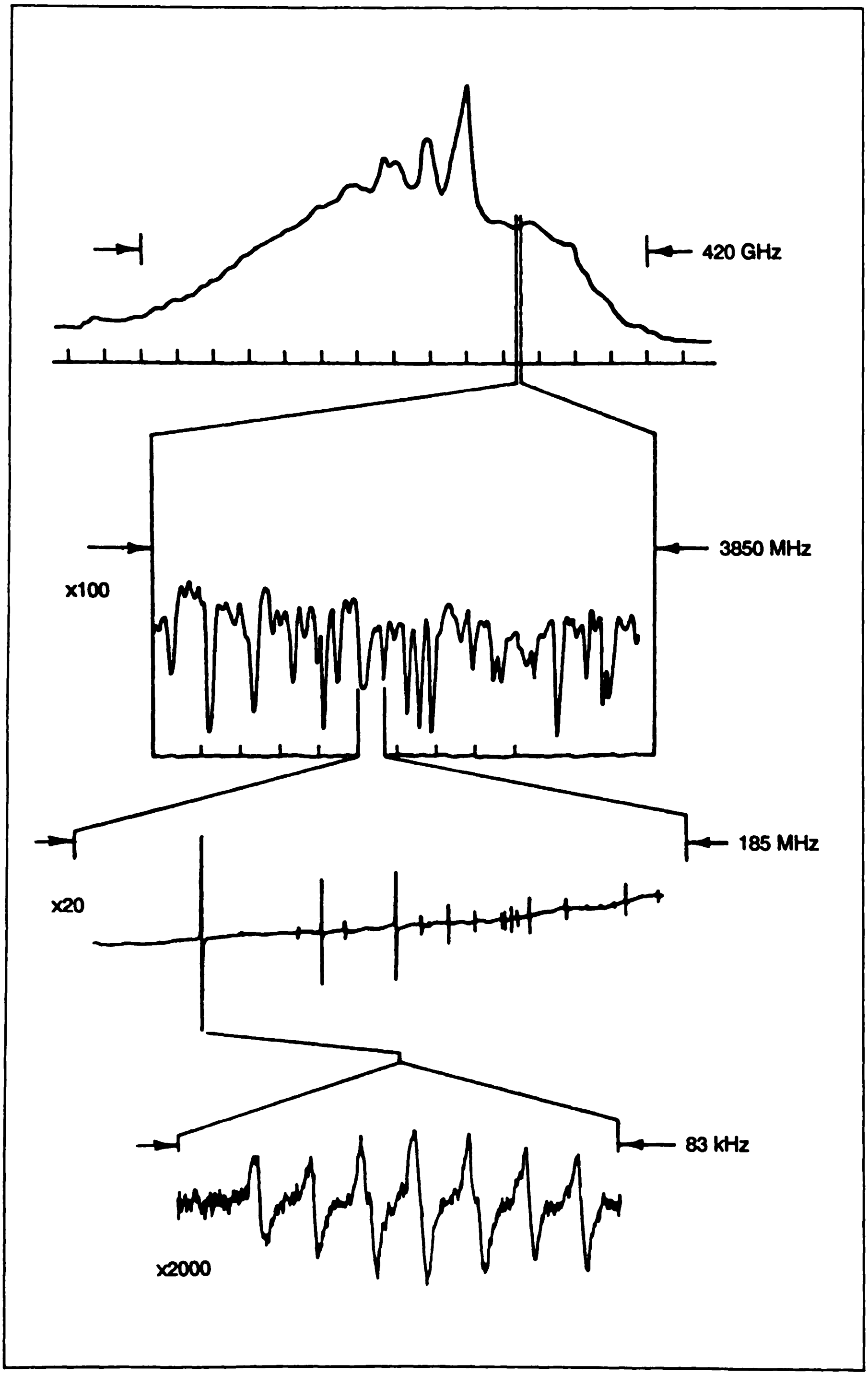
Atomic physics continues to set the standards for precision in all physical measurements. This is illustrated, for example, in Figure 27, which reflects the achievement of an improvement by a factor of more than 10^6 in precision during the past 12 years. Shown here are spectra for the sulfur hexachloride molecule. The top panel shows a conventional infrared absorption spectrum in the wavelength region of 10 microns. The next magnification below it, obtained with diode lasers, shows an expanded section; although an entirely new structure appears, the resolution is limited by doppler broadening that reflects the thermal motion of the molecules in the sample under study. In the next expansion of the spectrum, the doppler broadening has been avoided through use of saturation spectroscopy; here the resolution is limited only by the frequency instability of the laser itself. Again, however, this expansion reveals previously hidden structure in the spectrum. Finally, in the last magnification in the bottom panel of Figure 27, the jitter in the laser frequency has been sharply reduced as a result of electronic control, and the resolution in this part of the figure is typical of the maximum that can be obtained; the limitation on this resolution follows directly from the Heisenberg uncertainty principle and is fundamentally imposed by the finite time during which the molecules are held under observation. Here, again, a single sharp line in the previous magnification has been revealed to comprise a whole complex of spectral lines.

In general, atomic physics measurements are now possible to one part in 10^{15} to 10^{16}, which corresponds to measuring the distance from New York to Los Angeles within a small fraction of the diameter of a hydrogen atom. Perhaps even more remarkable, quantum electrodynamic (QED) calculations are still able to reproduce the experimental data at this level of precision.

The X-Ray Laser

Because of its enormous potential in holography of biological systems, in lithography in integrated circuit production, as a tool in fundamental spectroscopy, and, of course, in military applications, the search for an x-ray laser has been in progress almost since the discovery of the laser itself. In 1985, Mathews and his Livermore group reported the first definite evidence for lasing in the soft x-ray wavelength range. In these studies, two very high power laser beams (5×10^{13} W/cm^2) vaporized a selenium foil, creating a plasma of neon-like ions that were subsequently excited by collisions with electrons in the plasma. Subsequent transitions between $J = 2$ and $J = 1$ states of the $2p^53p$ and $2p^53s$ levels produced amplified radiation at 20.63 and 20.96 nm as shown in Figure 28. These two wavelengths were amplified by factors of about 700, as compared to the intensity of spontaneous emission lines. It bears noting, incidentally, that the use of neon-like ions followed a suggestion of Zharikin of the

Figure 27.



Moscow Institute of Spectroscopy. Obviously this work marks only the beginning of x-ray laser exploitation, and already workers in a number of laboratories around the world have reported similar and complementary results.

High-Power Lasers

In parallel with the development of very short wavelength lasers, there has, of course, been tremendous emphasis on the development of high-power lasers at the longer wavelengths. The primary motivation here has been that of developing drivers for the inertial confinement thermonuclear fusion program and more recently, again, for military applications. Here again, the experimental facilities are of impressive size. Figure 29 shows an overview of the NOVA laser system at Livermore, currently the world's most powerful such installation. It comprises ten parallel 400-ft glass amplifier chains and, as indicated above, produces power densities on target in the 10^{13}-W/cm^2 range. Figure 30 is a streak camera

Figure 28.

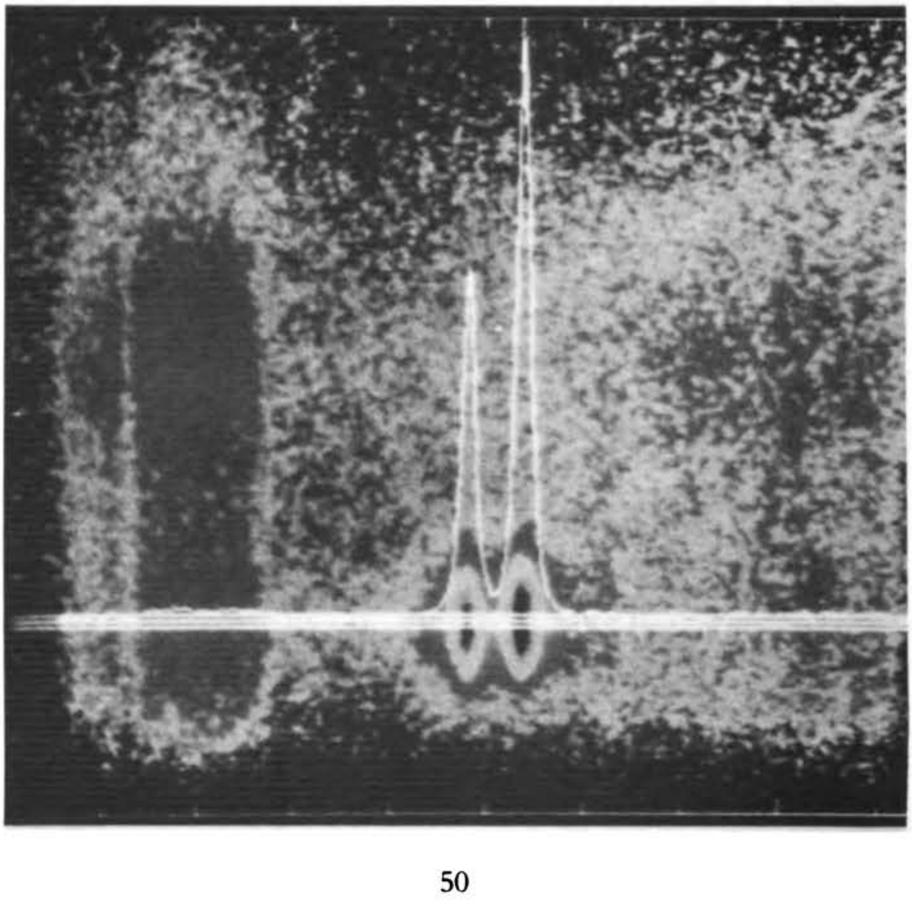
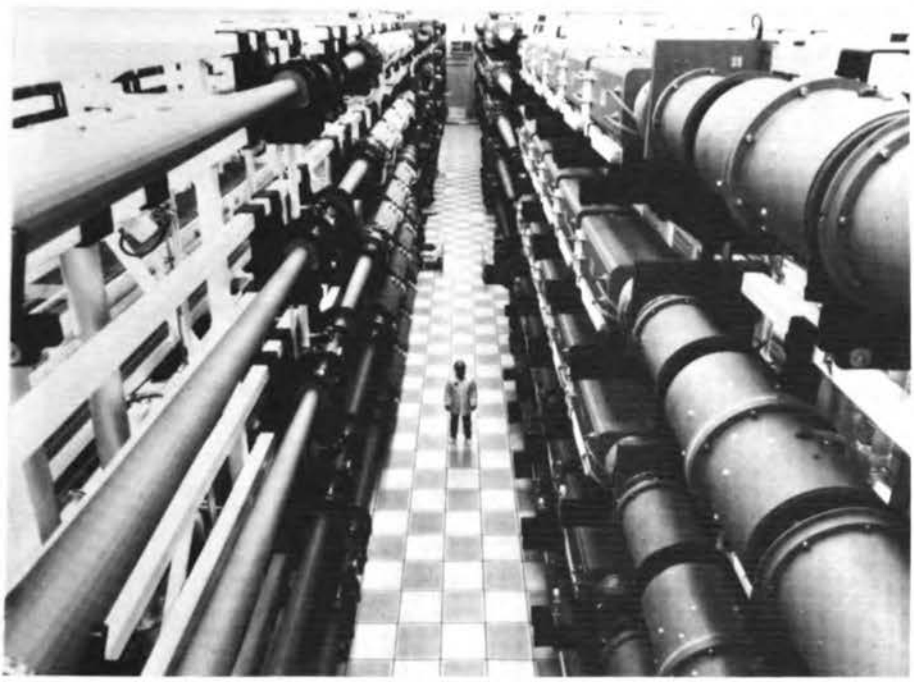


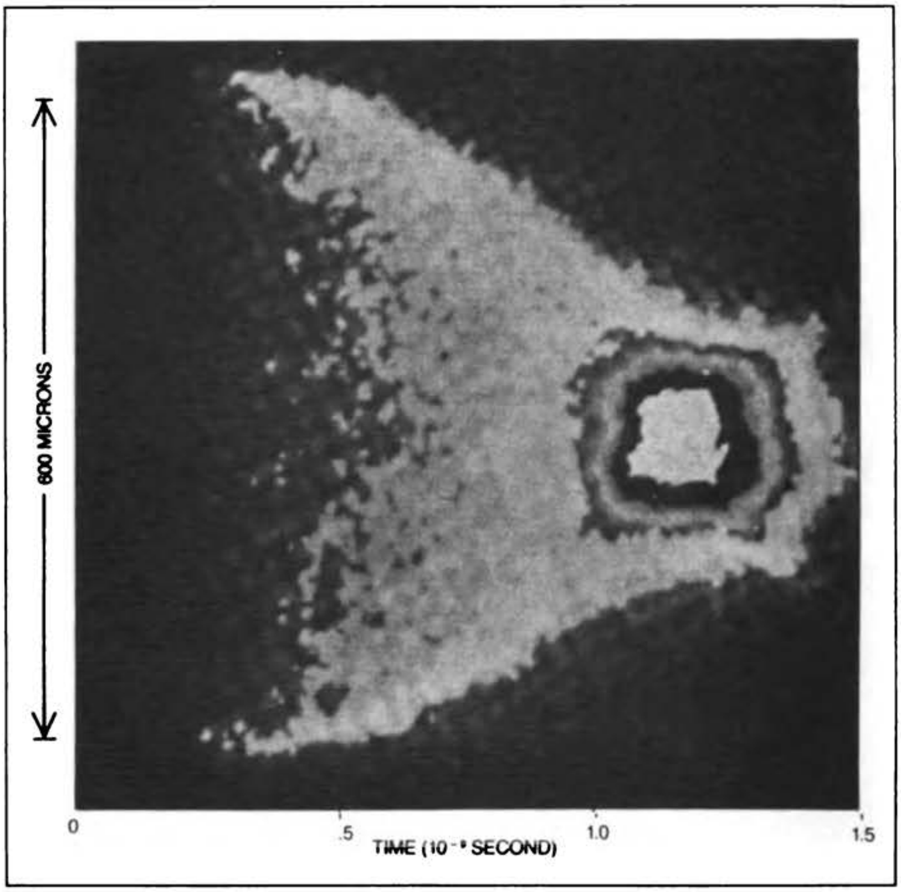
Figure 29.



photograph showing the compression and ultimate ignition of a glass microballoon target of deuterium and tritium obtained with the OMEGA high-power laser at the University of Rochester. Such direct coupling of the laser beam to the fusion target was one of the original approaches to inertial confinement and is still being investigated actively at Rochester and elsewhere.

An alternate indirect approach, wherein the laser energy is delivered into a high atomic number cavity (hohlraum) surrounding the fusion target itself so that the resulting soft x-rays from the laser bombardment of the hohlraum in turn compress and ignite the target, is also under active study. Although much of this work remains classified for military reasons, even in 1984, as shown in Figure 31, the Japanese were already publishing data on this approach. Currently in the open literature, the highest temperatures and power densities have been reported by Tsahiris et al. in Europe, using 300-ps pulses of 1.3-nm light from the Asterix III iodine laser into gold cavities from 250 to 1000 nm in dimension to yield power densities of about 3×10^{13} W/cm^2. Recently this group has reported power densities of 4×10^{15} W/cm^2 corresponding to an effective temperature of 5×10^6 K. In this area of high-powered lasers, McCrory and his collaborators at Rochester have developed a broad array of new measurement technologies, including electrooptical sampling devices that

Figure 30.

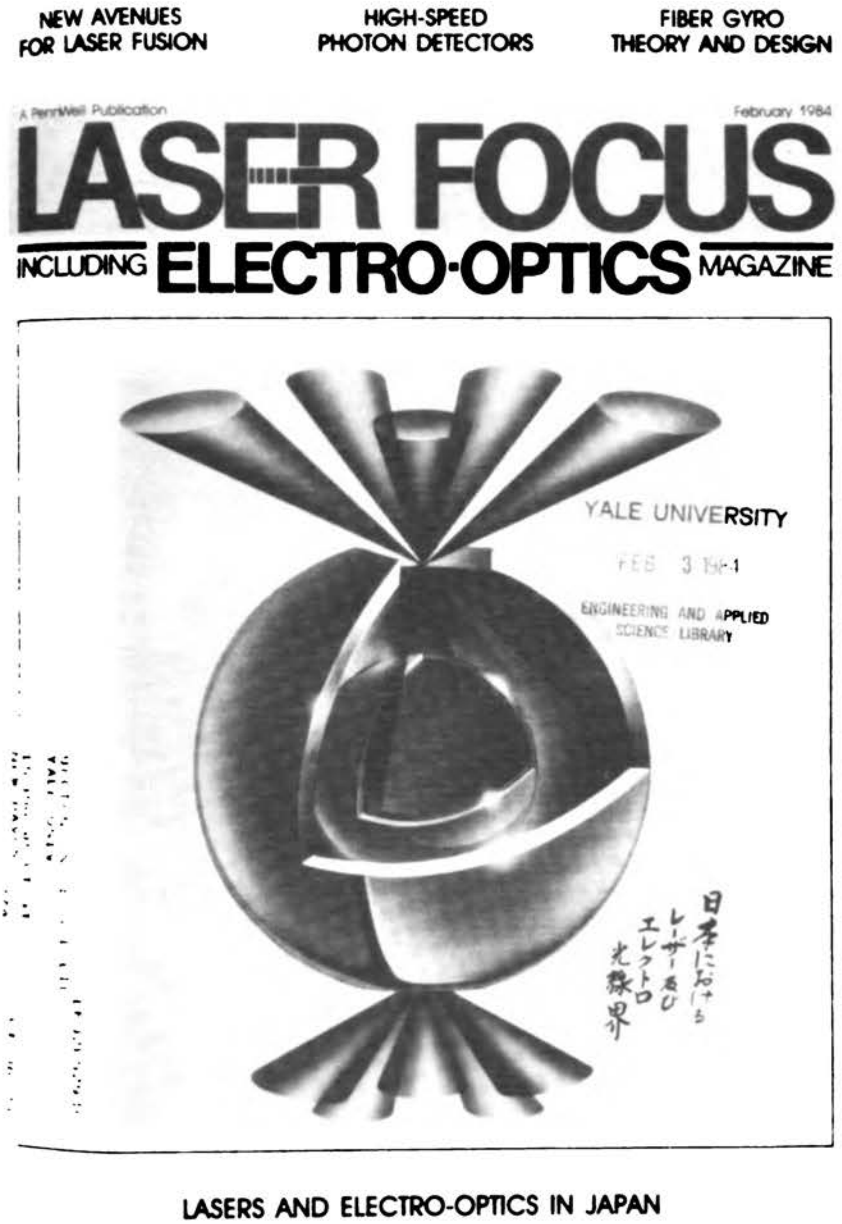


are capable of measuring transient electronic signals with 100-fs (10^{-15} s) resolution—an improvement by a factor of more than 100 on preexisting state-of-the-art devices. They have also developed a so-called chirped pulse laser amplification system that is capable of power densities of 10^{18} W/cm^2. Chirped pulse amplification expands and compresses the duration of short laser pulses using optical fibers and diffraction grating techniques.

The Free Electron Laser

Obviously of great interest at the present time is the free electron laser. Since its development by Madey at Stanford many years ago, it has remained an attractive candidate for high-power laser applications, but until very recently, none of the devices was able to convert more than 5 percent of the electron beam power into microwave radiation. Recently

Figure 31.



NEW AVENUES
FOR LASER FUSION

HIGH-SPEED
PHOTON DETECTORS

FIBER GYRO
THEORY AND DESIGN

A PennWell Publication

February 1984

LASER FOCUS
INCLUDING ELECTRO-OPTICS MAGAZINE

日本における
レーザーおよび
エレクトロ
光線界

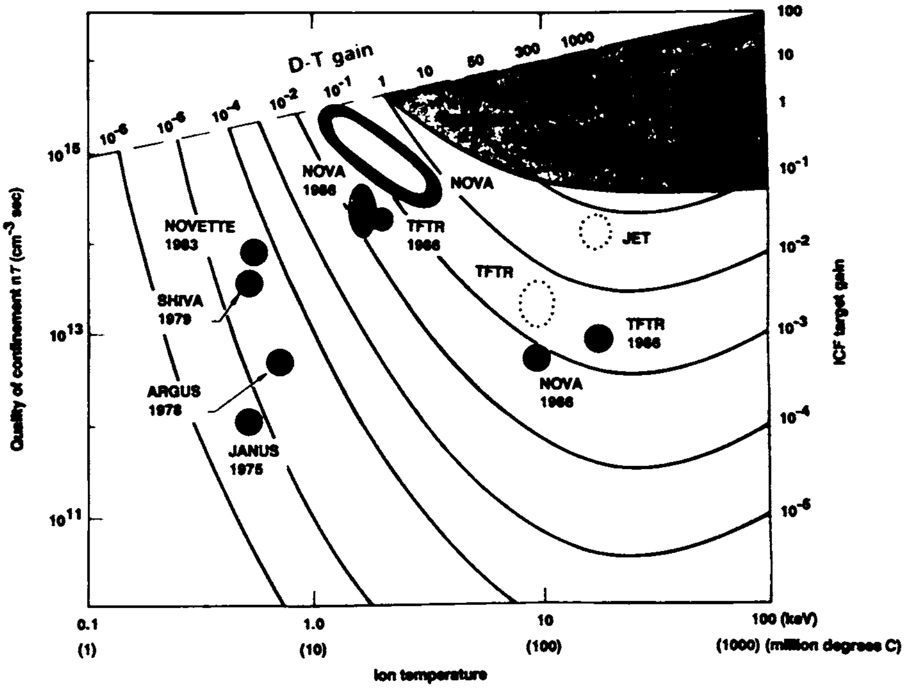
LASERS AND ELECTRO-OPTICS IN JAPAN

a Livermore-Berkeley team led by Andrew Sessler has made a dramatic improvement in this efficiency. By tapering the magnetic wiggler so that the resonance condition that is maintained as energy is withdrawn from the electron beam, Sessler has been able to achieve electron-to-microwave power conversion efficiencies in excess of 40 percent and has been able to obtain power amplification by more than 4 orders of magnitude in a single wiggler.

THE QUEST FOR THERMONUCLEAR POWER

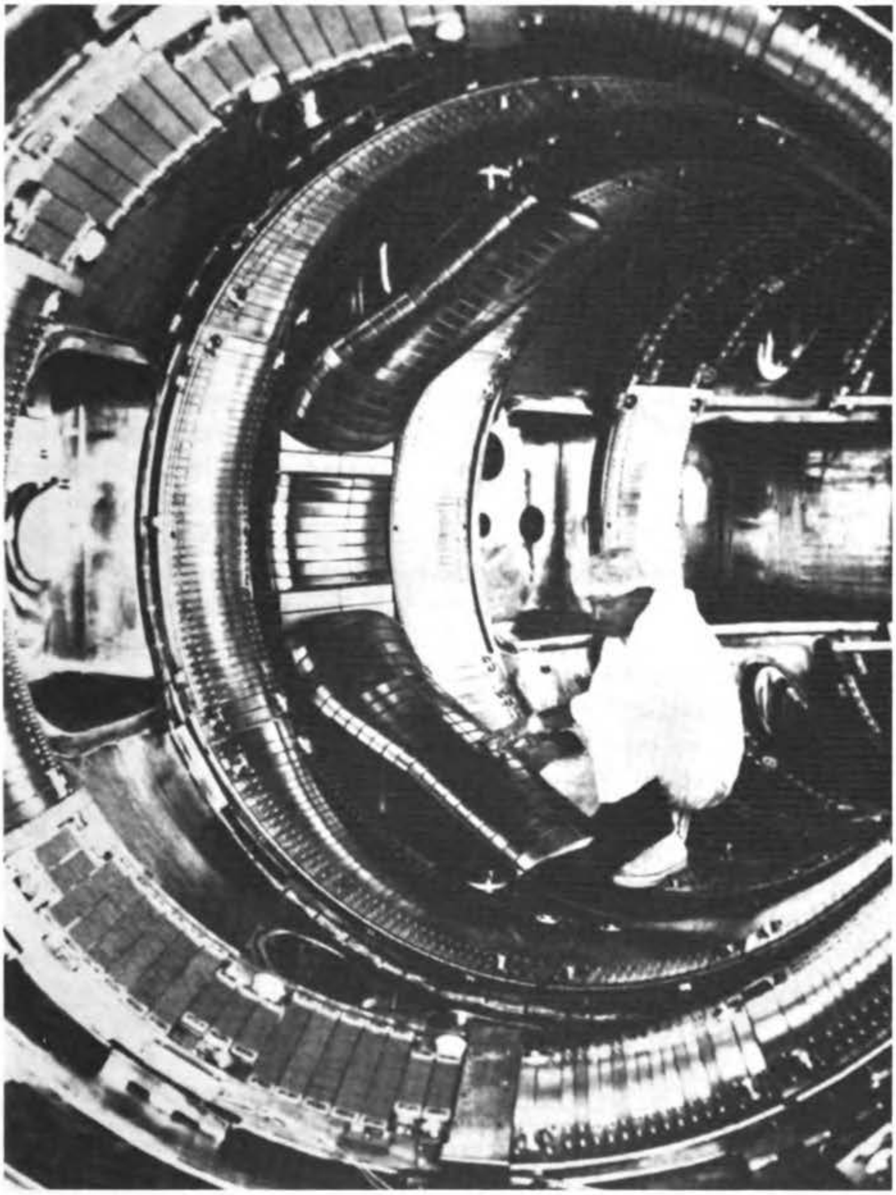
Figure 32 provides a summary overview of where we stand at the moment with respect to thermonuclear power. Here I plot the Lawson perimeter $n\tau$ versus the ion temperature. The crude measure of success in this field has traditionally been the Lawson criterion $n\tau = 10^{14}\,\mathrm{cm}^{-3}\,\mathrm{s}$. As indicated in Figure 32, none of the existing devices has satisfied all the conditions for ignition simultaneously, although several are very close to that goal, and it is expected that the goal will be comfortably achieved in unclassified work within the next year. It bears emphasis, however, that because

Figure 32.



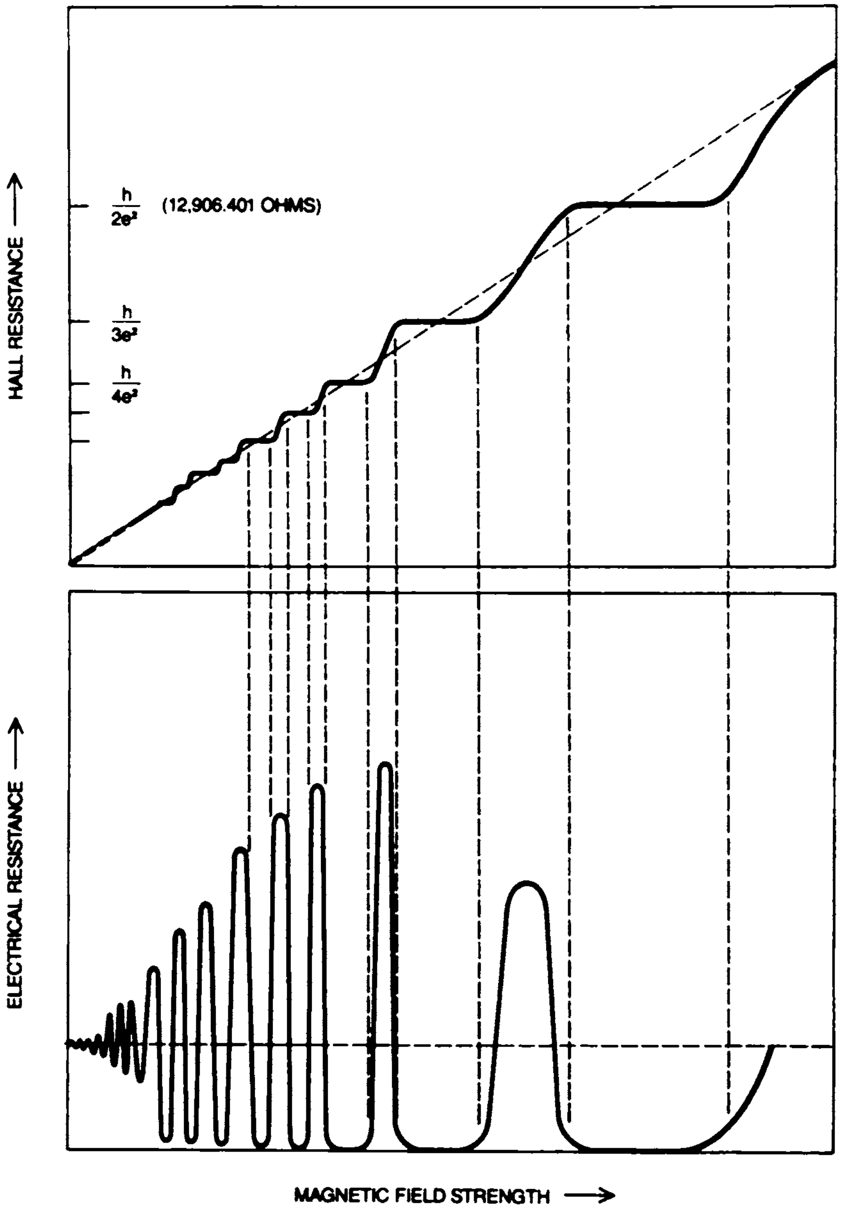
the engineering of an economically viable fusion power system will be orders of magnitude more demanding than was the case for nuclear fission, economic fusion power lies at least several decades into the future, even assuming laboratory demonstration in the coming year. Figure 33, which shows part of the TFTR Tokomak at Princeton, illustrates the complexity of the magnetic confinement systems involved, and Figure 29

Figure 33.



provides corresponding calibration for the inertial confinement systems. The fundamental engineering problem remains that thermonuclear fuel must simultaneously be compressed to over 20 million pounds per square inch and heated to over 50 million degrees.

Figure 34.



No area of modern physics has been more thoroughly studied or had more far-reaching applications than has condensed matter physics; indeed semiconductors are a hallmark of our era. But still, as in all other parts of fundamental science, even our most thoroughly studied subfields continue to provide us with surprises.

The Quantum Hall Effect

Among these recent surprises was the integral quantized Hall effect for which Von Klitzing received the 1985 Nobel Prize in physics. This effect is illustrated in Figure 34; the quantized Hall effect appears as plateaus in the Hall resistance of a sample (top panel) that coincide with the disappearance of the sample's electrical resistance (bottom panel) as the applied magnetic field is increased. At each plateau the Hall resistance is precisely given by h/ne^2 where n is integral and thus provides a new approach to the determination of Planck's constant h and the electronic charge e as well as a very convenient calibration technique in ultraprecise measurements.

It has been possible to understand these phenomena in terms of the systematic lowering of the Fermi level in the sample relative to its Landau bands; localized states created by the presence of impurity atoms in the sample are crucial to this understanding since they act as electron reservoirs, so that over a range of magnetic fields the extended states in the Landau band are either completely empty or completely filled.

The fractional quantum Hall effect is more complex. For example, when the lowest Landau band is one-third filled, a plateau is observed experimentally where the Hall resistance equals $3\ h/e^2$. In order to understand this special stability of fractionally filled bands, it has been necessary to include explicitly the electron-electron interactions and to use a wave function that depends simultaneously on the positions of all particles in the system.

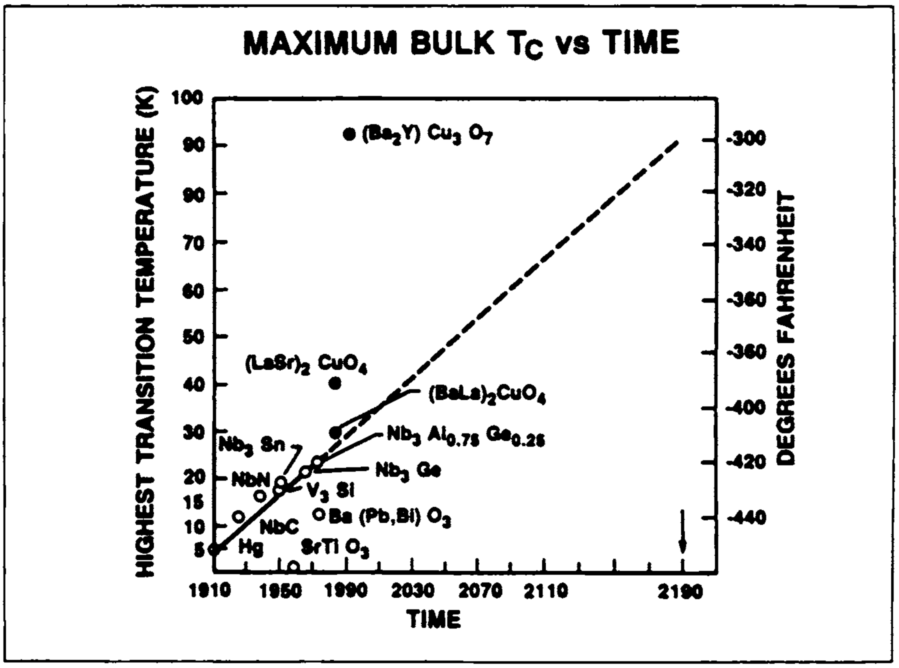
In 1983 Laughlin succeeded in constructing, for the first time, a wave function with the required stability when the fraction of filled states had values such as 1/3, 1/5, 2/3, 4/5, and 6/7, that is, the reciprocal of an odd integer of 1 minus such a fraction. It is an interesting prediction of such a model that if one adds an extra electron to a system in which the Landau level is 1/3 full, the extra charge should appear in three distinct places in the sample, and at each place precisely 1/3e should appear. These fractional charges, now called quasiparticles, behave very much like normal charged particles, and it is their behavior that is now believed to underlie the fractional Hall effect.

High-Temperature Superconductivity

Without doubt, however, the most dramatic development in condensed matter science during the past two years has been the discovery of high-temperature superconducting materials. The phenomenon of superconductivity, as noted above, was discovered by Kammerlingh Onnes in 1911, but only at very low temperatures. As shown in Figure 35, the highest transition temperature T_c) attainable increased more or less linearly with time over the intervening 75 years, and a great many physicists had concluded that the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity limited the maximum attainable transition temperature to something less than 30 K. Extrapolation of this 75-year history—as shown in Figure 35—would have suggested that a T_c of 90 K would not have been attained until something like the year 2190—if ever!

When the discovery of high-T_c superconductivity was first made public at the Materials Research Society meeting in Boston in December 1986, not only was it one of the greatest surprises in several decades of modern physics but it also touched off a firestorm of speculation and excitement concerning potential applications. The statement that its consequences would far outdistance those following on the discovery of the transistor was among the milder ones. Much of this initial euphoria has evaporated, but this in no way diminishes the importance of the discovery

Figure 35.



or, in the longer term, its potential consequences.

Figure 36 emphasizes, first of all, that the early story of high-T_c superconductivity is truly an international one, and one that does not depend on the availability of huge machines or large groups. The original focus on a ceramic appears to have come from work of Michel and Ravenau in the early 1980s at the University of Caen in France; in 1983 this was picked up by Mueller of IBM (Zurich) while he was reading in a monastery garden in Sicily. Returning to Zurich, Mueller teamed up with Bednorz and found that a lanthanum-barium-copper ceramic gave evidence of superconductivity at 35 K—higher than any other previously reported. Mueller and Bednorz published their results in *Zeitschrift fur Physik* in mid-1986 but stirred up relatively little interest except in the laboratories of Tanaka in Tokyo and of Chu in Houston. All three groups, at Zurich, Tokyo, and Houston, reported their latest results on December 18, 1986, on the last day of the Materials Research Society meeting, and by the following day literally hundreds of laboratories worldwide were attempting to fabricate and study the new ceramics. By January 28, 1987, Chu and his colleagues had reported superconductivity at 93 K in a ytterbium-barium-copper oxide ceramic. These results were followed quickly by reports of bismuth compounds discovered in Japan and thallium compounds discovered in Arkansas; the 125-K transition

Figure 36.

HIGH-TEMPERATURE SUPERCONDUCTIVITY

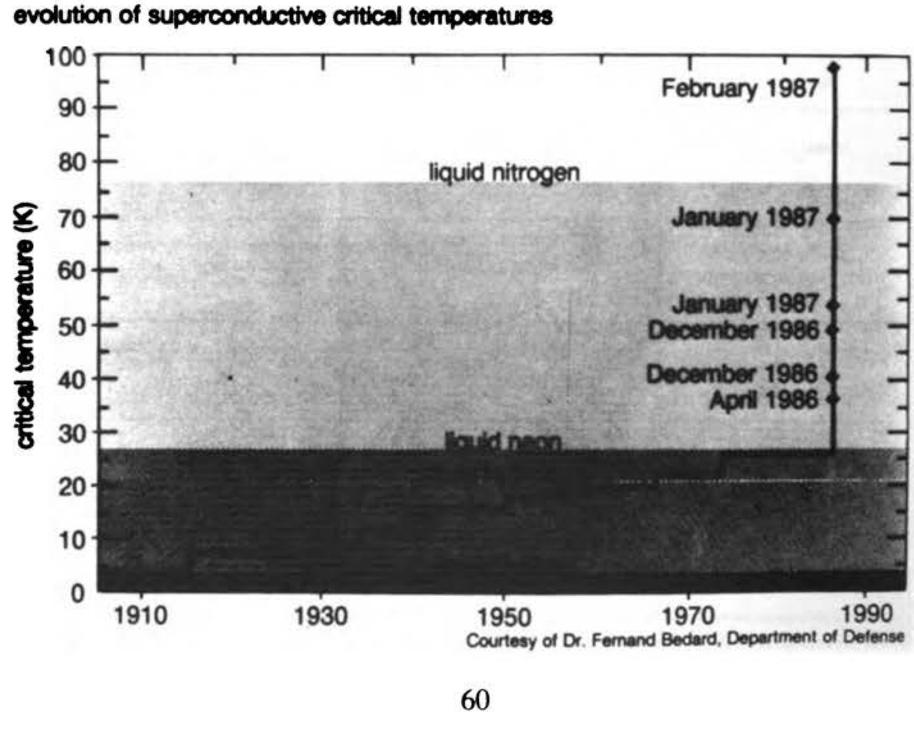
Material	Discovery	Rapid Follow-Upon Discovery
$(LaBa)_2CuO_4$ 30K	IBM (Zurich)	Tokyo, Houston, AT&T, Bellcore
$Y_1Ba_2Cu_3O_7$ 90K	Houston	Beijing, Tokyo, Bellcore-NRC (Can.) AT&T, Argonne, IBM
Bismuth Compounds 85-106K	Tsukvba Ibaraki	Houston, Dupont, Bellcore-NRC (Can.) AT&T, IBM
Thallium Compounds 106-125K	Arkansas	IBM, Dupont, Nat. Geophys. Lab Johns Hopkins, Sandia
$La_2Sr_1Nb_5O_{10}$ (225K)	Kagoshima	

temperature obtained in multilayer samples of the thallium compounds is the highest value yet confirmed widely in the field.

The lowest entry in this table was reported by Ogushi and his collaborators at Kogoshima University in Japan. It is doubly interesting, first because it has by far the highest transition temperature reported where both resistivity and Meissner effects have been available for publication, and second because it replaces the otherwise ubiquitous copper with niobium. This would have very important practical consequences inasmuch as it is impossible to hot press any of the copper oxide ceramics into copper matrices—the traditional technique used with all low-T_c superconductors—to obtain actual cables suitable for magnet winding and other uses without reducing the copper oxide and thus destroying the superconductivity. This would not be a problem with a niobium compound. Unfortunately, however, despite repeated attempts, no other laboratory has yet been able to reproduce the Kagoshima results.

One of the interesting features of Figure 36 is the fact that after the original IBM Zurich discovery, subsequent discoveries have originated in universities where the research programs have emphasized wide-ranging exploratory searches for new materials, whereas the detailed and rapid follow-up research emphasizing the characterization and understanding of each new class of materials has involved the industrial laboratories

Figure 37.



Courtesy of Dr. Fernand Bedard, Department of Defense much more heavily. I would argue that this reflects in part, at least, the fact that the industrial laboratories involved have substantially more modern and complete instrumentation than do the universities.

Figure 37 provides another view of the evolution of the critical temperatures of these new superconductors and emphasizes the dramatic progress made during the past two years. This figure also makes very clear the fact that the new ceramic superconductors require only liquid nitrogen cooling as opposed to liquid helium cooling. The economic benefits become clear when it is recognized that liquid nitrogen currently costs approximately $0.22 per gallon in the United States as compared to about $5.50 per gallon for liquid helium; it is perhaps easier to remember that the ratio of these costs is roughly that between the cost of a local beer and the cost of a premium whisky!

It is a well-established rule of thumb that for reliable operations, superconductors should be used at temperatures less than 0.75 T_c, so that a liquid nitrogen coolant system at 77 K really requires $110 \leq T_c \leq 115$ K. Fortunately, the multilayer thallium ceramics meet and exceed this requirement, although the original 123 copper oxide compounds do not.

Critical magnetic fields also pose no problem with the ceramic superconductors inasmuch as values ranging from 30 T along the c axis to 150 T along the a or b axes are reported at 4.2 K. The mechanical stresses associated with confinement of such fields, particularly in the geometries required in actual applications, considerably exceed the yield or crushing strength of any known materials, so that in effect the critical fields of the ceramic superconductors already exceed by large margins any values that might be usable in the foreseeable future.

Where the problem lies is in the area of critical current densities. These are very orientation dependent (by factors of up to 20) as well as magnetic field dependent and initially were found to be orders of magnitude smaller than those of the low-temperature superconductors in common use, such as NbTi and Nb_3Sn.

Figure 38 shows schematically the current density behavior required for a number of potentially important applications. For comparison, the shaded band shows the behavior of conventional low-temperature superconductors and the solid lines the current behavior of polycrystalline and single-crystal high-temperature ceramics.

This field of high-temperature superconductivity is one that has received an enormous amount of media attention during the past two years. Figure 39 is my own listing of potential applications in what I would consider the most probable ordering in terms of immediacy. Major progress is already being made in applications in computer interconnections and Josephson junction devices and in semiconductor-superconductor hybrids. Indeed, the Nevada-California Bi-State

Commission expects to select a supplier for a magnetically levitated train system for the 230-mile link between Los Angeles and Las Vegas by 1992 and will have it in operation by 1996. The anticipated travel time is 1.25 hours and the cost $2.5 billion as compared to a 2.15-hour travel time and a cost of $2.1 billion for the nearest competitor, the French TGV unit. Figure 40 is an image of the cross-section of the head of a child obtained at Loma Linda University in California using a 1-T superconducting magnet in a nuclear magnetic resonance (NMR) arrangement. Although currently all such images are based on the hydrogen content of the target, the availability of higher fields will make it possible to isolate and image other nuclei as well. At 8.4 tesla, for example, while the hydrogen nucleus resonates at 360 MHz, phosphorus resonates at 146 MHz and ^{13}C at 90 MHz. Because the exact resonance frequency depends on the detailed chemical and molecular environment in which the resonating nucleus finds itself, this technique makes possible not only the location of specific nuclei but frequently also the molecule in which they are bound. As a noninvasive and harmless technology, NMR permits studies of the metabolism of living systems that were previously entirely inaccessible, quite apart from its enormous importance in diagnostic medicine.

Figure 38.

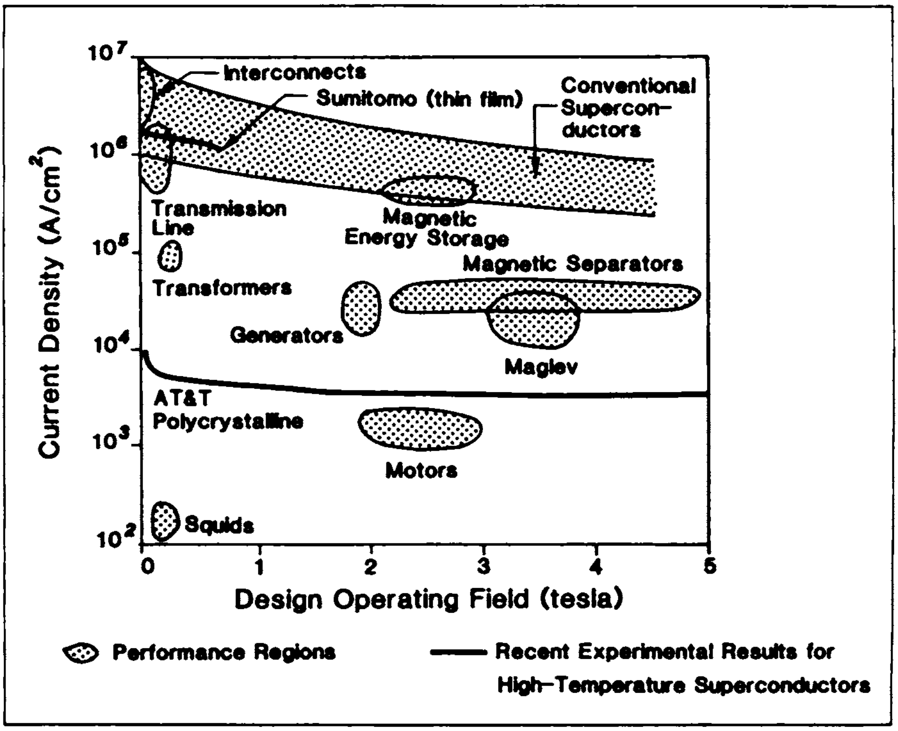


Figure 39.

SUPERCONDUCTIVITY APPLICATIONS

- Computer interconnections
- Josephson junction devices
- Semiconductor–superconductor hybrids
- Nuclear magnetic resonance imaging
- Underground electrical transmission cables
- Electrical energy storage
- Large electrical generators and motors
- Electrically powered automobiles
- Magnetically levitated trains

Annual worldwide sales of superconducting devices currently amount to about $400 million, and of this amount NMR devices and electronic instrumentation each account for about $150 million.

Predictions regarding the size of the future market in this area vary widely depending on the degree of optimism of those making the predictions. Figure 41 shows a compilation of recent Japanese predictions as to the probability of achieving a variety of applications within a ten-year time horizon and the predicted value of the application once implemented. U.S. estimates would be significantly more pessimistic.

Tailored Materials

In a very real sense we have entered the era of tailored materials. We can now fabricate solids and surfaces with desirable properties that in the past were simply unattainable. A good example is in the area of ion beam mixing. Many alloys that would be predicted theoretically to have desirable properties—the A-15 ones in conventional superconductivity, for example—cannot be fabricated with any of the standard techniques. By laying down alternate or sequential layers of the desired materials in the final alloy in the desired relative amounts and then subjecting the resulting layered structure to ionic bombardment, the heating along the ionic tracks mixes the components intimately, but there is no opportunity for segregation or separation before the alloy freezes. This is of growing importance in the fabrication of corrosion- and wear-resistant surfaces as well as catalytically active surfaces. Production of solid superlattices using molecular beam epitaxy techniques is now well established, and for the first time it has been possible to actually fabricate the quantum wells that occupy the first chapters of all quantum mechanical textbooks and to experimentally study their characteristics. In such structures, quantum-size effects are observed as the thickness of the layers in which the charge carriers are confined becomes smaller than the Bohr radius of the atoms involved. As a consequence, the electronic properties of the layered quantum-well materials are entirely different from those of bulk material of the same overall composition. Quantum wells are already in use in new laser systems, in nonlinear optical elements having very large susceptibility at room temperatures, in optical modulators, and in so-called self-electrooptical devices (SEED) based on the quantum confined Stark effect (QCSE).

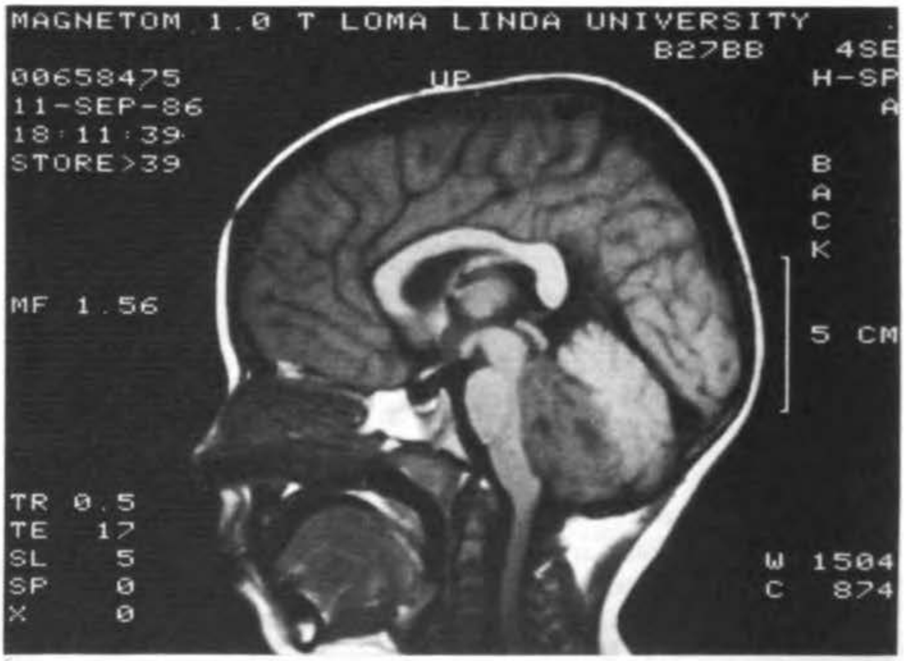


Figure 40.

Figure 41.

Predictions on Probability and Profits

Applications	Probability in 10 years (%)	Predicted value ($ million)
magnetic levitation railway	100.0	4,000.00
NMR-CT	100.0	303.00
free electron laser	100.0	120.00
SQUID	100.0	58.40
compact cyclotron	100.0	43.20
large-scale particle accelerator	100.0	17.60
thin film target materials	100.0	8.00
zero-resistance circuit boards	95.0	801.00
electromagnetic launching equipment	95.0	7.60
compact SOR	90.0	509.00
magnetic shields	90.0	72.09
oscilloscopes	90.0	14.40
ultraviolet sensors	80.0	6.40
magnetic separation equipment	75.0	120.00
large-scale electric power storage	70.0	2,168.00
standard voltmeters	65.0	0.70
electric power generators	56.0	35.60
zero-resistance LSI circuitry	55.0	507.80
motors	52.5	59.20
electric power lines	52.5	21.00
supercomputers	50.0	1,385.00
power generators	50.0	20.00
superconducting LSIs	45.0	254.56
magnetic propelled ships	30.0	1,200.00
magnetic energy storage	25.0	6.20
transformers	25.0	6.00
electric automobiles	20.0	640.00
electric ships	10.0	8.00
modulators, demodulators	0.0	0.00
electron scanning microscopes	0.0	0.00
home power storage	0.0	0.00
low-loss communications cables	0.0	0.00
total		12,392.75

exchange rate: Y125/$

NMR-CT: nuclear magnetic resonance computerized tomography
SQUID: superconductive quantum interference device
SOR: synchrotron orbit radiation

Use of Ion-Optical Systems

In addition to fabricating microstructures, we have learned how to use ion and electron beams to carve the desired structures from bulk material. The level of precision attained here is illustrated, for example, by Figure 42 from the work of Wolf and his collaborators at the Cornell National Research and Resource Facility for Submicron Structures. In the upper panel of this figure an intact tobacco mosaic virus is shown at the same magnification as the pattern below it, which was etched directly into a sodium chloride film with a 100-keV focused electron beam. The width of the lines in the pattern is less than 2 nm, and the degree of control of the electron beam at this scale is well illustrated by the precision with which the letters have been etched. The nanometer scale for the entire photograph is shown at the lower right; the magnification is approximately ×500,000.

Such precision is, of course, essential as we move forward to larger-scale integration in electronic circuitry and as we move from surface structures to three-dimensional ones built into the crystal substrate itself. It bears emphasis that in 1960 we could put one active electronic element on a typical silicon chip; in 1970, 10^3; in 1980, 10^6; and there are no immediate physical limitations that will prevent the placing of 10^9 elements on a single chip before the end of the present decade. The significance of this is widely misunderstood, however. The important parameters are cost, reliability, and energy efficiency—not size. Once in production, the modern chips are not much more expensive than were the original ones in 1960; either the chip works, and if it does it works essentially indefinitely, or it is discarded; and the very low input energy requirements of the modern chips make it possible to assemble systems of unprecedented complexity, sophistication, and speed without danger of their simply melting from the waste energy involved. Simple extrapolation of current technique suggests that by the year 2020 it will be possible to put some 10^{13} active elements—roughly equivalent to the number of synapses in the human brain—in a volume that is comparable to, or less than, that of the brain. We have not even begun to appreciate what the economic, societal, and military consequences of such development might be, and I have noted elsewhere that the morning when the average citizen awakes to find that his toaster is smarter than he is will be, at the very least, disquieting!

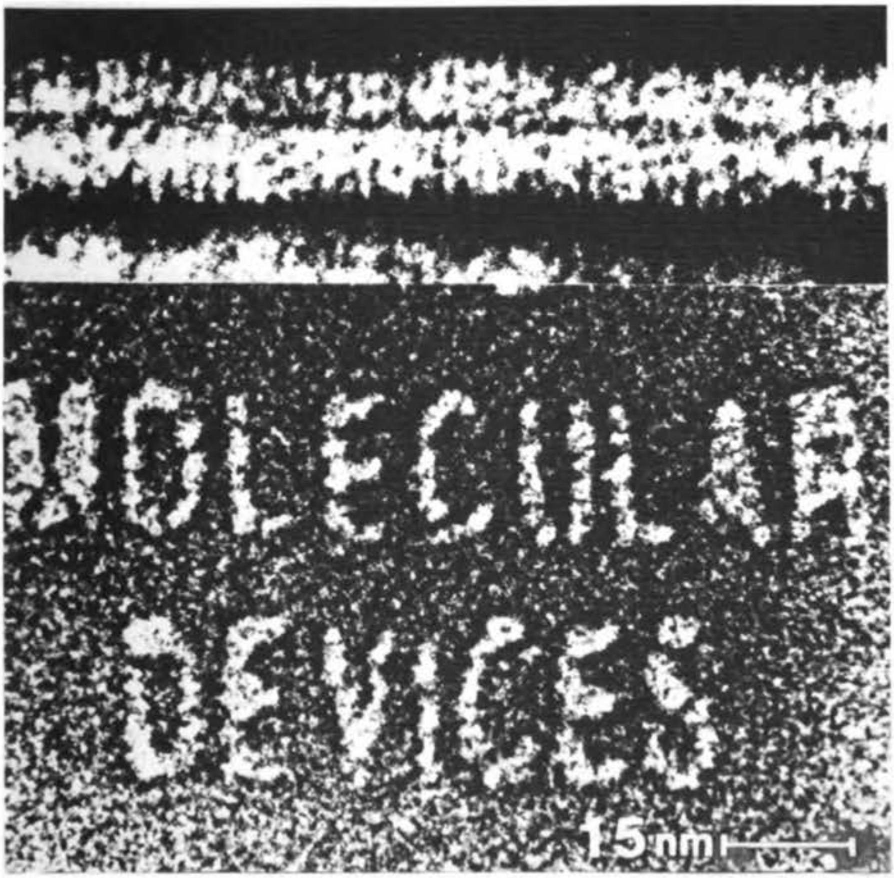
High-Temperature Materials

One of the major challenges currently facing condensed matter physicists and material scientists is that of improving high-temperature performance of materials. It is a matter of record that in essentially every instance, the efficiency of industrial processes is ultimately limited by the high-temperature performance of some component. Indeed, it has been estimated in a recent Oak Ridge National Laboratory study that each degree Fahrenheit by which the operating temperature of the average U.S. industrial process can be raised will be reflected in a $1 billion annual economic return.

OPTICS

There has been a renaissance in optics in recent years, in part as a consequence of pressure from military objectives demanding large-scale optical elements. Pressure from the communication and information-handling community has led to comparable progress in the design and fabrication of electrooptical and integrated optical devices. Optical fibers

Figure 42.



have reached a remarkable degree of development, so that they now have channel capacities over 1000 times greater than do coaxial cables and require repeater amplifiers at only about 100-km intervals, as contrasted to the 3- to 4-km intervals characteristic of coaxial systems. Two of the most active and interesting new areas in optics, however, have been microscopy and adaptive optics—optical elements that change their characteristics in real time to achieve specific purposes.

The Scanning Tunneling Microscope

The scanning tunneling microscopy for which Binnig and Rohrer of IBM (Zurich) received the 1986 Nobel Prize in physics has finally made it possible for individual atoms to be visualized clearly. This is illustrated in Figure 43, which is a scanning tunneling micrograph of gallium arsenide taken along its 110 crystal plane. The large spherical objects are the gallium atoms and the smaller, lighter ones those of arsenic.

Optical Phase Conjugation

The phenomenon of optical phase conjugation was first discovered by Zeldovich and his colleagues at the Lebedov Institute in Moscow. An intense ruby laser beam had been smeared by passage through a frosted plate and then transmitted down a long tube filled with high-pressure methane. What was observed was that the stimulated Brillouin scattering in the gas scattered photons back through the frosted plate, with the methane acting as a most unusual mirror; to their amazement, Zeldovich and his colleagues saw that the reflected wave, after its second passage through the frosted glass, formed an essentially perfect, distortion-free image of the source. The distortions introduced by the first passage through the frosted glass had been cancelled out in the second. This was in 1972.

Since then, active research on this phenomenon has been driven by the desire to use it in eliminating distortion in optical transmission through turbulent media, such as the earth's atmosphere, and in optimizing performance of optical devices generally. Obviously there are very important military applications here. Figure 44 illustrates the use of a phase-conjugation mirror to restore a detailed image. In this case the image of the cat was transmitted through a frosted glass and in the top panel was reflected back through the glass by a plane mirror, whereas in the bottom panel it was reflected back by a phase-conjugation mirror. The removal of distortion from the time-reversed beam is striking. Typically one uses stimulated Brillouin scattering, as in the original Zeldovich observation, or the now familiar four-wave mixing using nonlinear media to achieve the required phase-conjugation mirror.

Figure 43.

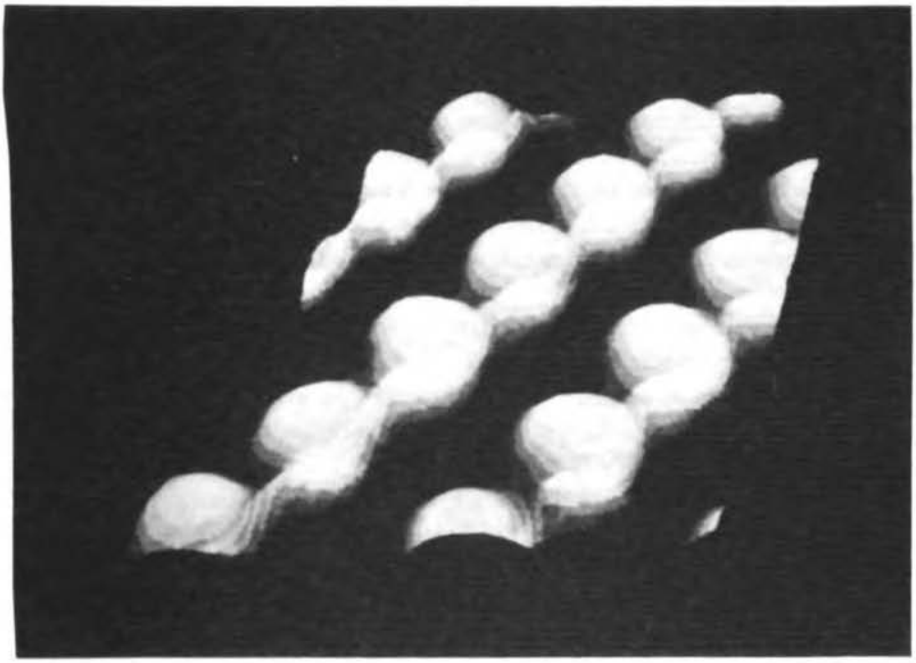
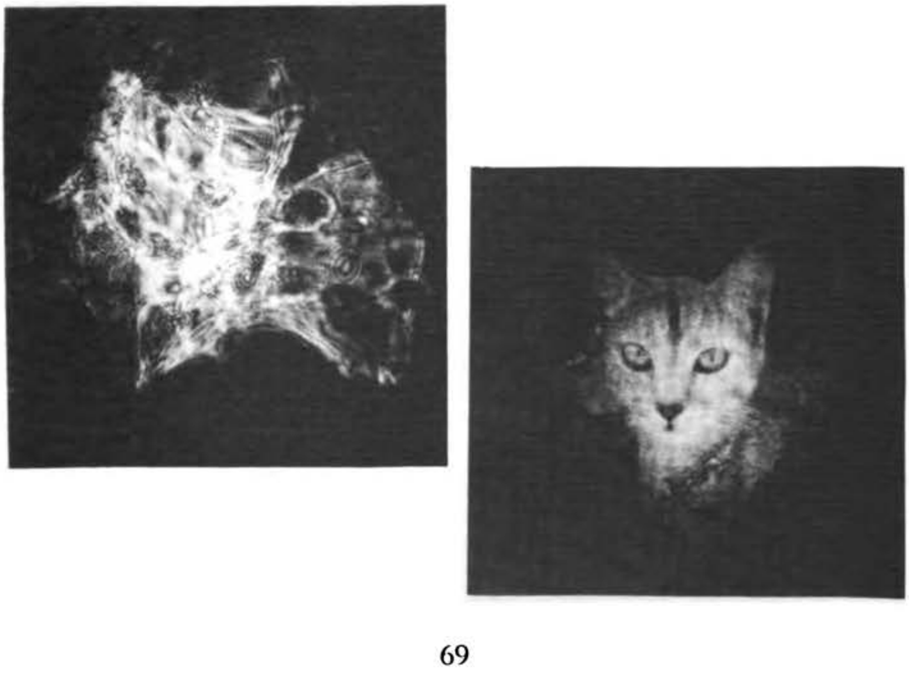
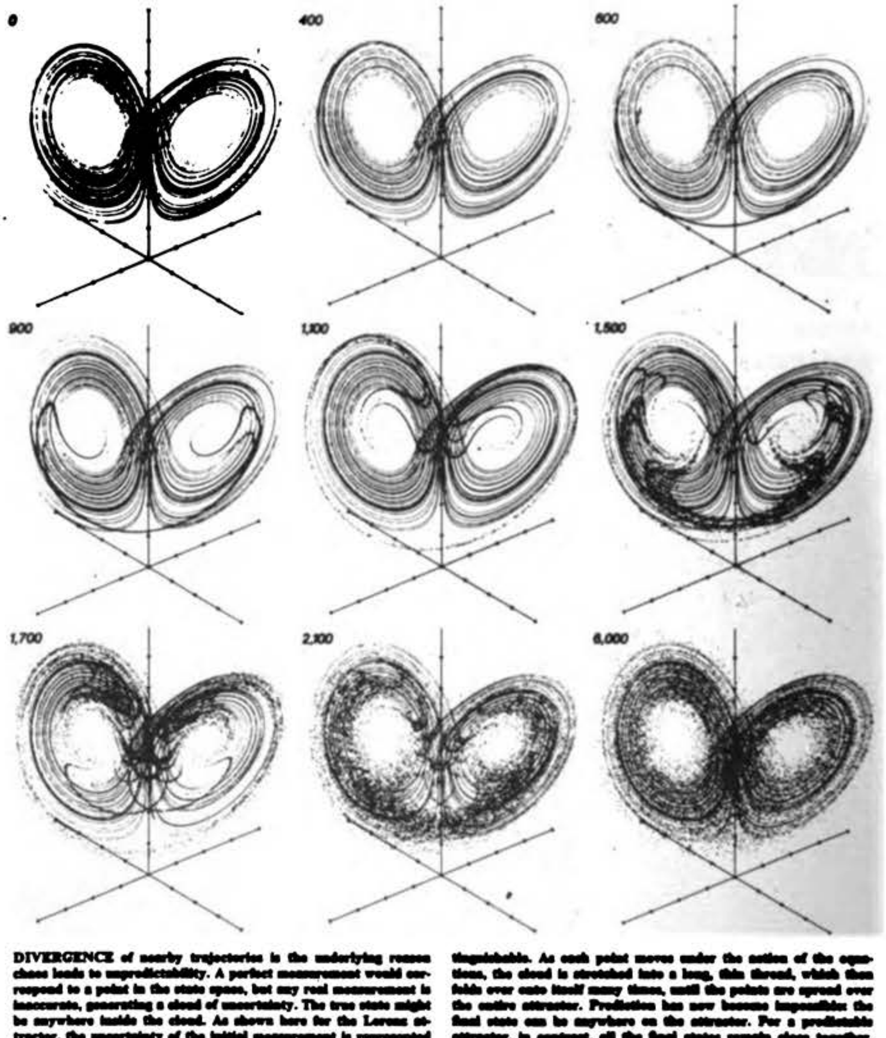


Figure 44.



One of the very surprising developments in recent years has been the recognition that there is order in chaos, that randomness has an underlying geometric form. It has been discovered that even very simple deterministic systems with very few elements have the capacity to generate random behavior of a fundamental nature—to generate chaos. In principle the future of such systems is completely determined by the past, but in practice very small uncertainties in the initial conditions become

Figure 45.



DIVERGENCE of nearby trajectories is the underlying reason chaos leads to unpredictability. A perfect measurement would correspond to a point in the state space, but any real measurement is inaccurate, generating a cloud of uncertainty. The true state might be anywhere inside the cloud. As shown here for the Lorenz attractor, the uncertainty of the initial measurement is represented by 10,000 red dots, initially so close together that they are indistinguishable. As each point moves under the action of the equations, the cloud is stretched into a long, thin thread, which then folds over onto itself many times, until the points are spread over the entire attractor. Prediction has now become impossible: the final state can be anywhere on the attractor. For a predictable attractor, in contrast, all the final states remain close together. The numbers above the illustrations are in units of 1/200 second.

amplified to such an extent that although the behavior may be predictable for short periods, over longer ones it becomes completely unpredictable.

The fact that there is order in chaos allows us to return to many problems such as turbulence, atmospheric phenomena, noise generation, the flow of blood through human heart valves, and the like—problems previously considered intractable, although nevertheless of vital importance.

Fundamental to this work has been the concept of attractors, geometric forms that characterize the long-term behavior of a system in its phase space. An attractor is the point, line, or surface in that state phase space toward which the system moves over the long term. Figure 45 shows the evolution of a particular attractor, the Lorenz attractor, in a fluid system with only three degrees of freedom. It was the first example of a chaotic or a strange attractor and was discovered by Lorenz in 1963. The study of chaotic systems is still a young field and one with enormous potential. Figure 46 shows a very simple physical situation involving both laminar and turbulent flow as well as cavitation, the sort of situation that even a few years ago would have been considered beyond the scope of realistic physical calculation but that now can be attacked effectively.

Figure 46.

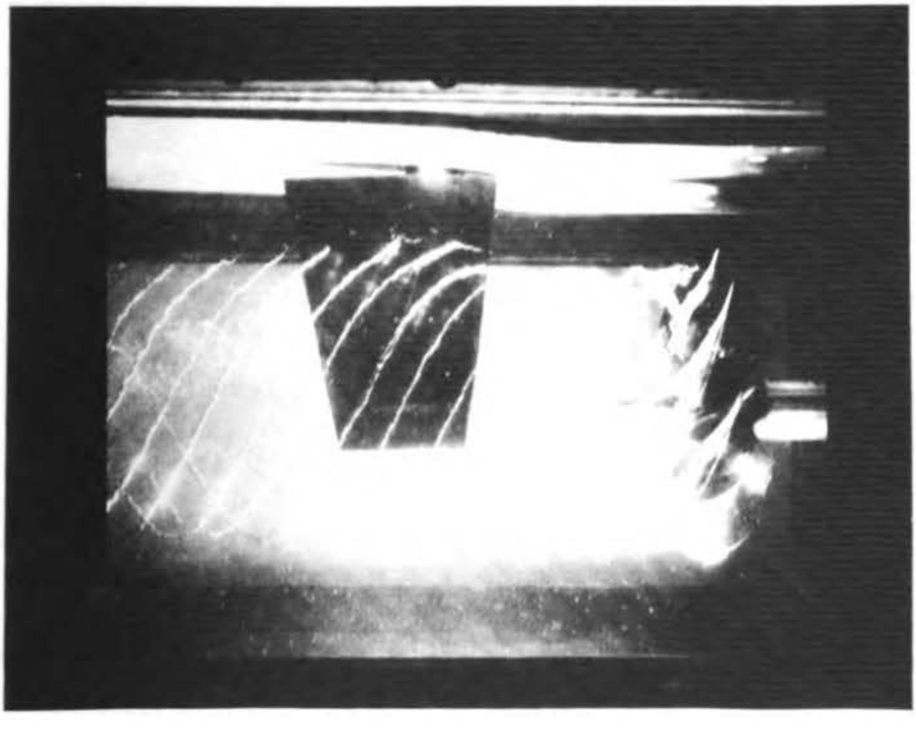
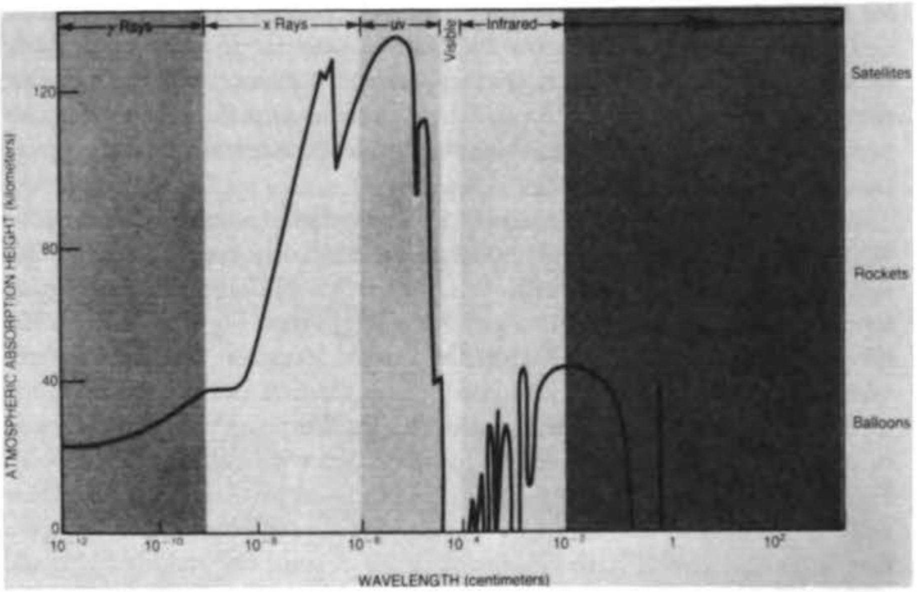


Figure 47.



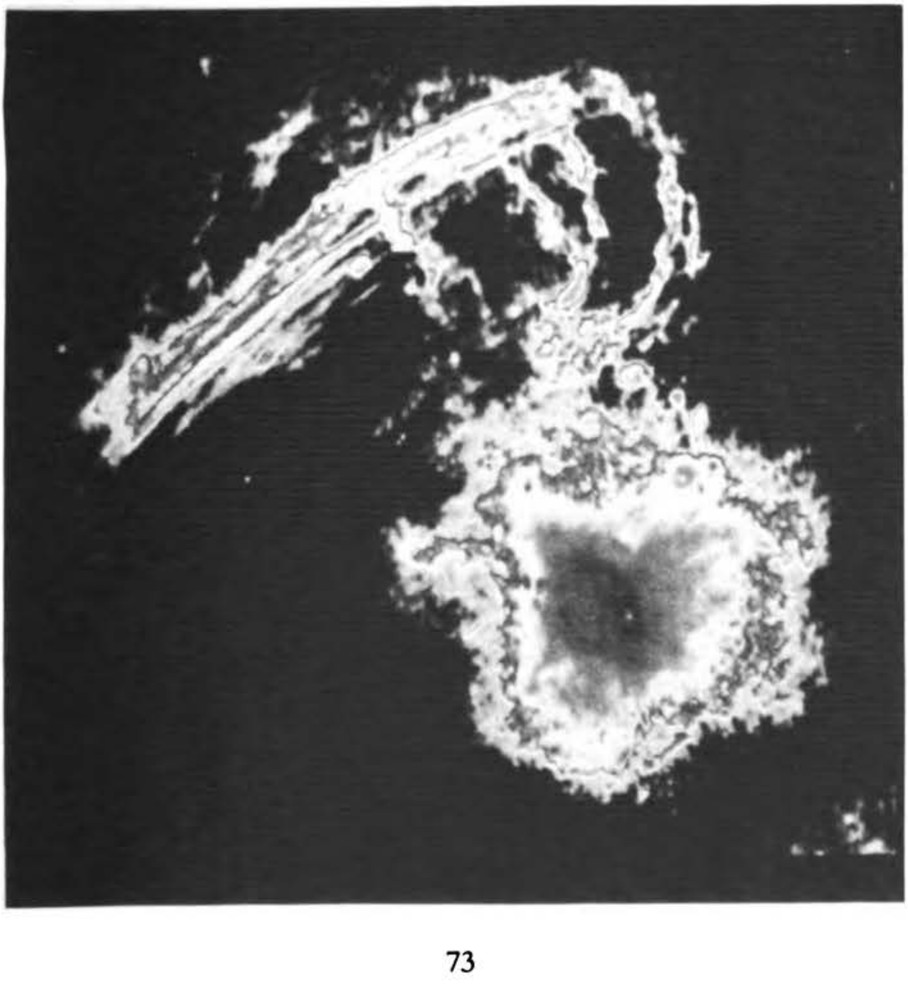
WINDOWS ON THE UNIVERSE

One of the dramatic changes in recent years has been in the number of windows through which we can view our universe. This is illustrated in Figure 47, in which the atmospheric absorption is plotted versus wavelength, showing the very narrow visible, infrared, and radio windows accessible to us on the earth's surface and the vastly greater range that opens up as we use balloons, rockets, and satellites to take our detectors into, and above, the atmospheric blanket. We find that through these new windows parts of the universe, both within and far beyond our parochial solar system, look very different from what we see through the traditional visible light window.

The Galactic Center

Astronomers now know the position of the center of our Milky Way galaxy in the sky to within 1/3000 of a degree, a precision comparable to that of locating an American quarter at a distance of two miles. Figure 48 is a contemporary radio map of this central region in Sagittarius A; in particular, this photograph shows the striking plasma filaments that are generated by the galactic magnetic field. These are truly enormous structures measuring hundreds of light years in length. None of these structures, and indeed nothing at all in the region of the galactic center, is accessible to visible light observation because dense intervening dust clouds in the plane of the galaxy block our line of sight. Both radio and infrared radiation, however, penetrate the dust, and although the details concerning our own galaxy are still somewhat ambiguous, there is rapidly growing evidence that our neighbor, the Andromeda galaxy, has a 50-million solar mass black hole at its center. Figure 49 illustrates the improved resolution with which we are now able to view our own galactic center, obtaining evidence that now suggests that we have a somewhat smaller but still enormous black hole at the center of our Milky Way galaxy. The top panel was obtained with the Infrared Astronomical Satellite (IRAS). The interstellar gas glows with the heat of absorbed starlight, and the elongated oval region is some 700 light years along its major axis. The second panel reproduces Figure 48. The third panel of Figure 49 is a radio map obtained with the Very Large Array (VLA) of

Figure 48.



the National Radio Astronomy Observatory; it shows the ionized gas within 5 or 6 light years of the nucleus of the galaxy and was collected at a wavelength of 6 cm. The bottom panel was obtained with the infrared telescope facility on Mauna Kea in Hawaii. The bright clusters to the right of this view are the infrared source IRS 16, a very dense star cluster very close to the galactic center.

Supernova 1987 A

As noted above, one of the more dramatic events of the past 2 years has been the observation of the first supernova visible to the naked eye in more than 400 years. The fact that two of the proton-decay detector systems listed in Figure 18 were able to detect neutrinos emitted in the early stages of the supernova explosion truly inaugurated the era of neutrino astronomy and provided astrophysicists with a crucial new calibration of their supernova models. The most complete of these models, that of Bethe and Brown, was completed prior to the observation of the supernova, but the experimental data are remarkably well reproduced by it. Figure 50 shows the model calculations during the period of maximum compression of the collapsing core, with time running downward and covering a total period of 12 ms. One of the remarkable results is that the outgoing shock wave shown in this figure encounters the infalling remnants of the initial explosion and, in effect, remains stationary for an extended period while this infalling matter rains through it. That a supernova explosion is the inevitable fate of any sufficiently massive star follows from the Bethe-Brown model and from subsequent calculations by Weaver, as shown in Figure 51. It bears emphasis that all elements heavier than iron are assembled in the hot shock wave following the explosion and are blown out into the cosmos, where they mix with the interstellar gas before condensing into new stars and possibly into planetary systems. There is a little star dust in each of us!

Large-Scale Structure in the Universe

The coming together of astrophysics, elementary particle physics, and cosmology has led to what can only be considered remarkable new insight into the early development and subsequent evolution of our universe. One of the more striking new results is the discovery of very large scale structure in the observable universe. Recently, Burns and his collaborators have discovered a linear string of galaxies more than a billion light years long originating in the regions of the Perseus and Pegasus constellations. It is by a very large margin the largest structure of any kind known and is surrounded by three major voids that are roughly spherical in shape and roughly 300 million light years in diameter. It is

Figure 49.

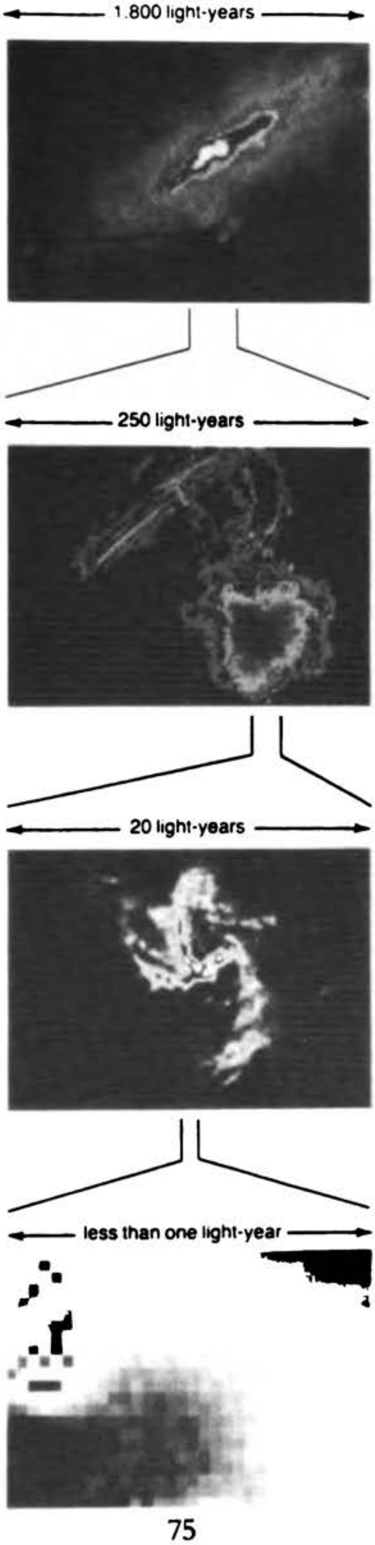
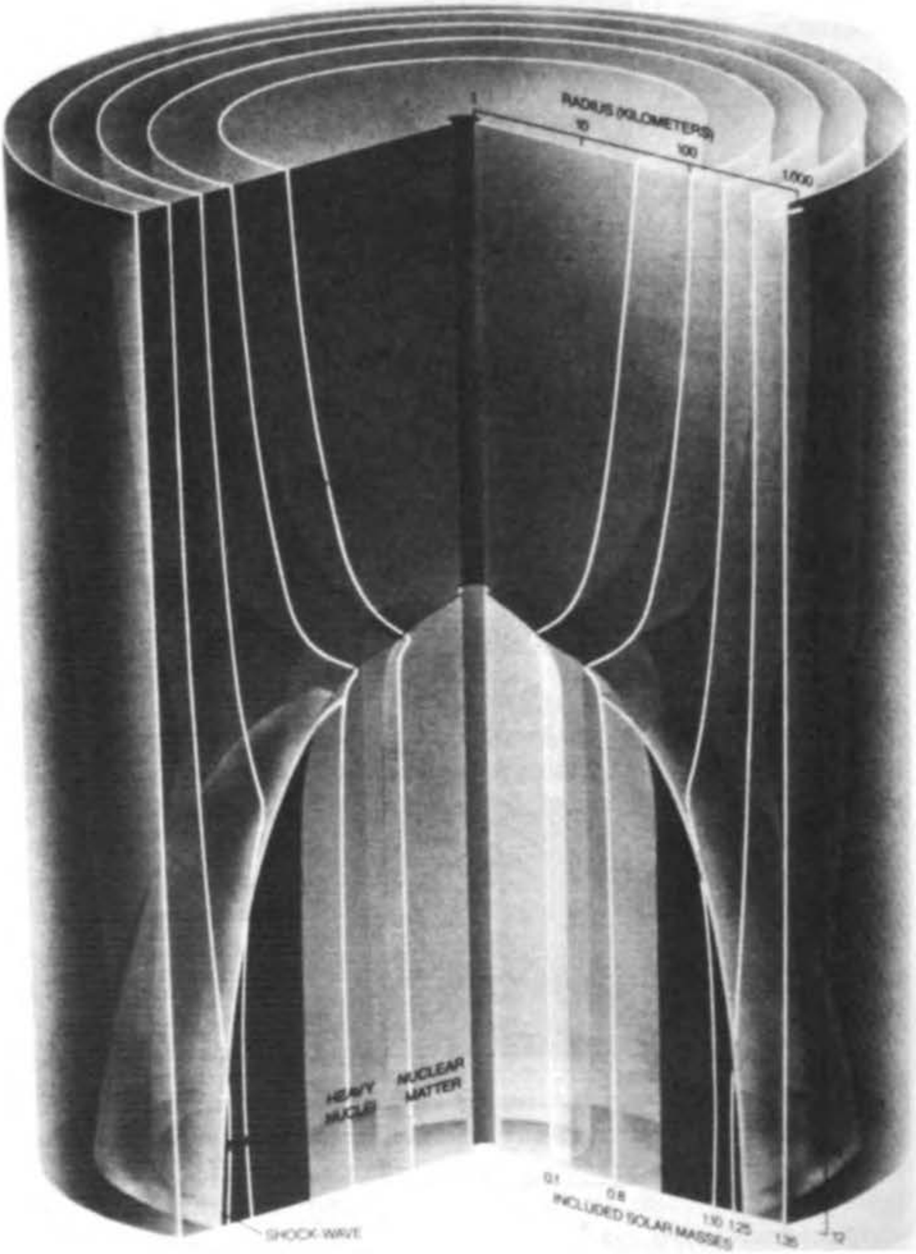

1.800 light-years
250 light-years
20 light-years
less than one light-year

Figure 50.

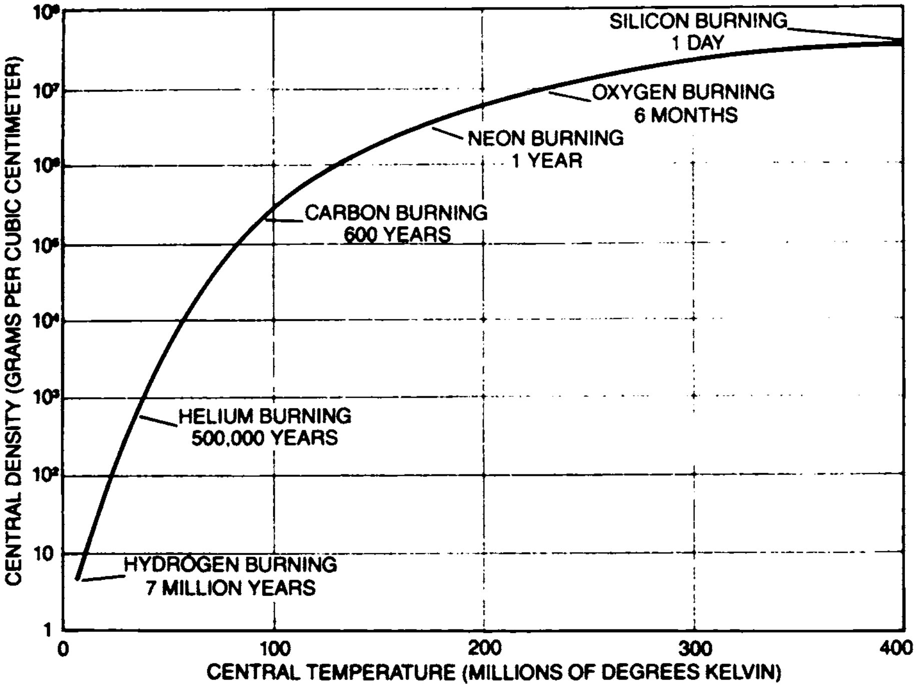

RADIUS (KILOMETERS)
1
10
100
1,000
HEAVY NUCLEI
NUCLEAR MATTER
SHOCK WAVE
0.1
0.8
1.10 1.25
1.35
12
INCLUDED SOLAR MASSES

gratifying that such voids and massive linear structures are precisely what emerged from recent Cray supercomputer simulations that followed a million model galaxies in an evolutionary model developed by Zeldovich in the Soviet Union.

Gravitational Science

As we focus more and more on such massive structures in our universe, we are forced to consider situations in which gravitational forces dominate all others. While gravitational radiation was one of the early predictions of Einstein's general theory of relativity in about 1916, this concept lay fallow until the 1960s when Weber, at the University of Maryland, mounted an ambitious program for its detection using large resonant bar detectors. In 1969 he announced detection of gravitational radiation from the galactic center, but these results have not been confirmed. Although still not unambiguous, the first generally accepted detection of gravitational radiation was that of Taylor and Hulse in 1974. They succeeded in showing that the systematic shift in the orbital period of a binary pulsar, over the past 14 years, can be almost precisely reproduced by calculations of the amount of energy and angular momentum

Figure 51.

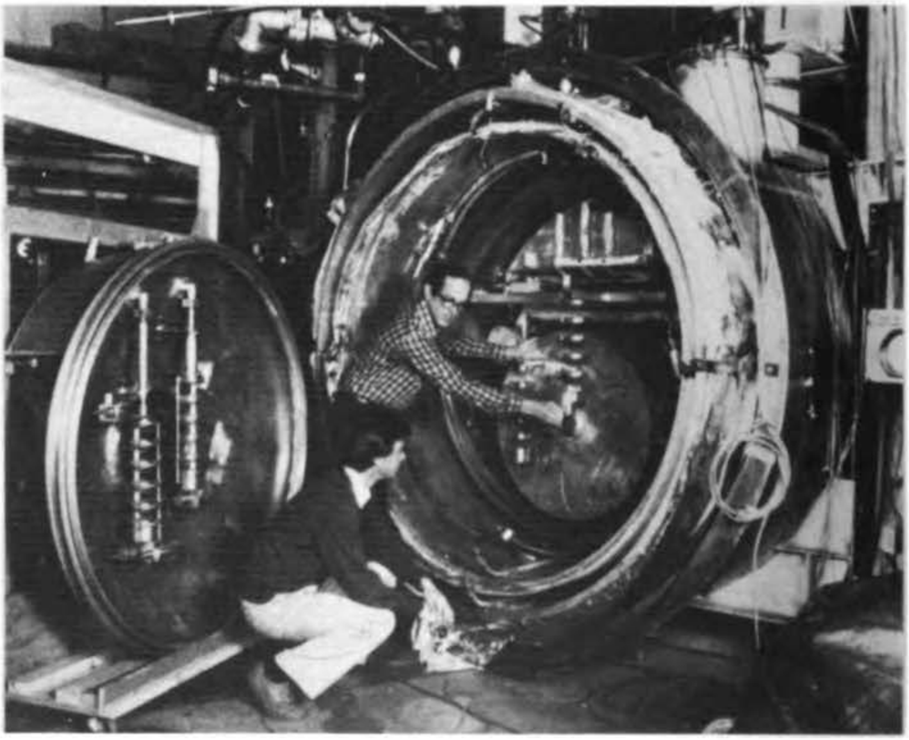


that gravitational radiation would have been expected to carry away from such a system.

In recent years gravitational science has finally become experimental science. Figure 52 is a photograph of the 4800-kg cryogenic resonant bar detector at Stanford University. Two other similar units are installed at the Louisiana State University and the University of Rome for ultimate use in a three-way coincidence detection system. These detectors are sensitive to mechanical strains of the order of 10^{-18} and already represent a triumph of instrumentation; a further factor of 10^5 is claimed to be possible before fundamental quantum limitations are encountered. For calibration, a supernova at the galactic center, converting 1 percent of its solar mass into a gravitational radiation pulse 1 ms in duration, would produce a strain of 3×10^{-18} on the earth.

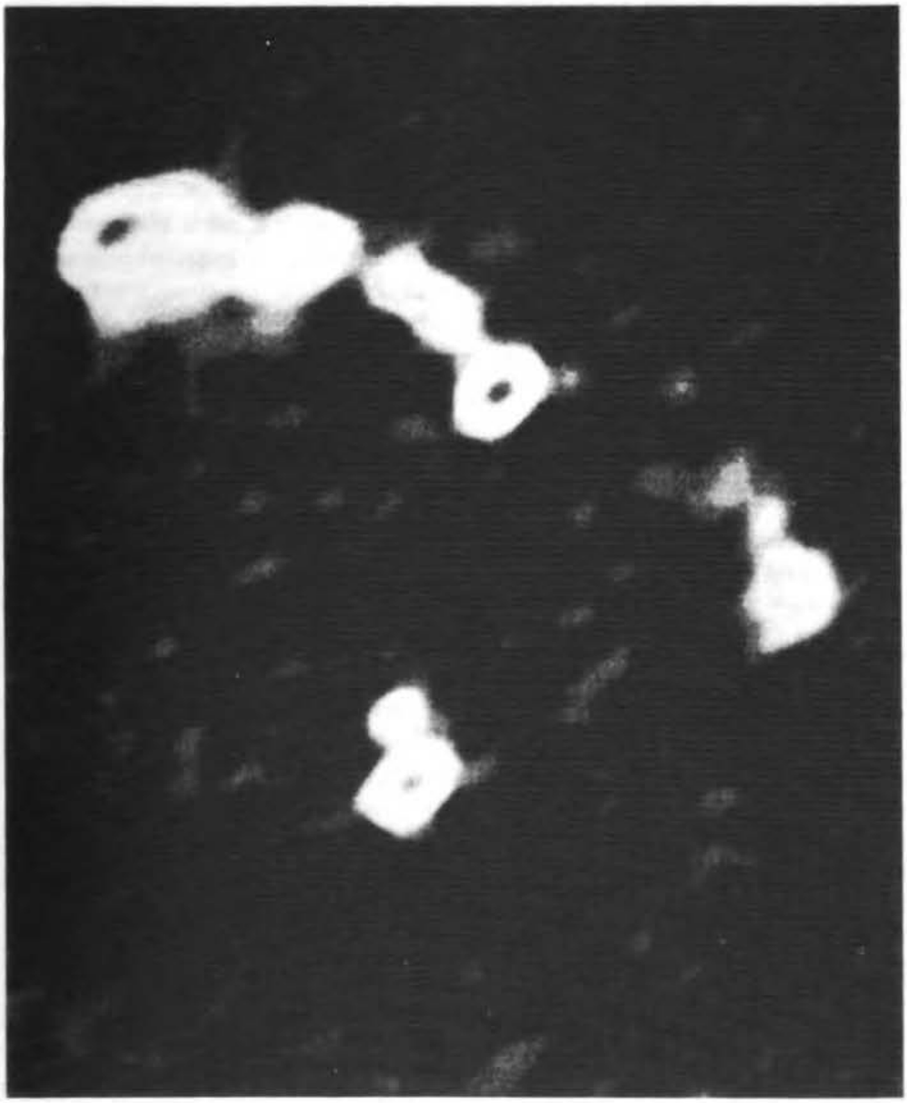
In parallel with these resonant bar detection systems, detailed planning is under way for the construction of very large Michaelson-type interferometers with kilometer-length arms terminating in pendulum-mounted mirrors. These massive experimental systems are designed to have sensitivities several orders of magnitude greater than is feasible with the resonant bar systems.

Figure 52.



Perhaps one of the most dramatic gravitational effects predicted by Einstein in his original publication on general relativity was the possibility of gravitational lensing, wherein the very large gravitational field of a galaxy, for example, which might happen to lie in the line of sight to a more distant astronomical object, so distorted the space-time in its vicinity that the light from the distant object could be deflected, leading to multiple images such as those shown in Figure 53, the first example of lensing discovered. These observations were made at the National

Figure 53.



Radio Astronomy Observatory. Einstein had recognized that if the alignment were incredibly precise, it might be possible to obtain a full ring image, but it was expected that no such alignment would ever be found. Remarkably, just such a ring image has been observed within the past six months.

During the past few years, evidence has been accumulating that we do not fully understand gravitational phenomena even on the earth's surface. These data come from precise studies with torsion pendula, from measurements in deep mines and in deep holes drilled in the Greenland ice cap, and from unexpected corrections required in the trajectories of Air Force cruise missiles. As yet, there is no consensus as to whether there is a fifth natural force, as some contend, or even whether it is attractive or repulsive if it exists at all. More measurements are clearly required.

It bears emphasis that if we do indeed live in a supersymmetric universe, the graviton, the quantum of gravitational radiation, will have supersymmetric partners—some of which will result in attractive and some in repulsive corrections to long-familiar Newtonian gravitation. Here, again, precise measurements on large objects such as mountains, dams, and ice caps can provide insight into the tiniest components of matter, and vice versa.

CONCLUSIONS

We have thus come full circle and have touched on a number of the frontier areas of modern physics. Physics has irretrievably and dramatically changed how man views his universe and himself. It represents one of the triumphs of the human intellect and one of mankind's greatest adventures. It is an adventure that continues. It spans the range of times from the earliest instant of creation to the far distant future, from the beginning to the end of time, and the range of sizes from the heart of the atomic nucleus to the outer fringes of our universe. In his size and lifetime, man falls in the middle range of both space and time; his explorations have already taken him to the farthest reaches of both. He has dared to understand.

We often forget what remarkable assumptions underlie our understanding of our universe. We now take it for granted that our universe started (space time began) in a cataclysmic explosion some 18 billion years ago; we assume that the laws of nature that we uncover in our earthbound laboratories today are the same laws that were valid then and that will be valid in the far distant future when our universe winds down to an end that still lies beyond our knowledge; and we assume that these same laws are as valid in the hearts of giant stars as they are in the outermost fringes of our universe—fringes that we are seeing today by light that left them when the universe was new. These are dramatic, arrogant assumptions—yet based on them, we have dared to recreate in our laboratories conditions that existed tiny fractions of a second after the creation and to extrapolate our understanding into the atomic nucleus and out to the farthest galaxies. Out of all this has come new and useful understanding. Perhaps the most impressive of all the aspects of physics is the dichotomy between the simplicity of its basic ideas and the immensity of its applications.

In considering these applications, I have always found it convenient to return to Thomas Robert Malthus, the English philosopher who lived from 1766 through 1834. Everyone is familiar with one form or other of the first law of Malthus, which in one of its more economical forms states that the resources available to man are limited. The equivalent of a second Malthusian law, which Malthus unfortunately did not live long enough to enunciate but for which I would give him credit anyway, is that man's ability to handle and use information is limited.

Both of these laws, however, are laws of social science and as such are strikingly different from the natural laws of physics. With sufficient ingenuity, it is always possible to end run social science laws of this sort, and physics is very much involved in that end running. It is, for example, the case that energy is the ultimate resource. With adequate energy, one can recycle indefinitely the elements in the earth's crust, mining waste heaps where necessary. It is possible to obtain unlimited pure water either by desalinating sea water or by pumping from deep underground aquifers, and it is possible to support agricultural enterprises far beyond our present ones by fixing nitrogen from the atmosphere and liberating phosphorus from the earth's rocks to provide the necessary fertilizers. Abundant energy can indeed allow us to end run the first Malthusian law. In parallel, the computer revolution, which is still in its infancy, can allow us to end run the second.

There have been four major revolutions in the past 200 years that have profoundly affected life on this planet.

The industrial revolution in the British midlands from 1760 through 1850 witnessed the use of energy to amplify the power of man's muscle. It was over in less than 100 years. It changed the face of society forever. It could not have been stopped once it was under way, and only a few misguided Luddites recognized that it was happening until it was all over.

The controlled release of nuclear energies, which perhaps can best be dated to Enrico Fermi's first reactor under the stands and at Stagg Field at the University Chicago in 1941, opened a whole new domain of energy; we have not used it as wisely as could have been the case. Inevitably, however, I am convinced that it will be recognized as the most environmentally benign source of bulk energy available to us and that pressures of acid rain, of the greenhouse effect, and of diminishing supplies of fossil fuels will inevitably force us to wiser use of this energy source.

The Green Revolution, for which Norman Borlaug received his Nobel Prize, dates from about 1960 in Mexico. It is almost universally misunderstood. It is based not on the development of new and dramatically more productive biological species, but rather on Borlaug's painstaking 20-year-long crusade to select stunted mutations of cereal crops that could accept energy-intensive application of irrigation water and of chemical fertilizer and remain standing so that their energy-enhanced yield of grain could be harvested. In short, the Green Revolution was the application of energy to agriculture. But unfortunately, particularly in the Third World where agricultural needs are most acute, energy supplies are inadequate to the task, and we are being driven back to discover new biological species that can be more productive, that can grow on less desirable land, and that can tolerate sea water, and so on.

And finally, the computer revolution dating to Babbage and Lovelace in Cambridge, England, in 1834 and to Aiken in Cambridge, Massachusetts, in 1934 is beginning to apply energy to amplify the power of man's mind. Like the industrial revolution before it, it will change the face of society. There is no way that it can be stopped, and relatively few of our citizens recognize that it is in progress. Despite the enormous impact that computers have already had on our society, the computer revolution is still in a very early stage, and the most dramatic and far-reaching impacts lie far ahead.

Prior to World War II, science and technology—natural philosophy, the search for understanding of nature, and invention, the search for mastery of nature—with very minor exceptions were distinct undertakings. The former was a gentlemanly pursuit, tolerated but not expected to yield anything of real value, whereas the latter was an eminently practical pursuit, primarily of a trial-and-error variety, whose entire goal was the development of goods or services. It was the wartime pressure for the development of radar, nuclear energy, and broad new medical services that wedded the two irretrievably. As I have noted above, modern science and technology are symbiotic and synergistic, and they increasingly play determining roles in the decisions of consequence in this country and throughout the world.

It is both tragic and scandalous that under such conditions, and at a time when changes in both science and technology are taking place with breathtaking speed, large segments of our public are totally unequipped to even understand the broad issues involved, let alone participate in their discussion or resolution. Under such circumstances, a growing fraction of our public is becoming alienated and uncoupled from the democratic process; no democracy can long exist under such conditions. I would submit that this is a matter of particular concern to the Department of Defense and to the military, where the need for new knowledge and new technologies, and for young minds trained to use that knowledge and those technologies creatively, has never been greater. I would further submit that the need has never been greater for the military and academic communities to make common cause. This can and probably must begin at the college and university level, but the serious problems occur much earlier, in the elementary schools and the high schools of the nation. I believe that by working together, our two communities—the military and the academic ones—can bring about the educational change that can track our scientific and technological change. It is a challenge that we ignore only at our peril.

In concluding his inaugural lecture in the Davis series ten years ago, Philip Handler said, "For myself I retain my faith that science which has revealed the most awesome and profound beauties we have yet beheld is also the principal tool that our civilization has developed to mitigate the conditions of man."

Ten years later I can only say that this is, if anything, even more true. Science has provided and continues to provide mankind with one of its greatest adventures, and at the same time it has illuminated the path through a sometimes hostile and frequently chaotic world. By showing how things work, it has indeed, within environmental constraints and the limitations of human wisdom, enabled us better to accommodate nature to man and man to nature.

ACKNOWLEDGMENTS

Obviously in a broad overview of this kind it would be both pointless and impossible for me to attempt a detailed referencing of all the sources and people from whom I have gained data and insight. But to all of them, my thanks! And let me finally express my appreciation to Ms. Lisa Close and Mrs. Dolores Berenda for their assistance in preparing this paper.

FIGURE CREDITS

M.B. Green of St. Mary's College, Figure 3
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Chris Quigg of Fermilab, Figure 5
Roy Schwitters of Harvard University, Figures 6 and 10
Carlo Rubbia of CERN, Figures 7 and 8
Leon Lederman of Fermilab, Figure 9
H.E. Haber and G.L. Kane, Figure 12
F.E. Close, Figure 13
David Jackson of the University of California, Berkeley, Figure 14
Yale Information Service, Figure 15
Peter Twin of The Daresbury Laboratory, England, Figure 16
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P. Chaudhari of IBM, Figure 43
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National Radioastronomy Laboratory, Figures 48 and 53
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CURRICULUM VITAE

D. Allan Bromley is the Henry Ford II Professor of Physics and Director of the A.W. Wright Nuclear Structure Laboratory at Yale University. Born in Westmeath, Ontario, Canada, he studied as an undergraduate in the Faculty of Engineering at Queen's University, in Canada, receiving the B.Sc. degree with highest honors in 1948. He received the M.Sc. degree from Queen's University in 1950 and the Ph.D. degree from the University of Rochester in 1952, both degrees in nuclear physics. He has been awarded 10 honorary doctorates from universities in Canada, France, Germany, Italy, South Africa, and the United States.

Having remained on the University of Rochester faculty from 1952 to 1955, he moved in 1955 to the Chalk River Laboratories of Atomic Energy of Canada, where he was senior scientific officer and section head. In 1960 he was appointed to a professorship in physics at Yale; he served as chairman of Yale's physics department from 1970 to 1977, founded the Wright Laboratory in 1963 and has been its director since that time, and was appointed to the Henry Ford II chair in 1972.

One of the world's leading nuclear physicists, he has carried out pioneering studies on both the structure and the dynamics of nuclei and is considered the father of modern heavy ion science, one of the major areas of nuclear science. He has also played major roles in the development of accelerators and of detection systems, and in computer-based data acquisition and analysis systems. He is an outstanding teacher, and over the past two decades, his laboratory at Yale has graduated more Ph.D.'s in experimental nuclear physics than has any other institution, worldwide. He has published over 450 papers in science and technology and has edited 18 books.

Apart from his research and teaching at Yale, he has played an active role in both national and international science and science policy. As chairman of the National Research Council's Physics Survey in the early 1970s, he contributed in a central way to charting the future of that science in the subsequent decade. As president of the American Association for the Advancement of Science—the world's largest scientific society—and of the International Union of Pure and Applied Physics—the world coordinating body for that science—he has been one of the leading spokesmen for U.S. science and for international scientific cooperation.

In recent years he has served as chairman of the U.S. side of both the Gandhi-Reagan Indo/U.S. and the Sarney-Reagan Brazil/U.S. Science and Technology Initiatives and is a member of the U.S./USSR Joint

Coordinating Committee for Research on the Fundamental Properties of Matter and of the Council on Foreign Relations.

He is a charter member of the White House Science Council, the senior U.S. advisory group in science and technology policy. In July 1988 he was awarded the highest U.S. scientific honor—the National Medal of Science—by President Reagan and was nominated for membership on the National Science Board.

He is married to the former Patricia J. Brassor, and they have two children, David John and Karen Lynn.