References and Notes

1. My thanks for help in the preparation of this article go to Charles Amick, M. F. Atiyah, Jerry Bona, Felix Browder, Alberto Calderon, S. S. Chern, Irving Kaplansky, Peter May, and Paul Sally.
2. L. A. Steen, Ed., *Mathematics Today* (Springer-Verlag, New York, 1978).
3. Also see "Mathematical developments arising from Hilbert problems," in *Proceedings of Symposia in Pure Mathematics* (American Mathematical Society, Providence, R.I., 1976), vol. 28.
4. L. Carleson, "On convergence and growth of partial sums of Fourier series," *Acta Math.* **116**, 135 (1966).
5. K. Heegner, "Diophantische Analyse und Modulfunktionen," *Math. Z.* **56**, 227 (1952).
6. A. Baker, "Linear forms in the logarithms of algebraic numbers," *Mathematika* **13**, 204 (1966).
7. H. M. Stark, "There is no tenth complex quadratic field with class number one," *Proc. Natl. Acad. Sci. U.S.A.* **57**, 216 (1967); "On the gap in a theorem of Heegner," *J. Number Theory* **1**, 16 (1969).
8. A. van der Poorten, "A proof that Euler missed . . . Apéry's proof of the irrationality of $\zeta(3)$," *Math. Intell.* **1**, 195 (1979).
9. K. Appel and W. Haken, "Every planar map is four colorable," *Bull. Am. Math. Soc.* **82**, 711 (1976). Also see the article by Appel and Haken in (*2*).
10. R. Mandelbaum, "Four dimensional topology: An introduction," *Bull. Am. Math. Soc.* **2**, 1 (1980).
11. S. A. Amitsur, "On central division algebras," *Isr. J. Math.* **12**, 408 (1972).
12. J. F. Adams, "On the nonexistence of elements of Hopf invariant one," *Bull. Am. Math. Soc.* **64**, 279 (1958).
13. P. Enflo, "Recent results in general Banach spaces," in *Proceedings of the International Congress on Mathematics* (Canadian Mathematics Congress, Vancouver, B.C., 1975), pp. 53-57.
14. P. C. Eklof, "Whitehead's problem is undecidable," *Am. Math. Mon.* **82**, 775 (1976).
15. F. W. Lawvere, in *Model Theory and Topoi*, C. Maurer and G. C. Wraith, Eds. (Springer-Verlag, New York, 1972), pp. 1-12.
16. J. W. Cooley and J. W. Tukey, "An algorithm for the machine calculation of complex Fourier series," *Math. Comput.* **19**, 257 (1965).
17. A. Robinson, *Non Standard Analysis* (North-Holland, Amsterdam, 1966), pp. xi and 293.
18. E. J. Dubuc, "C^∞-schemes" (Preprint Series No. 3, Mathematics Institute, Århus University, Århus, Denmark, 1979/80).
19. D. Gorenstein, "The classification of finite simple groups," *Bull. Am. Math. Soc.* **1**, 47 (1979).
20. Harish-Chandra, "Harmonic analysis on real reductive groups, III," *Ann. Math.* **104**, 117 (1976). See also A. Borel and W. Casselman, Eds., "Automorphic forms, representations and L-functors," in *Proceedings of Symposia in Pure Mathematics* (American Mathematical Society, Providence, R.I., 1979), vol. 33, part 1, pp. x and 322.
21. R. C. Kirby and L. C. Siebenmann, "On the triangulation of manifolds and the Hauptvermutung," *Bull. Am. Math. Soc.* **75**, 742 (1969).
22. R. K. Lashof and M. G. Rothenberg, "On the Hauptvermutung, triangulation of manifolds and h-cobordism," *ibid.* **72**, 1040 (1966).
23. S. S. Chern, "A simple intrinsic proof of the Gauss-Bonnet formula for closed Riemannian manifolds," *Ann. Math.* **45**, 747 (1944).
24. W. Klingenberg, "The theorem of the three closed geodesics," *Bull. Am. Math. Soc.* **76**, 601 (1965).
25. S. Smale, "What is global analysis?", *Am. Math. Mon.* **76**, 4 (1969).
26. R. Osserman, "The nonexistence of branch points in the classical solution of Plateau's problem," *Bull. Am. Math. Soc.* **75**, 1247 (1969). Also see E. Bombieri, "Recent progress in the theory of minimal surfaces," *Enseign. Math.* **25**, 1 (1979).
27. H. Lewy, "An example of a smooth linear partial differential equation without solution," *Ann. Math.* **66**, 155 (1957).
28. C. Fefferman, "Monge-Ampere equations, the Bergman kernel and geometry of pseudoconvex domains," *ibid.* **103**, 395 (1976).
29. R. O. Wells, Jr., "Complex manifolds and mathematical physics," *Bull. Am. Math. Soc.* **1**, 296 (1979).
30. R. M. Miura, "The Korteweg-de Vries equations: A survey of results," *SIAM (Soc. Ind. Appl. Math.) Rev.* **18**, 412 (1976); also J. Bona, "Solitary waves and other phenomena associated with model equations for long waves," preprint.
31. N. M. Katz, "An overview of Deligne's proof of the Riemann hypothesis for varieties over finite fields (Hilbert problem 8)," in (*2*), pp. 257-306.

Physics

D. Allan Bromley

Those aspects of man's knowledge of the natural universe that are both universal and permanent make up physics: universal in the sense that behavior unraveled in an earthbound laboratory is assumed to be equally valid in the farthest reaches of the universe, and permanent in the sense that, once demonstrated conclusively now, an addition to our understanding of nature is assumed to be valid back to the beginning of the universe and forward into the far distant future. Although physics is frequently among the most arcane of the sciences, its applications have profoundly affected the lives of every human. Yesterday's frontier has very often proved to be tomorrow's application.

The past 5 years have been the most exciting, challenging, and productive in world physics since the late 1920's, just after the discovery of quantum mechanics. We appear to be on the threshold of an entirely new understanding of physical phenomena on a more fundamental level than ever before. And, gratifyingly, we find that in contrast to the fragmentation that characterized physics—and indeed many other sciences—in past decades, the underlying unity and coherence of our science is once again emerging. Concepts and techniques developed in one subfield are rapidly exploited in others, to the enrichment of all.

Obviously, this brief review of so dynamic a field cannot possibly be complete. What I have tried instead to do is select, in each of the major subfields of physics, a few areas which will illustrate the renaissance and in which I believe major progress will be made in the years ahead. I shall follow the natural hierarchy, from the microscopic to the macroscopic, from the depths of the atomic nucleus to the fringes of the known universe.

Elementary Particle Physics

Concerned with the ultimate structure of matter and the fundamental forces and symmetries of nature, elementary particle physics moves inexorably to ever higher energies to probe ever shorter distances and to establish the ordering principles that nature has chosen.

The annus mirabilis in this field was 1974. Not only was there evidence produced for an entirely new building block of nature—in the discovery of the ψ particles—but also the grand unification theories aimed at bringing together electromagnetism and both the weak nuclear force (responsible for radioactivity) and the strong nuclear force (responsible for binding nuclei and for nuclear energies) were first introduced.

Prior to 1974, after enormous effort, both experimental and theoretical physicists generally had concluded that three massive, fractionally charged entities, the quarks, were the building blocks underlying the natural universe. The discovery of the ψ particles showed conclusively that there was yet a fourth quark, carrying a totally new quantum attribute arbitrarily christened as "charm"; within the past 2 years the discovery—at even higher energy—of the Υ particles proved the existence of a fifth quark, this one with a quantum attribute equally arbitrarily called "bottom" (see Fig. 1). And almost all physicists are convinced, on the basis of theoretical symmetry arguments, that a sixth quark carrying the attribute "top" will be discovered as somewhat higher energies become available to experimenters. The necessary facilities are now under construction, both

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in the United States (Brookhaven and Stanford) and in Europe (Geneva and Hamburg).

These quarks are the building blocks for the so-called hadrons, particles that interact through the strong nuclear force and that fall into two quite distinct classes: the baryons, of which the proton is the lightest known member and all of which are assumed to be composed of different combinations of three quarks, and the mesons, of which the pion is the lightest member, all of which are assumed to be composed of different quark-antiquark combinations.

Although there have been reported observations of free quarks, identified by their characteristic electrical charges, which must be fractions of those on the electron and the proton, most physicists are now convinced that the forces that bind quarks are such that it is impossible to ever isolate a free quark and that any attempt to do so results only in the production of quark-antiquark pairs—that is, mesons. This, of course, will not preclude detailed study of quarks, even though they may be trapped forever inside hadrons, and with ever higher energy probes such studies will be of increasing importance.

Nature has also given us three electrons: the long familiar one, the heavier muon, and the recently discovered, and even heavier, tau particle; these are believed to be structureless point particles, and each has a corresponding and, up to now, different neutrino. Together, these particles make up the lepton family, interacting through the weak nuclear force. Until very recently all measurements on neutrinos had been consistent with all three having zero rest mass, traveling always with the velocity of light, and having a particular handedness. New, and as yet unconfirmed, data appear to support the suggestion that the three neutrinos are not really different and that over a period of time each of them "oscillates," spending part of its life in each manifestation. A necessary corollary is that the mass of the electron and muon neutrinos is not exactly zero, while the tau neutrino can have large mass and indeed, in some very preliminary and speculative models, can carry the long-sought missing mass of the observable universe. But all this requires further study.

We thus find ourselves with six quarks (almost) and six leptons (maybe), and an extremely fundamental question is whether more remain to be found. As shown in Fig. 1, we have only searched up to 11 billion electron volts (GeV) and have found five quarks. Is it reasonable to believe that when the Isabelle machine at Brookhaven takes us to 800 GeV we will find only one more? Indeed, there are some preliminary theoretical suggestions that this may be the case. Group theory has provided the unifying mathematics for our understanding of the symmetries and patterns of particle physics, but philosophically many physicists have been somewhat troubled by the success of the SU(6) group in describing nature. Why not SU(9) or SU(17)? Very recently, however, it has been suggested that nature may be organized according to the E8 group, the most complex of a five-member closed family of mathematical oddities, the exceptional Lie groups, and if this should turn out to be so, then there are only six quarks and six leptons. One of the major open questions facing physicists, then, is whether the complexity of the microcosm is limited—as E8 would suggest—and as soon as higher energies become available there will be an international race to find the sharp spikes, such as those shown in Fig. 1, that are the unique signatures of an entirely new entity. Should new entities appear, the obvious question will be whether there are even more fundamental building blocks from which the quarks are constructed. Preliminary theories are already under development, although as yet without any solid foundation, that attempt to explain all of nature as resulting from combinations of only two entities—the so-called maons or rishons (the name depending on the architect of the theory).

In parallel with this work on the building blocks has been that on the grand unification theories of the natural forces. From Maxwell's genius came the recognition that electricity and magnetism were one and the same, and with the addition of quantum mechanics this led to quantum electrodynamics, the most precise and thoroughly tested theory known to us, which describes the photons or particles of light that transmit the electromagnetic force—or, in other language, are the particles of the electromagnetic field. During the past year, pioneering experiments at Hamburg and elsewhere have provided the first direct evidence for the gluons, which are the corresponding particles of the strong nuclear field, and arising from the unification theories has come an expanded theory, quantum chromodynamics, which has the potential of describing, in a unified way, electromagnetism and the weak and strong nuclear forces. Direct evidence supporting coalescence of the weak and electromagnetic forces has already come from a recent pioneering Stanford-Yale experiment in which 32-GeV polarized electrons were scattered from protons and deuterons.

Summary. From massive quarks deep in the hearts of atomic nuclei to the catastrophic collapse of giant stars in the farthest reaches of the universe, from the partial realization of Einstein's dream of a unified theory of the forces of nature to the most practical applications in technology, medicine, and throughout contemporary society, physics continues to have a profound impact on man's view of the universe and on the quality of life. The author argues that the past few years, in terms of new discoveries, new insight—and the new questions—have been among the most productive in the history of the field and puts into context his selection of some of the most important new developments in this fundamental science.

As yet, however, despite intensive search, we have not found the corresponding particles, the so-called intermediate bosons, of the weak nuclear field. Our conclusion is that these are so heavy that substantially higher energies will be required to produce them, and they are the objects of another major search in particle physics. In contrast to the photon, which has no electrical charge, we know that the intermediate bosons must form a threefold family: two of the same mass having equal and opposite charge ($W^{\pm}$) and one much heavier and uncharged (Z°). Although we cannot predict the masses of these bosons with any real precision, the ratio of the masses is a critical parameter of quantum chromodynamics and its measurement will pose a crucial test for the theory. Current theories suggest mass equivalents of 80 and 90 GeV, respectively.

One of the most striking predictions of the grand unified theories is that the baryon and lepton families are not totally separate—as has always been supposed—and that the proton can, and indeed must, decay eventually into lighter leptons, probably into an antielectron (positron) and an uncharged pion. For this decay to occur there must be a totally new field coupling the baryons and the leptons, and from the fact that the measured lower limit on the lifetime of the proton is so long, 10^{30} years, it can be argued that the particle of this new field (now sometimes called the leptoquark) must have an enormous mass corresponding to 10^{15} GeV—actually heavier than a bacterium—and far beyond any energy ever anticipated to be available on the earth. This particle will thus never be seen, but we can in principle detect the decay of a proton even though the decay rate is so small that a human would have to live several hundred years before a single one of his body protons decayed. Already two massive experiments are under way in the United States that are claimed to be sensitive to proton lifetimes as long as 10^{33} years, while the unified theories predict 10^{31} years. If this decay is observed, it will be a striking confirmation of the unified theories.

To realize Einstein's unification dream it will be necessary to include gravitation in the unified theories; happily, there has been major progress in recent years in supergravity theory, in which the first step toward unification, the quantization of the gravitational field, has been taken successfully. An, at first sight, bizarre new field emerges here too. In the past it has been taken as an article of faith in physics that particles with odd multiples of the spin of the proton (fermions) and those with even multiples (bosons) form quite distinct families obeying very different statistics; only one fermion but an infinite number of bosons could occupy a given quantum state. In supergravity, however, there are two predicted field particles—the graviton (a boson) and the gravitino (a fermion)—and the theory requires a supersymmetry that encompasses both of them. Although neither of these field particles has been observed as yet, a very extensive search is being made for the gravitons that are expected to be emitted from the cataclysmic processes of a supernova explosion in this or neighboring galaxies. This, too, is one of the frontiers of elementary particle physics.

Fundamental to the grand unification scheme is the physical idea that as we go to ever smaller distances the electromagnetic, weak, and gravitational forces become stronger while the strong force becomes weaker. In our present measurements we resemble the legendary blind man exploring an elephant; our impression of the fundamental natural force depends critically on how we approach it.

If we succeed in delineating the fundamental building blocks and the fundamental force of nature, it will stand as one of the greatest triumphs of the human intellect. At the same time it bears emphasis that after more than 50 years we still have no generally acceptable philosophical interpretation of the quantum mechanics that has been so successful in describing the physical universe, and so-called hidden-variable variants of quantum mechanics, designed to recapture some of the determinism whose lack many find offensive, continue to be actively discussed and tested.

Nuclear Physics

Nuclei form a crucial bridge between the few-body problems characteristic of particle physics and the extreme many-body problems characteristic of plasma and metal physics, where only statistical considerations apply. In nuclei, the number of interacting entities, the nucleons (neutrons and protons), is large enough to yield an enormously rich array of phenomena while small enough to make microscopic understanding at least within the realm of possibility. Figure 2 is a map of the nuclear domain.

Analogous to the situation in particle physics (see Fig. 1), at every higher energy at which nuclear physicists have made precision measurements, they have found sharp structure indicative of new modes of nuclear motion. Intrinsic spins approaching 100 times that of the proton have been identified, as have strange molecular states in which, at certain specific energies, the nucleons present arrange themselves into well-defined subunits, which move in stately minuets relative to one another. Over the years, a wealth of information has been collected on these as well as on simpler nuclear quantum states.

Among the most dramatic discoveries in recent years has been that these quantum states can also be understood in terms of very simple underlying building

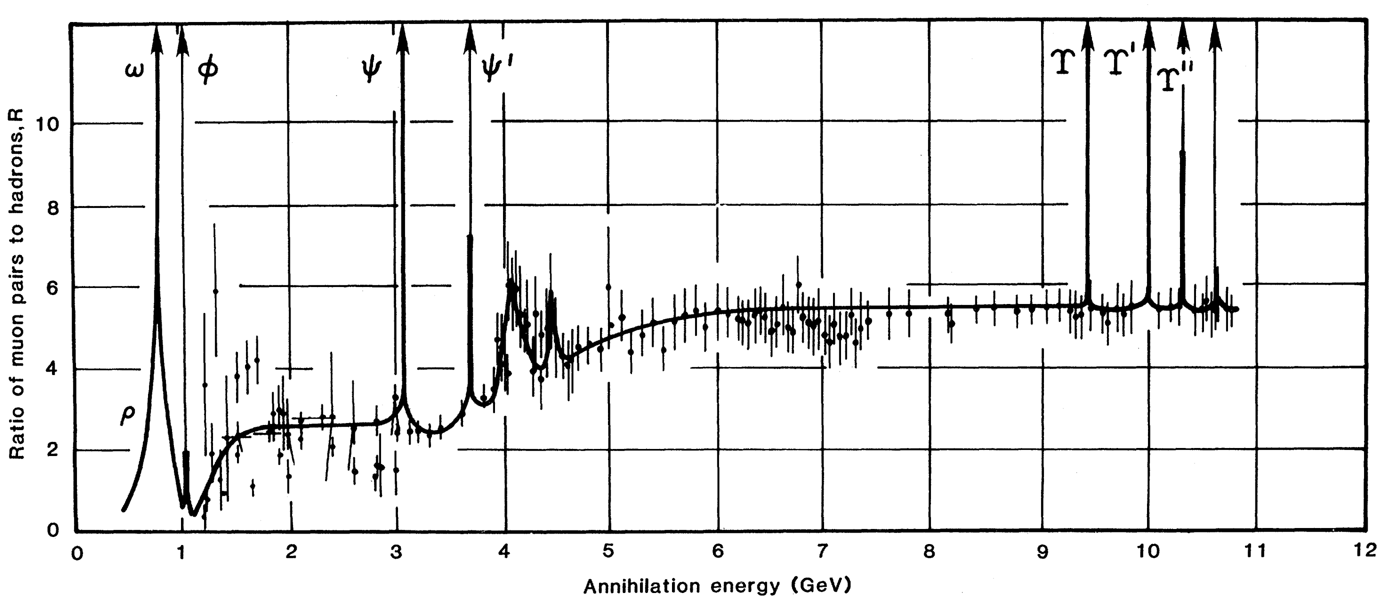

Fig. 1. Ratio R rises from about 2.5 at energies below 3 GeV to about 5.5 at energies above 5 GeV. The most plausible interpretation of the increase is that a threshold for the creation of a new kind of quark has been crossed in this interval. What is more remarkable than the overall increase in R is that the curve has a series of tall and extraordinarily narrow peaks. The three peaks clustered near 1 GeV represent production of the ρ, ω, and ϕ mesons, which have quark compositions involving combinations of $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$. The spike at 3.1 GeV is the ψ meson, made up of a $c\bar{c}$ quark-antiquark pair. The ψ was discovered in 1974 during a measurement of R; the ψ', which is an excited state of the same $c\bar{c}$ system, was found 10 days later. The broader peak at 4 GeV represents several short-lived particles and is now recognized as the threshold for the creation of a pair of charmed mesons. The three peaks at 9.4, 10.0, and 10.3 GeV are the Υ, Υ', and Υ'' mesons made up of $b\bar{b}$ quark-antiquark pairs in their ground configuration and two different excited configurations. The very small peak at 10.6 GeV, if real, may represent the first evidence for unbound bottom mesons. In this figure R is the ratio of the yield of muon pairs to total hadrons produced when an electron and positron annihilate at the energy shown on the abscissa. The three original quarks, up (u), down (d), and strange (s), and the newer charmed (c) and bottom (b) quarks all have their corresponding antiquarks, represented here by $\bar{u}$, $\bar{d}$, $\bar{s}$, $\bar{c}$, and $\bar{b}$, respectively.

blocks, obeying the simple rules of group theory, analogous to the situation in particle physics. Postulated originally on an empirical basis—and subsequently understood and justified as reflecting known characteristics of the fundamental nucleon-nucleon force—these building blocks are pairs of nucleons. At low energies only two kinds of pairs are involved: those which carry zero total angular momentum (s bosons) and those which carry two units of angular momentum (d bosons). Higher f and g bosons are expected at higher energies but they have not yet been identified. Models that include the s and d bosons and their interactions have been remarkably successful in reproducing nuclear data throughout the periodic table, with the older rotational and vibrational collective models emerging as special cases of the boson models in restricted nuclear mass regions. Most important has been the success of the new models in the intermediate regions between those where the older models appeared to be valid, so that for the first time we have a consistent understanding of low-energy nuclear structure phenomena throughout the periodic table. Building on this success, there is preliminary evidence for equivalent simple dynamic symmetries in nuclear reaction data and at least the promise of uncovering the essential physics underlying the very large body of reaction data now available.

One of the most recent and potentially far-reaching developments in this work has been the extension of these boson models to odd-mass nuclei. Here, in addition to the bosons in the core, we have a valence nucleon that is obviously a fermion. Within this framework we are again faced with the necessity for a supersymmetry that will encompass both bosons and fermions, just as in the case of supergravity. Preliminary results in the nuclear case are extremely encouraging, in that the supersymmetry theories predict certain characteristic patterns of excited quantum states of odd-mass nuclei compared to those of the neighboring even-mass ones; certain states that older models would have included in the odd-mass spectra, for example, are forbidden by supersymmetry. Work in the past few months has shown striking agreement, in the few cases where complete data are available, between the supersymmetry predictions and what is observed experimentally. It will be gratifying indeed if this new supersymmetry emerges first in nuclear physics, and yet

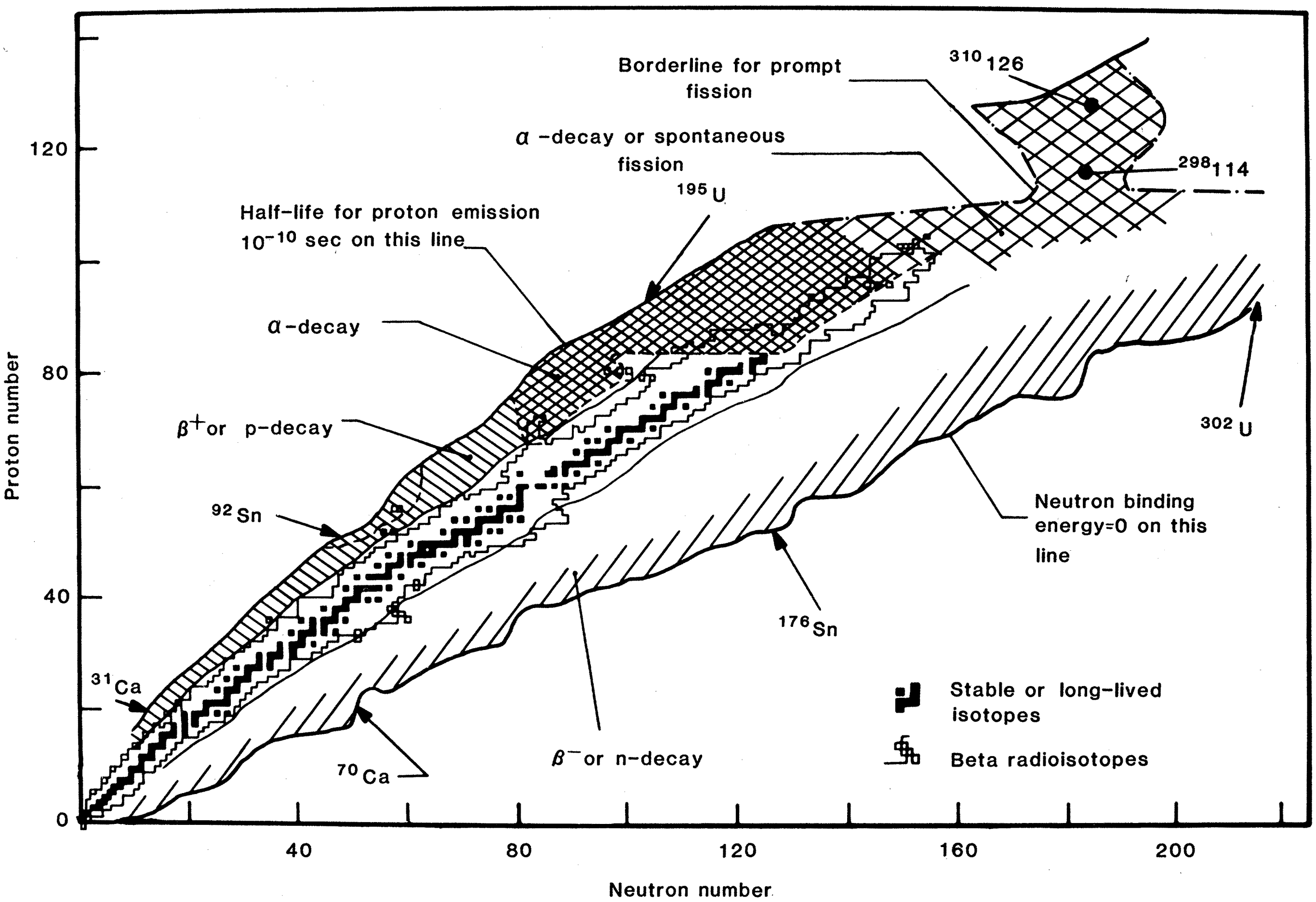

Fig. 2. The nuclear stability diagram is obtained by plotting the nuclear binding energy as a surface defined by the number of protons (Z) and the number of neutrons (N) present. For low N and Z the most stable species are those having $N = Z$; but with increasing Z, the electrostatic repulsion between the protons forces the stability toward nuclei where N is greater than Z. The black squares represent the nuclei that are stable in nature; this simply means that their lifetime against spontaneous decay is long compared with the lifetime of the solar system. There are some 300 in all. A light line outlines the region that has been explored thus far in nuclear physics; it contains some 1600 different nuclear species (isotopes). The outer lines define the region where calculations indicate that nuclear species should be stable against instantaneous decay through the strong nuclear forces. The lower line is the so-called neutron-drip line; any species formed below it spontaneously and instantaneously emits neutrons (n) and moves to the left until it reaches the line and the boundary of stability. Emission of tightly bound α-particles (helium nuclei containing two protons and two neutrons each) competes favorably with direct proton (p) emission at the upper boundary, and spontaneous fission limits the stability region for very heavy nuclei. Two of the postulated islands of stability far beyond the natural range are indicated at $Z = 114$ and $Z = 126$. It is clear that a vast range of nuclear species remains to be explored. While the most stable uranium isotopes have masses of 235 and 238 respectively, as shown here, uranium isotopes ranging in mass from 195 to 302 would be expected to be stable against instantaneous breakup.

another example of the use of the nucleus—the only entity in which all of the forces of nature operate simultaneously—as a microscopic laboratory in which to test and examine the most fundamental natural concepts.

But it must be emphasized that we have only begun to explore and understand nuclear phenomena; we have been very much limited to the nuclear Fermi surface and nuclear orbitals very close to it. In a very real sense we are like the solid-state physicist who grew up to believe that the world contained only Einstein crystals and who was told of the existence of liquids. We have been barred by the Pauli exclusion principle from using nucleon probes deep in the nuclear interior. These limitations are now being removed as we move to new energy domains. At higher energies we gain access to mesons as probes; in one of the most powerful reactions a kaon (carrying one unit of the quantum attribute "strangeness") converts a neutron, deep in a nucleus, to a lambda particle, the lightest strange baryon—only 20 percent heavier than the neutron—and a pion emerges to conserve energy and momentum. Because the lambda is so much like a neutron the struck nucleus remains otherwise essentially unchanged and becomes a so-called hypernucleus; and because the lambda is different from the neutron it can occupy quantum states forbidden to the neutron by the Pauli principle. Already vital new data have emerged from the hypernuclear studies even though these are in their infancy.

And with precise beams of high-energy electrons and hadrons we can probe the separate behavior of neutrons and protons as never before. In particular, we become sensitive to the fact that nuclei are vastly more complex than earlier simplified pictures had suggested, with the nucleons adventuring, for the short times allowed to them by the Heisenberg uncertainty principle, into higher excited configurations (the so-called Δ, for example) and the whole being bathed in clouds of pions carrying the strong nuclear field. Electron measurements are particularly sensitive to these pion currents, but here again our studies are only beginning.

With the advent of beams of all nuclear species it has become possible to stress nuclear matter in entirely new ways and in previously inaccessible parameter ranges. Higher densities, higher centrifugal forces, higher Coulomb fields that occur in close collisions of massive nuclei all yield new and characteristic information about the nuclear—and the general—many-body problem. In an entirely new and unexpected nuclear interaction called deep inelastic scattering, for example, mechanisms that are still unknown rapidly transfer kinetic energy of relative motion into internal excitation of the interacting nuclei and the two come apart, almost exactly as in nuclear fission, driven by their mutual electrostatic repulsion.

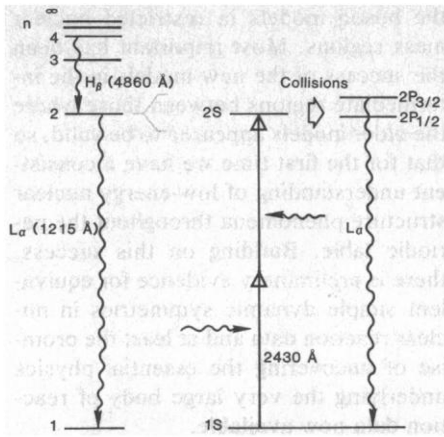

Fig. 3. A simplified level scheme for atomic hydrogen. Two-photon excitation of the metastable 2*S* state from the 1*S* ground state promises to yield extremely high resolution—ultimately higher than 1 part in 10^{16}. The excitation can be monitored by observing the collision-induced 2*P*-1*S* Lyman-alpha (L_α) fluorescence in the vacuum-ultraviolet spectral region. The principal quantum number *n* next to the left panel shows the convergence of the energy spectrum to the dissociation limit $n = \infty$. By arranging for the two photons in the central panel, each tuned to precisely half the energy of the level under consideration, to strike the atom simultaneously but from precisely opposite directions, the normal Doppler broadening is eliminated.

Whereas in high-energy particle physics we drive ever increasing energies into ever smaller volumes to probe small-distance phenomena, in ultrahigh-energy heavy nuclear collisions we drive ever increasing energies into relatively large volumes containing large numbers of nucleons and thus become sensitive to the possibility of totally new collective phenomena. It has been suggested, for example, that in such collisions it may be possible to create an entirely new kind of matter, in which nucleons give up much of their mass to form a dense cloud of pions in which the diminished nucleons move. Such systems, if they exist, are predicted to have fascinating characteristics. Whereas normal nuclei range in mass number from 1 to about 250, these new systems would range from about 350 to 100,000. Moreover, they would have a voracious appetite for neutrons, so that by exposing them, say, to a large nuclear reactor we could store an enormous amount of energy in them by direct neutron absorption. Unhappily, we still do not have any good ideas about how to recover this stored energy—but I am confident that if we are successful in discovering these new systems the ideas will follow in short order.

We are entering a new era of understanding of nuclear phenomena at a more fundamental level than has ever been available before. Major new facilities are under construction in Germany, France, Japan, and the Soviet Union that will move the frontiers of the field forward by a quantum jump.

Plasma Physics

More than 95 percent of the matter of our universe exists in a plasma state, an electrically neutral soup of nuclei and electrons; this is truly the fourth state of matter. Densities can be as low as 1 to 100 nuclei per cubic centimeter in interstellar space, as high as 10^8 to 10^{20} in laboratory plasmas, and 10^{22} to 10^{25} in stellar interiors.

Currently, plasma physics research is very largely focused on the attainment of thermonuclear reactions on a terrestrial scale—in brief, fusion power. Our sun, as a fusion reactor, in each second burns 164 million tons of hydrogen to yield 160 million tons of helium ash, with the missing 4 million tons appearing through $E = mc^2$, as raw energy radiated throughout the cosmos. In the sun, gravitation provides the confinement required to maintain the reaction conditions—temperatures approaching 100,000,000°C and pressures, simultaneously, in excess of 20 million pounds per square inch. Obviously, duplication of these conditions terrestrially poses formidable engineering problems.

The Holy Grail in this field is the Lawson criterion, $n\tau = 10^{14}$, where n is the plasma density in nuclei per cubic centimeter and τ is the containment time in seconds. Very general arguments suggest that at the Lawson criterion, assuming that the appropriate temperatures have been reached for the fuel species in use, the plasma will be generating as much energy as is required to sustain it—that is, we will have reached a break-even point. Two complementary approaches are being pursued. In the first, magnetic confinement, a dilute plasma (low n) is confined for a relatively long time (high τ) in a magnetic bottle; in the second, inertial confinement, a very dense plasma (high n) is confined for a very short time (low τ) by an implosion induced by delivering enormous energies symmetrically to a solid fuel pellet in a time so short that the inertia of the fuel prevents its dispersal prior to fusion. These energies can—and will—be delivered by pulses of photons, electrons, protons, or ions as heavy as xenon, depending on the specific approach chosen.

The technologies are incomplete in all of these approaches and all have characteristic strengths and weaknesses. Currently, the magnetic confinement techniques with toroidal tokamak geometries have obtained the most promising results. The Alcator device at Massachusetts Institute of Technology has been reported to be within a factor of 3 of the Lawson criterion, while the Princeton Large Torus (PLT) device has produced the highest plasma temperature yet obtained, 60,000,000°C. In the inertial fusion area, the Lawrence Livermore and Los Alamos SHIVA and HELIOS lasers, respectively, rated at 20 terawatts each, are providing vital plasma physics data but have not yet approached the factor of 10,000 compression of the fuel pellet that is calculated as required for break-even fusion. These fuel pellets typically consist of a thin (1 micrometer) glass microballoon, 100 to 200 micrometers in diameter, containing 10 to 100 atmospheres of a deuterium-tritium gas fuel mixture and having a metal coating to initiate the implosion compression wave. Although crucial data have been obtained from inertial studies with electron and light-ion drivers, it now appears that heavy-ion drivers such as xenon have significant advantages with well-developed accelerator technologies. However, these are still in the design stage.

Plasma physicists generally are optimistic about reaching the break-even point within the next few years in fusion; however, reflecting the truly formidable engineering problems (as compared to those involved in nuclear fission, for example), very few are optimistic that, having achieved break even on that time scale, we can achieve economic fusion-based electrical power before about 2020.

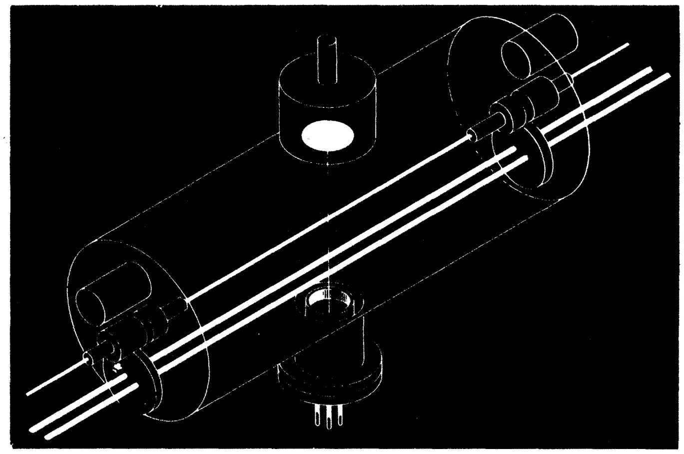

Fig. 4. Single-atom detection is made possible by pulsing a laser beam through a gas proportional counter. A tunable dye laser is used to select atoms of a given type and to remove one electron from each of the selected atoms. Because a proportional counter can be used to detect one electron, a single atom in the laser beam can be detected. One-atom detection is comparatively simple, yet it is so selective that one atom in a volume containing more than 10 billion billion atoms of another type can be singled out and recorded. It also provides spatial definition and time resolution so that selective measurements can be made for a defined volume of space and at an arbitrary time—all at the ultimate limit of one-atom sensitivity. In this example a second laser beam is used to produce the atom by dissociating a molecule. [From Oak Ridge National Laboratory]

Atomic and Molecular Physics

In part because the electromagnetic force is the most fully understood in physics, measurements on atomic and molecular systems have traditionally been possible with a precision very much higher than that attainable anywhere else in physics. This trend continues.

Until recently, a ubiquitous limitation on attainable precision was the familiar Doppler effect reflecting the random thermal motion of target atoms or molecules. In a technological tour de force, it has been demonstrated that the tunable laser makes possible the removal of this limitation, as illustrated in Fig. 3. Currently, accuracies approaching 1 part in 10^{16} are becoming feasible, and if history has taught us anything it is surely that such a major increase in experimental precision leads to revolutionary as well as evolutionary changes in understanding. One part in 10^{16} is on the edge of making possible a direct test of whether the fundamental constants of physics—to which I shall return below—are really constant in time, quite apart from opening up to entirely new study a host of old and new problems in atomic and molecular physics.

The combination of tunable lasers and microwave spectroscopy has also opened up the field of Rydberg atoms—a field dating from 1879. In 1890 Rydberg proposed his famous expression for the wave numbers of an atomic spectral series, $\sigma = C - R(n + \delta)^{-2}$, where n is a running integer, now recognized as the principal quantum number of the radiating state (see Fig. 3), δ an approximate constant, at least for large n, and R a universal constant—the so-called Rydberg number. The quantum mechanical foundations of this expression were among the first results obtained by Schrödinger in 1926.

Only recently has it been possible to explore the high-n atomic domain; clearly the atomic energy-level spacing goes as n^{-2} and becomes very small for large n. But there are other interesting properties: The atomic radius varies as n^2, and indeed if it were possible to fuzz in the electron orbit of some recently studied Rydberg states they would be visible to the naked eye; the radiative lifetime against decay varies as n^3, hence these Rydberg atoms live a very long time; they are highly polarized by an electric field with polarizability varying as n^7; and they are easily destroyed in collisions since their geometric area varies as n^4.

By using tunable lasers to induce the large energy jumps from the atomic ground state and a microwave field to fine-tune among the closely spaced atomic energy levels near the dissociation limit, it has been possible to study Rydberg states having n values $\lesssim 100$. For many reasons these provide marvelous test systems for all manner of atomic phenomena and are being widely exploited.

Of particular interest has been the recognition that suitably prepared Rydberg atoms act as very efficient detectors of room-temperature blackbody thermal radiation from, for example, the walls of the chamber in which the atoms are contained. At room temperature the flux of blackbody radiation is about 25 watts per square centimeter, which corresponds to electric and magnetic fields of about 10 volts per centimeter and 10^{-2} gauss, respectively, at a frequency of 1.5×10^{12} hertz. This electric field can cause a large shift ($\sim$ 2.2 kilohertz) in Rydberg levels relative to the ground state of the atom and are readily measurable. (It should be noted, moreover, that this magnetic field can cause a shift of 1 part in 10^{16} of the atomic hyperfine frequency used in atomic clocks and, as I have noted above, this is now at the level of experimental precision in atomic physics.) Of very great interest here is the question of whether Rydberg atoms can be prepared in suitable states to serve as efficient detectors of cosmic 3 K blackbody radiation.

The recent development of techniques whereby single atoms and molecules can be isolated for detailed study (see Fig. 4) is only part of a general development of methods for preparing atomic systems in completely defined quantum states, making them excellent test systems for very fundamental physical questions: To what extent are the electron and proton charges identical in magnitude (1 in 10^{20})? To what extent are the electron and positron masses identical (1 in 10^{7})? To what extent is the mass of the universe uniformly distributed (1 in 10^{51})?

If, indeed, the weak and electromagnetic forces are unified, then in atoms weak forces are present (albeit very weakly), and a characteristic signature for their presence would be the fact that they violate parity conservation while electromagnetic forces do not. Extensive searches have been made for such violations in heavy atoms, where the effects are predicted to be largest, but the results remain ambiguous because of uncertainties in the calculation of many-body atomic wave functions. The extraordinarily difficult experiments on hydrogen, where these uncertainties should be minimal, are still in progress.

One of the most exciting areas of molecular physics in recent years has been that in which the entire arsenal of physical probes, including x-ray spectroscopy, Mössbauer spectroscopy, and neutron diffraction, has been brought to bear on the structure and dynamics of the large molecules of life. The mechanisms whereby the heme iron-based group in the hemoglobin molecule carries out its vital mission transporting oxygen to the cells of the mammalian body have now, and for the first time, been understood in terms of the quantum mechanical tunneling of the smaller molecule through the series of potential barriers—some small, some large—established by the structure of the larger hemoglobin molecule. This is a major triumph of understanding and one that opens up entirely new vistas of research as the processes of life become accessible to detailed study at the quantum level.

Physics of Condensed Matter

As the ambient temperatures drop to those characteristic of our planet, atoms and molecules coalesce to form the familiar solids and liquids of condensed matter.

Solids. Over the past several decades spectacular progress has been made in understanding and exploiting the structure of solids. Central to this have been the concepts of translational invariance—of periodic crystalline structures repeated infinitely in all directions—and of the electronic wave functions and band structures appropriate to such systems. Recently, however, major attention has been focused on departures from this translational invariance, or long-range order. Perhaps the most abrupt departure possible is that at the surface. And it is here, in surface physics, that some of the most important developments in recent years have occurred. A second departure is in the area of amorphous solids, where short- rather than long-range order reigns; here, too, there has been promise of new understanding and applications (see Fig. 5).

One of the most powerful and wide-ranging new probes for phenomena in both solids and liquids is synchrotron radiation. Long the bane of high-energy electron accelerator designers, it has only recently been recognized as a source of electromagnetic radiation of continuously variable wavelength, ranging from the ultraviolet through the hard x-radiation regions, with intensities many orders of magnitude greater than were previously available.

From studies of photoelectrons and Auger electrons ejected from surfaces by these synchrotron photos it has been possible to learn an enormous amount about surfaces and about the interactions of gases with surfaces. It is now known, for example, that at room temperatures, when a clean aluminum surface is exposed to oxygen, only some of the oxy-

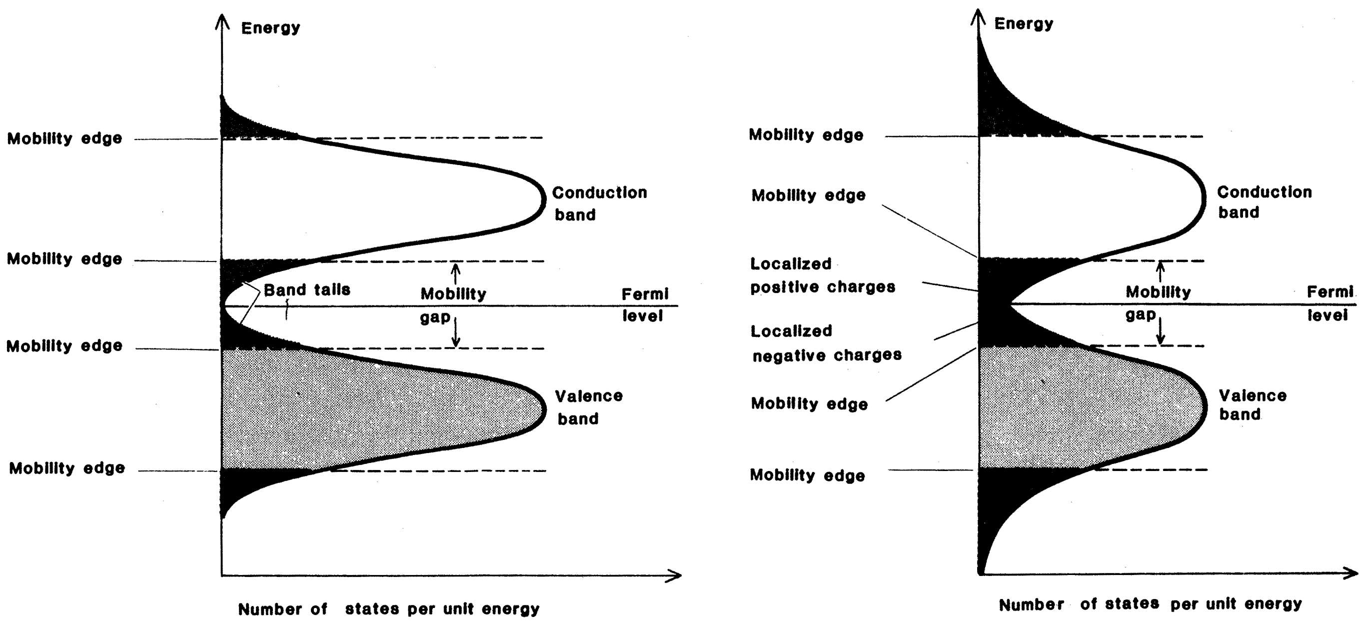

Fig. 5. Amorphous semiconductors that are not strongly disordered (left) have valence and conduction bands similar to those in the corresponding crystalline semiconductor. The distinguishing feature of the bands in amorphous solids is the replacement of the sharp band edges present in crystals by what are called band tails, or localized states, that extend into the energy gap. The localized states are separated from the extended states in the main part of the bands by mobility edges. The region that lies between the mobility edges of the valence and conduction bands is called the mobility gap. It plays the same role in amorphous semiconductors that the energy gap plays in crystalline semiconductors. Chemical impurities or defects in the configuration of local bonds can lead to sharp structural changes (not shown) in the mobility gap. If the disorder is large, as is expected in multicomponent glasses (right), the band tails of the valence and conduction bands can overlap in the mobility gap. This leads to a redistribution of electric charge as electrons move from one localized state to another to lower their energy. The result is a high density of positively and negatively charged traps, which decrease the mobility of the carriers and make the material less sensitive to efforts to modulate its conductivity by chemical means—that is, by doping. [From D. Adler, *Scientific American* (May 1977), p. 36]

gen reacts to form the oxide, Al_2O_3, while a large fraction is chemisorbed to the surface, from which it can be driven, by increasing the temperature, into the oxide form. Similarly, it is known that carbon monoxide molecules, alighting on a clear nickel surface, always align themselves perpendicular to the surface. All this depends on knowing the photon energy precisely, measuring the energy of the ejected electrons precisely, and working backward to deduce the exact chemical and structural environment from which the electrons were removed—and extremely elegant techniques have been evolved for this deduction.

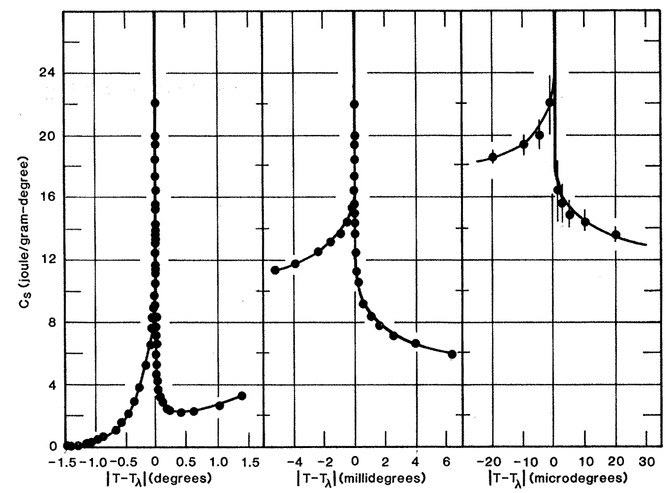

Fig. 6. Specific heat of liquid ^4He in the vicinity of the λ point—that is, the transition from the normal (high-temperature) to the superfluid (low-temperature) phase. Notice that the abscissas are in degrees, millidegrees, and microdegrees in the three panels, illustrating the detailed temperature-dependent structure in the neighborhood of this second-order phase transition. The solid lines are empirical fits to the experimental data points. [From M. J. Buckingham and W. M. Fairbank]

In the field of amorphous solids it is now recognized that band structure—long thought to be characteristic of periodic crystalline structures—persists as a signature of short-range order (see Fig. 5). From this it follows, and has been demonstrated, that many of the electronic devices familiar in solid-state electronics can be achieved in amorphous materials at greatly decreased cost, at decreased sensitivity to contaminants, and in much larger areas. Attention has focused on the development of techniques for immobilizing the dangling atomic bonds that are inevitable in an amorphous material through additions of small atoms such as hydrogen, lithium, and fluorine, and for otherwise modifying the density of states in the band gap to achieve the desired electronic properties.

With both crystalline and amorphous materials, a new technique in which very high power laser pulses of nanosecond duration are used to anneal the surfaces has found wide and dramatic application. By keeping the pulse duration short enough and the power level high enough, only a few hundred angstroms of the surface melts and almost instantly refreezes. In some applications advantage is taken of the fact that not only does this refreezing remove all damage resulting from earlier treatment processes (ion implantation, diffusion, and so on), but also unwanted trace contaminants are generally more soluble in the liquid than in the solid phase and are thus swept to the surface by the solidification front, leaving ultrapure base material in the crucial annealed regions. In other applications, laser annealing is used to create an ultrapure crystalline layer on an amorphous substrate, which can thus be of any desired area. The latter is of particular importance in the production of solar cells and in the tailoring of magnetic bubble memories.

Phase transitions. In condensed matter one of the most dramatic phenomena is the phase transition between solid and liquid, liquid and gas, normal and superconducting or superfluid states, magnetic and nonmagnetic states, and so on. Study of these phase transitions at a fundamental level has been one of the most active areas of modern theoretical physics. I should distinguish first between first- and second-order phase transitions: in a first-order transition the quantity in question (the volume of a substance during a melting transition) changes discontinuously, while in a second-order transition the quantity (the specific heat in the transition from normal to superconducting states in liquid helium) changes continuously and there is a discontinuity in its first derivative (see Fig. 6). Put another way, there is no preliminary evidence of melting at temperatures below the melting point (first order), whereas, as shown in Fig. 6, there is such preliminary evidence in the vicinity of the temperature of a second-order transition to superconductivity (or ferromagnetism). An extensive body of theory involving the so-called renormalization group has been developed in recent years to permit description of this temperature behavior in the vicinity of a second-order phase transition. This work has led to the striking suggestion that in addition to order, the behavior of systems in the vicinity of phase transitions should depend critically on the dimensionality of the problem; that is, melting of a two-dimensional system should be strikingly different from that familiar in three-dimensional systems. Furthermore, a perfect two-dimensional solid would be expected to show none of the sharp Bragg scattering characteristic of neutron and x-ray scattering on a perfect three-dimensional solid. Beyond this, it has been recognized that the effective dimension of a physical situation need not be integral and that, as in the Regge treatments of angular momentum in particle and nuclear physics, dimensionality can sometimes usefully be considered as a continuous parameter.

Such considerations have forced a profound reevaluation of how solids behave and have given impetus to the discovery of other than three-dimensional systems as subjects for study. Effective one-dimensional systems have been found in complex metal-doped organic compounds such as polyparaphenylene, wherein the metal atoms line up to form essentially one-dimensional chain conductors. One of the most fascinating two-dimensional systems is that of a layer of electrons floating on the surface of liquid helium cooled to below 1 K, where the electron concentration can be varied experimentally over very wide limits from 10^4 to 10^9 per square centimeter. Several resonances have been observed in the absorption of radio frequency by this two-dimensional system as it is cooled below a transition temperature T_c, and the accepted interpretation is that a transition to a triangular electron lattice has taken place at T_c.

The goal of the theories in this work is that of reproducing experimental observations in the regions of the second-order critical phase transition points as functions of the temperature T but in the form $(T - T_c)^\beta$ (see Fig. 6), where β is called the critical exponent. It has been found that although β is essentially independent of the specific system—whether it is a ferromagnet or a superconductor or something totally different—it does depend critically on the symmetry of the system and the number of space dimensions involved.

One of the most surprising and gratifying aspects of all this renormalization group work, however, has been the recognition that the entire formalism, appropriately reinterpreted, has direct applicability in general field theory. Here the emphasis is on the field fluctuations and their characteristic ranges; specifically, the focus is on the whole concept of scaling, where we try to evolve a theory that is valid over widely disparate scales of distances. The transfer of phase transition formalism, via the renormalization group, has really come into its own in the concept of asymptotic freedom in quantum chromodynamics, where the predicted quark-quark force decreases—the quarks become free—as we go to ever smaller distances. This is yet another illustration of the essential unity of physics.

Technology-driven research on solids. Fundamental research on the properties of solids in two particular areas is very much technology-driven. We now import more than 90 percent of such materials as chromium, tantalum, cobalt, manganese, and strontium—all essential to various aspects of a high-technology society; worse, the economically viable ore supplies of these materials in the world are dwindling rapidly. We are thus driven to resource replacement and to the provision of new materials that are equivalent structurally and in erosion, corrosion, and other behavior to those already in short supply. This has again brought surface physics into sharp focus and has led, for example, to the development of physical as opposed to chemical alloys, wherein chemically incompatible substances are implanted, by ion beam techniques, to yield the required characteristics. This field is an open and vitally important one.

Increasing pressure for large-scale integration in solid-state electronics also provides impetus for condensed matter research. In 1960 we typically placed one device on a single chip; in 1970, the number of devices was 10^3; and in 1980, it is 10^6. Nor have we come within orders of magnitude of any intrinsic physical limitation. The 10^9-bit chip lies in our future. At the same time we have witnessed cost reduction by a factor of 10^5 in electronic devices in the past 20 years, and we anticipate that the trend will continue while the characteristic reliability and low energy demand of these devices are retained. It may be worth putting this in a somewhat different perspective. The entire contents of the Library of Congress corresponds to about 70 trillion bits of information; currently, it would require 20 of the world's largest capacity, random-access memories to accommodate this information. At presently projected rates of change, the entire contents of the Library will fit comfortably within a single memory unit within the decade of the 1980's. On a more personal note, the average human brain has a bit capacity of about 10^{13}. Twenty years ago an equivalent computer memory would have occupied about one-tenth of a cubic mile; an extrapolation (with some trepidation) of current trends suggests that by 2050 we will be able to fit these 10^{13} bits within a solid-state memory slightly smaller than the human brain.

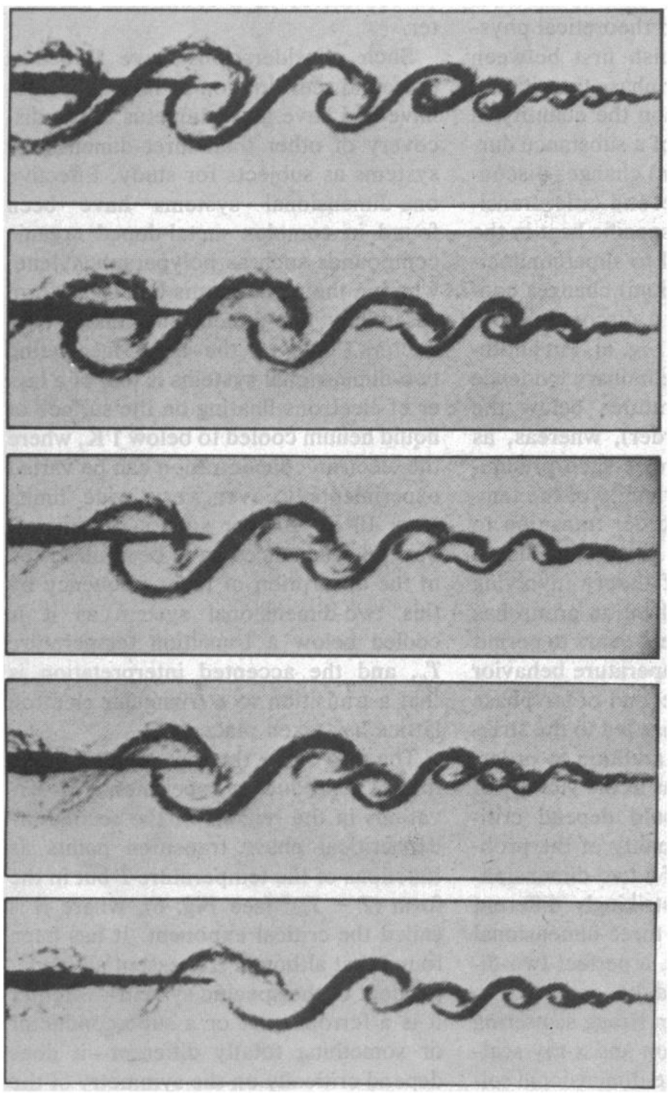

Fig. 7. Shadowgraph showing the turbulent mixing layer between two streams of the same density, both flowing from left to right in each panel. The upper stream is flowing at 10 meters per second and the lower at 3.5 meters per second. The pressure is 8 atmospheres and each panel is 5 cm in height. This sequence was obtained by a group at the California Institute of Technology, using nitrogen and a helium-argon mixture as the materials in the two streams. By using appropriate materials having different characteristics but the same density, it is possible, as here, to scale situations of almost arbitrary dimensions for detailed study.

The ultimate consequences of such developments are beyond our present imaginations, but already they have entirely changed the character of much of physics. We can now ask questions of a complexity and sophistication that would have been out of the question even 5 years ago.

I mentioned above the pairing of nucleons that leads to the s and d bosons which are revolutionizing our understanding of nuclear physics. Pairing of electrons to zero total angular momentum (Cooper pairs) lies at the heart of the earlier and enormously successful Bardeen-Cooper-Schrieffer model of superconductivity in metals. Experimental work in this area is now addressed to the search for higher transition temperatures; a reliable superconductor with a working temperature above the boiling point of liquid hydrogen at 21 K (obviating the need for helium) would be a great technological boon.

Fluids. Superfluidity of the light isotope of helium, ^{3}He, has greatly extended our knowledge of quantum phenomena, since its characteristics are totally different from those of superfluid ^{4}He; this reflects the fact that ^{3}He nuclei are fermions while ^{4}He nuclei are bosons. In contrast to the Cooper pairs of electrons that have a relative angular momentum of zero, the ^{3}He nuclei in the superfluid pairs have one unit of angular momentum; in consequence, this superfluid displays "texture" and marked anisotropies with respect, for example, to an applied magnetic field that serves to orient the pairs macroscopically. This remains a wide open field of quantum physics.

In the area of classical fluids, turbulence stands out as one of the major unsolved problems of modern physics. On the borderline between ordered and disordered motion, turbulence has resisted mathematical treatment—falling, as it does, between the realms of simple approximation and of statistical simplicity. And yet it is ubiquitous in our technological society; it results in jet engine noise, in heart valve failure, in conditioning much of our weather, and in accounting for much of the lost energy in high-speed transportation. Turbulence theories have been proposed by applied mathematicians, beginning essentially with a Moscow group in 1941, but it was not until around 1950 that these theories were introduced into Western Europe and North America. The time correlation function approach to fluid mechanics was introduced in 1955 and continues to be exploited, primarily in the U.S.S.R., while ever larger computer simulations have characterized work in Europe and the United States.

Recently this problem has been taken up again in the United States, and substantial progress has been made. This can be illustrated with one of the simplest cases, a slab of fluid uniformly heated from below. At low heat flow, the fluid flow is laminar and uniform. As the heat flow is increased, a first instability, predicted long ago by Rayleigh, appears in the form of convection rolls (see Fig. 7), which are periodic in one dimension and of infinite length in the perpendicular dimension. As the heat flow increases these convection rolls begin to oscillate sinusoidally along their length, and as it further increases additional modes appear sequentially. It is characteristic of these modes that the period of each new mode is double that of the mode preceding it. As more and more modes appear the system has a longer and longer time separation between repetitions of a given configuration, and in the limit when this separation becomes infinite (that is, the system never repeats) we have turbulence.

It has also been demonstrated that inclusion of a nonlinear coupling linking even the lowest three modes will also lead eventually to turbulence. This work has led to the introduction of the so-called strange attractor surfaces in the phase space of the problem. System trajectories not originally on these surfaces move toward them, and once they reach them remain on them and move chaotically as a turbulent signature. We have only begun to exploit this new insight into fluid behavior.

Among the fascinating questions that remain open in fluid physics are those associated with the movement of tectonic plates—of the continents themselves—over the face of our planet. Having moved rapidly from a far out idea to generally accepted truth in a remarkably short time, the mechanisms underlying plate tectonics remain essentially unknown. So also are the details of the mechanisms responsible for geomagnetism.

Relativistic Astrophysics

One of the most important discoveries in modern astrophysics was that of the 3 K blackbody cosmic radiation—the Doppler-shifted echo of the primordial Big Bang. Recent measurements confirmed that this radiation is truly of blackbody character, but showed that it has a small directional anisotropy that can be interpreted—in terms of a Doppler shift—as proof that the solar system is moving in the direction of the constellation Leo with a velocity of several hundred kilometers per second. Permeating all space as it does, this K radiation in effect gives

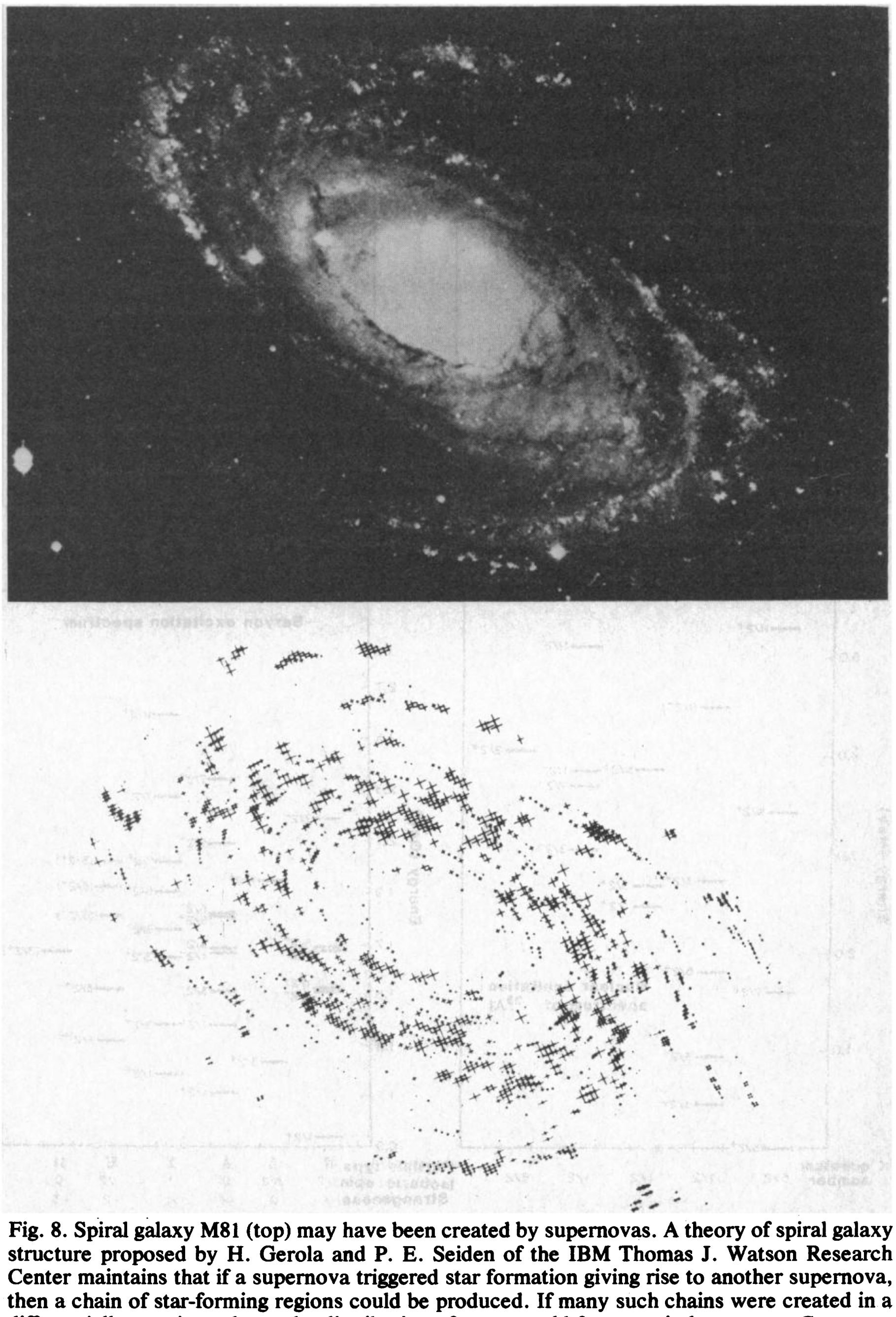

Fig. 8. Spiral galaxy M81 (top) may have been created by supernovas. A theory of spiral galaxy structure proposed by H. Gerola and P. E. Seiden of the IBM Thomas J. Watson Research Center maintains that if a supernova triggered star formation giving rise to another supernova, then a chain of star-forming regions could be produced. If many such chains were created in a differentially rotating galaxy, the distribution of stars would form a spiral structure. Computer simulation of this theory for the M81 (bottom) gives rise to a distribution of bright infant stars (crosses) that looks like the actual distribution (top).

us a uniform background, a new ether, against which motion of the material elements of the universe can be tested.

Among the most dramatic denizens of the night sky are the spiral nebulae, whose very appearance suggests that they should be amenable to relatively simple physics. This has not been the case, and none of the mechanical or hydrodynamical models has been successful in reproducing the obvious stability of the spirals over very long times. It was thus of great interest—and indeed highly instructive to physics generally—when a group of researchers with primary training in biology remembered that in biological systems short-range ordering can lead to long-range effects (physicists should have learned this from amorphous solids). Building on this recognition, the group evolved a very simple physical model dividing the general space occupied by a nebula into cells with a random probability of a supernova occurring in each; the shock wave from the supernova was assumed to stimulate star formation in adjacent cells, and the whole volume was given an angular velocity. Rather convincing support for this shock-wave hypothesis has been obtained in the preliminary x-radiation findings from the new Einstein satellite observatory. As shown in Fig. 8, not only does this model generate characteristic star patterns very reminiscent of the spiral galaxies, it also exhibits the desired long-term stability.

Surely one of the most striking processes in physics is that of gravitational collapse; but it is a process which we still do not understand, although steady progress is being made. It is known that in following the evolutionary track long ago identified for them by Hertzsprung and Russell, stars having initial masses less than about 1.4 times that of our sun are destined for white dwarf status; the system is stabilized by electron degeneracy pressure at a density of some 1000 tons per cubic inch and radiates energy until it becomes a clinker in space—a somewhat ignoble end. For stars with initial masses between 1.4 and 2 times that of our sun, neutron degeneracy pressure resists gravitation and stabilizes the system at a mean density of about 10^9 tons per cubic inch—they become neutron stars, giant quantum mechanical systems some tens of kilometers in diameter.

The neutron star is such a marvelous entity that if it did not exist we would almost have had to invent it. All of classical and quantum physics is required for its description. Its solid crust is believed to consist of the purest iron found anywhere in the universe; just under this is a thin sphere of superconducting protons maintaining a surface magnetic field of 10^{12} G, and this, coupled with a high rotational velocity, leads to a surface electrostatic field of 10^{12} V/cm. The superconducting shell encloses a neutron superfluid having zero viscosity. As a superfluid, this inner neutron sphere cannot rotate coherently; instead, an array of tiny vortices (whirlpools) must develop, all having axes parallel to the star's axis of revolution—current theories suggest perhaps 10^4 such vortices per square centimeter in a triangular lattice array. Near the center of such a star, where densities approach 10^{15} grams per cubic centimeter, neither the composition nor the structure is known. We simply do not know the equation of state for matter under such extreme conditions.

For stars having initial masses greater than 2 solar masses, even the neutron degeneracy pressure cannot resist gravitation, and the collapse continues. It may well be that stable quark stars eventually develop, and it is clear that what happens in the collapse must depend on the

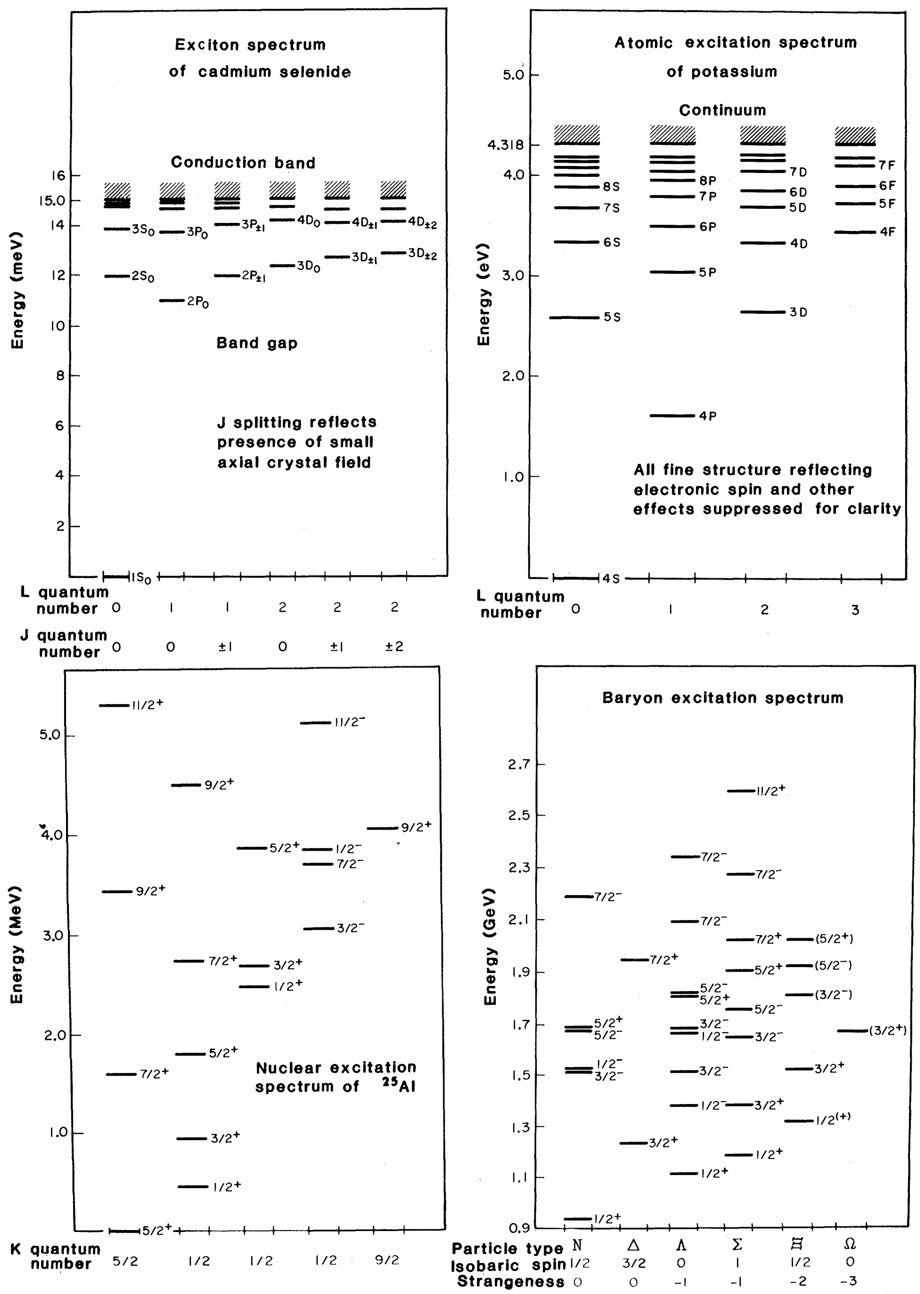

Fig. 9. Quantum excitation spectra for four different physical systems. In each case the spectra have been drawn to show the typical classification of quantum states into families having common quantum numbers. Particularly striking is the similarity in general appearance of these spectra, despite the range of 10^{12} in the excitation energies involved. The exciton is an entity formed by the electron raised from the valence band of a solid coupled to the hole from which it was removed; the potassium spectrum is that of the extranuclear electrons; the nuclear spectrum is that of the nucleon configurations in ^{25}Al with increasing excitation energy; and the baryon spectrum is that of the underlying quark configurations (here only u, d, and s) that make up these baryons.

ultimate structure of matter as determined in elementary particle physics. But long before the more exotic collapse phenomena can be manifested, the surface gravitational fields reach such magnitude that even photons projected outward from the surface fall back. A black hole forms, forever cut off from the rest of the universe, characterized only by its mass, angular momentum, and electrical charge. Much of the apparent missing mass of our universe may indeed be lurking in such black holes, if not in the tau neutrinos mentioned above.

An intriguing speculation is that small primordial black holes, formed as a consequence of density fluctuations in the original Big Bang, may still exist. Our view of the demise of such holes has been changed radically by the realization, only a few years ago, that our entire picture of gravitational collapse was a classical nonquantum one. Introduction of the concepts of quantum theory, in particular the possibility of matter pair creation in the very strong fields existing near the surface of a collapsing star, has raised the possibility that black holes may not be entirely cut off from the universe; while one member of a created particle-antiparticle pair may indeed be captured by the black hole, the other member can escape, thus evaporating energy from the hole.

The last stages of black hole evaporation would be expected to be violently explosive. Current calculations suggest that if primordial black holes exist, and if there are any in our part of the universe, then such black holes—having the mass of Mount Everest packed within the diameter of a hydrogen atom—would just about now be reaching their explosive phase. Their temperature—about 10^{12} K—would be unrivaled by anything since the primeval fireball of the Big Bang.

Among the most important recent observations in astrophysics has been that of gamma-ray bursts. Since 1973, earth-bound satellites carrying gamma-ray detectors have shown about 100 different bursts of gamma radiation occurring characteristically in times of the order of 1 second, but no information was available on the source of these bursts. On 5 March 1979, a burst 100 times more intense than any previous one was finally pinned down, by an international array of solar system satellites, as almost certainly originating from the supernova remnant N49 in the Large Magellanic Cloud. The burst, 0.15 second in duration, can then be calculated as having released gamma-ray energy at a rate of some 10^{45} ergs per second, exceeding the luminosity of our entire Milky Way galaxy. An entirely consistent picture emerges if we postulate that the neutron star remnant of the N49 supernova underwent some internal adjustment on 5 March 1979—a starquake—and the corresponding shift in the surface, with its enormous electromagnetic fields, accelerated electrons sufficiently to produce electron-positron pairs, which subsequently decayed with emission of characteristic 511-keV photons. But because of the neutron star's intense gravitational field, these photons were gravitationally red-shifted to the 400-keV line actually measured by one of the Soviet satellites.

So cataclysmic an event in our sister galaxy would be expected to have produced gravitational as well as electromagnetic radiation, and the owners of gravitational wave antennas operational on 5 March 1979 are searching their records for even slight evidence of the event, since the sensitivities of existing antennas are still probably marginal. The coming generation of gravitational wave antennas with large sapphire bars, ultralow temperatures, and ultrasensitive strain measuring devices promises to open up entirely new domains of gravitational physics to experimental study.

We have already made impressive progress in understanding our universe, given that we have viewed it only through the rather narrow electromagnetic wavelength windows in our atmosphere that are transparent. Space technology has given us a few primitive satellite observatories outside the atmosphere, and these have already revolutionized our understanding. With the major expansion of extra-atmospheric observation that the Shuttle technology will permit—at all wavelengths from radio waves to hard gamma radiation—I am confident that we will be repeatedly surprised and that our current knowledge, impressive as it may be, will prove to be merely a glimpse of the wonders that nature has in store.

Conclusion

It has frequently been suggested that physics, like many other sciences, is fragmenting into ever finer subfields and specialties which rapidly cease to communicate with or understand one another. Although this may appear superficially true, I have tried to show that it is actually far from the case; the concepts, techniques, and technologies of physics are rapidly transferred from subfield to subfield and this transfer is frequently our greatest strength. And we do speak a common language. Although the scales change, the underlying physics is not all that different. In Fig. 9 I show typical excitation spectra for excited quantum systems in condensed matter, atomic, nuclear, and elementary particle physics. While the ordinates change by a factor of 10^{12}—from millielectron volts to billions of electron volts—the characteristic behavior is remarkably similar. And frequently the most exciting developments and the most important advances take place in the interfaces between our artificial subfield boundaries; this is far from accidental.

Lest anyone become convinced, however, that we understand more than we really do about nature, let me conclude by considering some of the basic constants of our universe. Expressed in a fundamental unit, the time it takes a photon to cross an elementary particle, the age of the universe is $\sim 10^{40}$; its diameter, also expressed in terms of the elementary particle, is $\sim 10^{40}$; the ratio of the strong nuclear to the gravitational force between elementary particles is $\sim 10^{40}$; and the mass of the universe, expressed in proton masses, is $\sim (10^{40})^2$. This gives us the distinct impression that nature is attempting to tell us something but we have no idea what it might be. We do not know why this common very large number 10^{40} appears; we do not know why it is common; nor do we know how, or if, it changes with time. It has been long suspected that, reflecting the expansion of the universe, the gravitational constant G may decrease systematically with time—and that the other so-called fundamental constants such as the elementary charge on the electron and proton may also change. Studies of the relative abundances of nuclear isotopes such as ^{187}Os and ^{187}Re have shown that this change (if any) in the electronic charge during the 4.5-billion-year lifetime of the solar system has been less than 1/300 of the rough predictions of the G-varying model. We simply do not understand what appears to be a simple common aspect of our universe—but we have, after all, only been observing it scientifically for a tiny fraction of its 12 billion or more years.

Obviously, in a review covering as broad a scope as this one I cannot hope to acknowledge and reference my indebtedness to the very large number of persons whose work I have quoted or drawn upon. But I am particularly indebted to my colleagues and students at Yale with whom I have had the pleasure of discussing many of these matters on many occasions, as well as to Phil Abelson for the challenge to undertake this review and to Frances DeGrenier for her help in preparing it.