TWENTY YEARS OF PHYSICS

THE NUCLEUS

By D. ALLAN BROMLEY

NUCLEAR PHYSICS emerged from the war years in the 1940's as a field rich in applications but pitifully weak in fundamental understanding. In the next two decades, building on the impetus and insight achieved in the crash program of the 1940's, major progress has been made both in understanding and in application. The rich canvas of nuclear phenomena has been sketched in, and exquisite detail has emerged in many areas. Many other areas remain blank and await exploration and exploitation; indeed it has been necessary, repeatedly, to extend the boundaries of the canvas itself. Nuclear physics remains in the frontiers of man's understanding of his universe. To a unique degree it has also forced significant changes in contemporary society and civilization.

Nuclear physics may be characterized as that branch of quantum physics, or more particularly strong-interaction physics, which deals with systems having baryon number greater than one. In other words, the nucleon is the fundamental system unit.

The existence of nuclear physics as a separate discipline reflects a delicate balance in the strong interactions. At distances comparable to a nucleon Compton wavelength the strong interactions are extremely strong, of the order of GeV, and operable only between nucleon pairs. Their effect is repulsive, thus preventing the formation of elementary particles of baryon number greater than 1.

The range of the force between two nucleons is characteristic of the pion Compton wavelength and includes a weakly attractive region just strong enough to form a single, two-nucleon, bound state—the deuteron. Were it not for the small pion mass, models describing complex nuclei as combinations of individual nucleons would represent singularly poor approximations, and the mean level spacings for the higher baryon numbers, the isotopes of the natural elements, would be of the order of GeV as in the elementary particles. Because of the difference between the pion and the nucleon masses however, a nonrelativistic local nucleon wavefunction is acceptable, and typical nuclear level spacings would be estimated to be smaller than or equal to $M_\pi^2/2M_N = 10$ MeV. This spacing results in a wealth of quantum phenomena easily accessible to detailed study.

As an assembly of limited numbers of strongly interacting entities, the nucleus poses some of the most interesting many-body problems in physics. It bridges the gap between the few-body problem characteristic of elementary particles and the extreme many-body problems characteristic of solid state, theory of metals or plasma physics. In the former, detailed microscopic calculations are possible, at least in principle, whereas in the latter, only statistical approaches are feasible. In bridging the gap, nuclear phenomena hold promise of providing a unified understanding of many-body problems generally.

As the only many-body system in which all the known natural forces act simultaneously, the nucleus also provides a microscopic laboratory for the examination and testing of fundamental conservation and symmetry laws underlying all of physics. Extensive advantage has been taken of this possibility only in recent years; many vital problems remain.

NUCLEAR MORPHOLOGY

We begin with an overall look at the size and shape of the nucleus. After two decades we continue to be surprised by even the gross behavior of the nuclear shape. The constant density of nuclear matter (at some 240 million tons per cm^3) ensures that the nuclear radius is roughly proportional to $A^{1/3}$, where A is the atomic number. Increasingly detailed electron elastic-scattering measurements from Robert Hofstadter and his group at Stanford have pinpointed systematic deviations from the gross behavior. Light nuclei are essentially all surface, whereas extremely heavy nuclei, in addition to a relatively thin skin layer, may have lower central density, reflecting mutual electrostatic repulsion of their protons. More important, very recent electron-scattering measurements, together with studies of mesic-atom x radiation and to a lesser extent scattering of protons, have demonstrated conclusively that essentially all nuclei have a neutron halo—the neutron distribution extends beyond that of protons. The electron-scattering studies at very high energies (500–750 MeV) are now sufficiently precise also to show systematic radial charge-density fluctuations. These are predicted as corresponding to the individual orbital groups in a shell model but are strongly damped relative to model predictions. This marks only the beginning of an attack on the deep internal structure of nuclei.

NUCLEAR STRUCTURE

In the late 1940's, the technology, the instrumentation and the new nuclear

The author's first nuclear-physics job, junior research officer for NRC, Canada, started 1 May 1948. After earning a PhD at Rochester in 1952 he stayed three more years, and then went to Chalk River. In 1960 he came to Yale, where he is professor and director of the Wright Nuclear Structure Lab.

insight gained during the Manhattan Project were brought to bear in enthusiastic and imaginative fashion on the task of acquiring systematic bodies of information regarding nuclear systems. Earlier work had been of rather limited and fragmentary character.

By 1949 an enormous mass of largely uncorrelated data relating to nuclear electromagnetic moments, spins, level excitation properties and spectra had been accumulated. One of the most striking features of these data was the clear-cut evidence for magic numbers—certain numbers (2, 8, 20, 50, 82 and 126) of either neutrons or protons for which particularly stable structures were apparently attained, which is reminiscent of the noble gases in chemistry. Despite strenuous efforts, however, all attempts to construct a shell theory for nuclear structure in analogy with the familiar atomic-structure models met with complete failure until 1949, when Maria Mayer, and independently J. Hans D. Jensen and his collaborators, recognized the crucial importance of the spin–orbit interaction for nuclei.

Shell models

With this addition to the earlier shell models, spectacular success was achieved; the observed magic numbers appeared automatically as a consequence of energy gaps in the predicted model sequences. With remarkably few exceptions, all ground-state spin data could be correlated with the simplest possible shell model wherein for even numbers of neutrons and protons, the individual spins and orbital angular momenta were paired to a resultant zero nuclear spin, whereas for an odd number of one nucleon species and an even number of the other, the nuclear spin was attributable entirely to the odd nucleon as, indeed, was the major part of the magnetic dipole moment. In regions near magic numbers, moreover, the excitation spectra were understandable as reflecting promotion of the odd nucleon into higher shell-model states relative to an inert core or as reflecting removal of a nucleon sequentially from the different shell-model states of the core.

Although graced with remarkable success, such extreme independent-particle models were obviously oversimplified and were replaced by intermediate-coupling models wherein all nucleons lying outside the nearest magic core (the valence nucleons) were considered on an equal footing, bound to the core, and interacting with each other through assumed residual interactions not already incorporated in the interaction with the core. With this added sophistication, and of course parameter freedom, the shell models correlated a remarkable body of nuclear data and provided a measure of order in the chaos that had existed in the late 1940's.

Indications of other trouble appeared almost at once, but were largely ignored in the general enthusiasm for correlation of data. Electric quadrupole moments were systematically much too large to be explained entirely by the valence nucleons. James Rainwater, in 1950, suggested that this could only imply that the core nucleons were also involved and that this in turn implied a nonspherical shape for the core except in the case of closed-shell configurations. This suggestion of collective nuclear motion was of crucial importance.

Collective models

In its simplest and least precise form, the collective model developed by Aage Bohr and Ben Mottelson in Copenhagen, recognized that the equilibrium nuclear shape resulted from an effective competition between the long- and short-range components of the nuclear force in favoring deformed and spherical shapes respectively.

Striking evidence for the statically deformed shapes came from the characteristic $E_J = AJ(J+1)$ excitation spectrum of a quantum-mechanical rotor, which had already been found in many regions of the periodic table. Similar evidence for vibrational character was found in the equispaced excited spectrum $E_n = (n + \frac{1}{2})\hbar_\omega$ characteristic of some nuclei that are in regions between closed shells and the deformed regions where on the basis of the above simple model, not enough valence nucleons are present to stabilize core deformation.

Interrelationships of models

The simple collective models were quickly extended to yield generalized shell models differing from the previous ones in that the potential defining the individual nucleon orbitals assumed a deformed spheroidal shape to match that of the matter distribution, as would necessarily result from any Hartree–Fock or self-consistent treatment of the problem.

The resulting generalized, collective, nuclear models again correlated an enormous number of nuclear data and suggested new measurements. Although they were initially developed for medium- and heavy-mass nuclei, in 1957, A. E. Litherland and collaborators found that even very light nuclei had striking collective characteristics. This posed a marked advantage inasmuch as these light nuclei had a sufficiently limited number of nucleons present so that a detailed, intermediate-coupling, shell-model calculation was also feasible, and the two model results could be intercompared. Eric Paul, in 1956, emphasized the remarkable fact that in the case of F^{19}, with the data then available, these models agreed with one another better than did either with experiment. This, in turn, led Philip Elliott and Brian Flowers to their SU(3) group-theoretic approach to shell-model calculations. In essence this approach specified certain linear combinations of the shell-model wavefunctions that provide almost complete overlap with the collective wavefunctions and permit a systematic classification of shell-model states to yield collective behavior.

Although this work illuminated the interrelationship of these two model approaches for light nuclei, simple shell-model considerations were not adequate to reproduce the characteristic "collective" phenomena in heavy nuclei (namely, in even–even nuclei, for example, the low excitation of the first excited 2^+ state, the strong electric-quadrupole matrix element connecting it with the ground state 0^+ and the gap ~ 1 MeV in excitation, before more complex levels are encountered). Two other shell-model failures became apparent; it could not reproduce observed total energies of nuclei, and it gave no simple prescription for the mixing of configuration that has been demonstrated by experiment.

Three major theoretical attacks were mounted in attempts to remedy these failures. Brueckner theory was developed to represent more correctly nuclear binding energies; whereas the force between two nucleons is taken into account to only first order in ordinary shell theory, here it is taken to all orders. Other than binary nu-

clear interactions are entirely ignored so that in effect Brueckner theory is an independent-pair model, in contrast to the earlier independent-particle models. Applied first to considerations of postulated infinite nuclear-matter systems and elaborated by many en route, this theory now gives a reasonable representation of nuclear binding energies, the radii of selected closed-shell nuclei such as Ca^{40} and O^{16} that have thus far been calculated, and most recently the interaction potential measured between colliding O^{16} nuclei in heavy-ion studies at Yale.

The second and third theoretical attacks, pairing and collective-motion theory, were developed in analogy with the approaches used for superconductivity and in plasma oscillations, respectively. These latter theoretical attacks focus on the relative energies of low-lying excitations in nuclei rather than on the absolute binding energies as above. Although this separation is artificial, it is based on the not unreasonable assumptions, first, that the very strong, short-range, two-particle correlations are not essential for the prediction of such relative excitations although they critically affect the binding energies and, second, that the configuration mixing, which is important for the highest energy nucleons, is that involving their transfer from orbits near the top of the Fermi sea to available empty low orbits above it together with the resultant particle-hole coupling.

New collective models

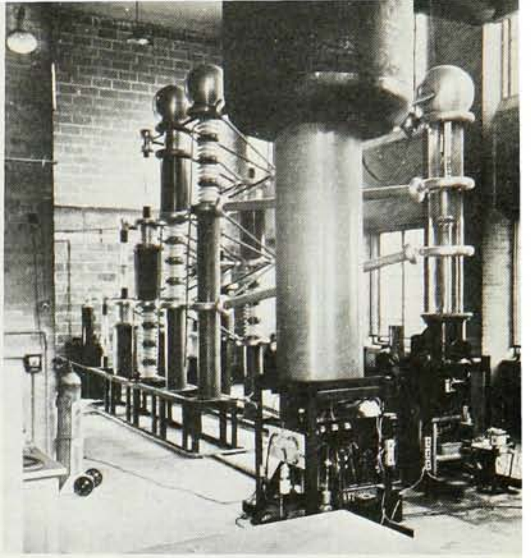
With very few exceptions the nuclear collective models have been treated empirically with the model parameters established through systematic fitting of nuclear data. Bohr's collective Hamiltonian, which is basic to much of current work, was derived from hydrodynamic considerations and involves seven, essentially arbitrary, functions of the nuclear-shape parameters that customarily have been fitted to experimental results. Quite unexpected experimental results during the past few years have forced a much more microscopic treatment.

Characteristic of nuclear vibrational models has been the assumption of an equilibrium spherical shape with respect to which the vibrations are parameterized. In such a model no electric quadrupole moment is possible, and it was thus with considerable surprise that Cd^{114}, one of the assumed best examples of a vibrational nucleus, was found to have an electric quadrupole moment, in its first 2^+ excited state, that was nonzero—and indeed comparable in size to that for a well defined rotor nucleus.

In an attempt to understand this apparently contradictory result, Michel Baranger and Krishna Kumar undertook a microscopic study of the osmium nuclei that span the transition at the upper end of the rare-earth region, from strongly deformed to essentially spherical nuclei. Assuming a pairing plus quadrupole nucleon–nucleon interaction they first calculated the seven Bohr Hamiltonian parameters with Hartree–Fock techniques and with the resulting Hamiltonian predicted the static and dynamic properties of the osmium isotopes. In 1967 these predictions were tested experimentally at Yale, Brookhaven and Oak Ridge, and found to be in remarkable accord with the new measurements. They are harbingers of a new era in nuclear theory of complex nuclei of a much more fundamental nature than has been available previously. Here the fundamental input is an assumed nucleon–nucleon interaction. The approximations are still extreme and the internal structure of the theory somewhat obscure because of the formidable calculational problems involved. However, a most promising start has been made.

Optical models

Although introduced initially by Robert Serber and collaborators, in 1949, to explain the forward production of intense neutron fluxes in deuteron bombardment, the nuclear optical model, in which the potential experienced by an incident projectile is assumed to have both real and imaginary components to include reflection, refraction and absorption, was effectively developed in 1954 to reproduce systematic low-energy neutron scattering and absorption measurements. It has proven to be a most convenient parameterization and representation of the gross characteristics of nuclear interactions. Only in recent years, however, have parameters for the real and imaginary potential wells been adequately established for all light projectiles. This field has become so highly developed that utilization of existing parameter sets permits prediction of neutron-scattering cross sections to better than 1% over the energy range less than 14 MeV—a fact of enormous consequence to nuclear engineers as well as to nuclear physicists. Nucleon–nucleon potentials have also been synthesized from realistic nucleon–nucleon interactions, and the former have been combined to produce nucleus–nucleus potentials appropriate to the interaction of complex ions.



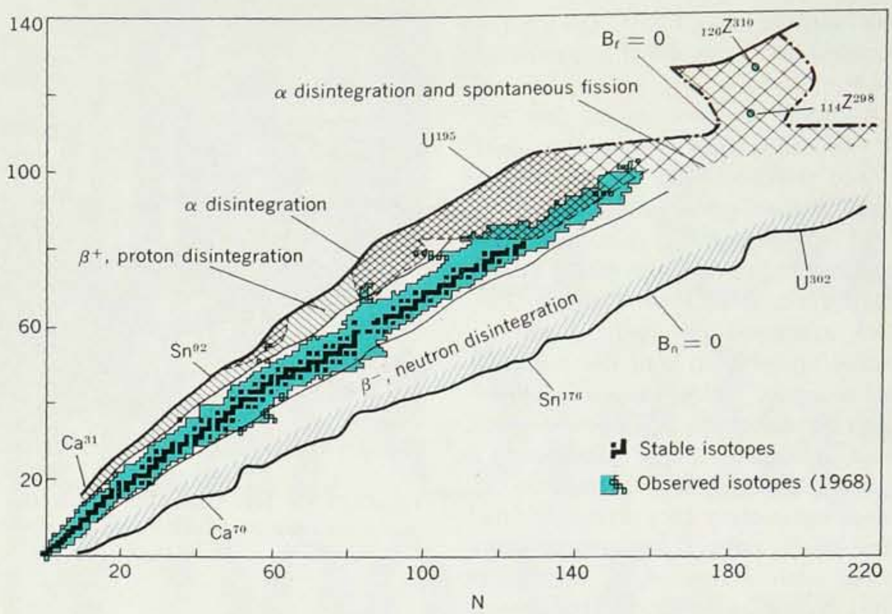
3.5-MV VAN DE GRAAFF accelerator began running at Chalk River in 1948.

Since it is clear that, in any reaction, the incident projectile and the emergent product must scatter in the field of the target and residual nuclei respectively, it is not surprising that the resultant distortion of the incident and outgoing particle waves can be adequately represented by the corresponding optical-model solutions, giving rise to the ubiquitous distorted-wave Born-approximation (DWBA) techniques for the extraction of nuclear-spectroscopic information (matrix elements) from reaction data.

Polarization phenomena have indicated the necessity for including a specific spin–orbit potential in addition to the dominant central terms of the optical model. More recently it has been found necessary to include an isospin term in the potential to reflect the fact that it is deeper for protons than for neutrons.

Isospin-analog states

Isospin is an old concept in nuclear physics introduced by Werner Heisenberg in 1932; it is the quantum number that characterizes the nuclear system beyond those required in the atom. In 1937 Eugene Wigner developed the connection between isospin and the



EXTENDED NUCLEAR CHART. The $B_n = 0$ line indicates the onset of instability against direct neutron decay; above that line delayed neutron emission is possible following primary β^- weak-interaction decays. Delayed proton emission following β^+ decay occurs to the left of the valley of stability. The limiting isotopes, as calculated for calcium, tin and uranium, are indicated to provide a measure of the vast number of nuclear species still unobserved. Spontaneous fission acts to limit the regions of calculated stability for heavy species; exact calculations are difficult since the probability for spontaneous fission characteristically changes by eight orders of magnitude for each MeV change in effective barrier height. (Figure from G.N. Flerov.)

charge independence of nuclear forces, but for the next 25 years the isospin formalism was applied only to very light nuclei ($Z \leq 10$) since it was universally believed that in heavier nuclei the Coulomb matrix elements would be such as to mix differing isospin states almost completely. In 1961 Bruce French and Malcolm Macfarlane first suggested that isospin would retain its utility as a nuclear quantum number even in much heavier nuclei; this suggestion received striking confirmation in the same year with the discovery of isobaric analog states in heavy nuclei by C. A. Anderson and Calvin Wong.

As was discovered by John Fox and collaborators, in 1964, these states may be studied as resonances in the scattering of protons, for example, so that the full power of resonance techniques can be brought to bear on the effectively equivalent problem of the structure of the low lying parent states. In recent years the study of isobaric states per se and their utilization as probes of nuclear structure has occupied a large fraction of the total research effort in the field.

NUCLEAR REACTIONS

During the decade following 1948, a major fraction of study in nuclear reactions and scattering was accomplished with relatively low-energy projectiles (frequently less than 5 MeV); so the major part of the work involved study of resonant interaction proceeding through well defined compound states. This spectroscopy, utilizing the available methods of the quantum theory of angular momentum in the analysis of angular-distribution and correlation data, has provided an enormous body of data concerning nuclear dynamics.

As available energies increased, coupled with adequate energy resolution to permit isolation of individual residual states, emphasis in reaction studies shifted to direct interactions that effectively involve coherent summation over a very large number of distant resonance in the intermediate system; the detailed microscopic analyses typical of the resonance studies were replaced by more macroscopic optical analogies (Fraunhofer and Fresnel diffraction, etc.) and by other rather grossly approximated reaction theories.

In 1960, Torlief Ericson noted that proper application of statistical correlation techniques to reaction excitation functions under such conditions (where something approximating a continuum of intermediate states were involved) could permit extraction of the average energy width, hence lifetime, of these intermediate states. This has been widely exploited, and the systematics of such lifetimes have recently been established as functions of both excitation energy and of atomic number.

Stemming from Stuart Butler's classic paper in 1952, direct transfer reactions, in which one, or at most a limited number, of nucleons are exchanged between projectile and target, have proven to be the most prolific source of nuclear-structure information. Those involving transfer of single nucleons have probed the location and structure of single-particle and single-hole states in direct fashion. When more than one nucleon is transferred, coherence phenomena enhance the sensitivity of the reaction to small as well as large components of the state wavefunctions involved and to the phases of these components as well. Although these reactions are now very well understood for light projectiles ($A \leq 4$), the situation with heavier projectiles is still in its infancy both experimentally and theoretically.

NEW ISOTOPES, ELEMENTS

Having remained at 92 for some 4 billion years, the number of elements had increased to 96 in 1947. The continuing program of transuranic-element study by Glenn Seaborg and his collaborators at Berkeley pushed this number to 103 in 1961; that by G. N. Flerov and his collaborators at Dubna contributed element 104 (kurchatovium) and most recently (Sept. 1967) element 105, as yet unnamed. From here the focus has moved to much heavier species. Shell-model calculations have suggested that rather than decreasing steadily, as have the lifetimes of the new elements thus far discovered, more stable species may appear with increasing mass. There exists the possibility that one or both of elements 114 and 126 may correspond to the next magic proton number beyond the 82 of lead. Coupled to the next open magic neutron number of 184 it would be expected that the isotopes of mass 298 and 310, respectively, would have particularly stable (doubly magic) structures and thus lifetimes that have been estimated in the range from seconds to days.

In 1948 the number of known isotopes of the stable elements numbered perhaps 500; in 1968 the number is closer to 1600. Flerov has estimated that bombardment of uranium with 3-GeV uranium ions will provide at least 5000 isotopes. It has become clear that exploration into the far wings of the valley of beta stability in a nuclear chart provides vital new input into our understanding of the systematics of nuclear structure. Whereas the fission process provides an important production mechanism for the neutron-rich species, to the right of the valley, heavy-ion reactions and heavy-ion induced fission provide an approach to a wealth of new proton-rich species to the left of the valley. These may be of particular importance in testing the most recent predictions concerning nuclear equilibrium shapes in previously inaccessible regions where neutrons and protons continue to fill the same shell-model orbitals.

Although the semiempirical nuclear-mass (or binding-energy) formulas were first proposed by Carl F. von Weizsäcker in 1935 and have been repeatedly improved and modified thereafter, it was only in 1966 that formulations were devised that permitted extrapolation with some confidence far from the valley of stability and prediction of relative stability against decay by strong interactions (for example, essentially instantaneous decay by way of nucleon emission). Using such a formula, one can predict that, for example Sn^{92} and Sn^{178}, and U^{195} and U^{302} have such stability.

HIGH-ENERGY STUDIES

Nuclear physicists have enthusiastically utilized all available accelerating facilities in the many-hundred MeV and GeV energy range, where it becomes possible to probe the internal nuclear structure. Perhaps the most important studies have been of the p, 2p variety, in which a nucleon can be removed from a shell-model configuration throughout the nuclear volume. These were initiated in Uppsala in the early 1950's and extended subsequently and to higher energies in many laboratories. The advantage here is that at higher energies the impulse approximation becomes valid and analysis of the experimental results is greatly facilitated. Vitally important problems now under attack are those of determining the nucleon momentum distribution in nuclei and the extent to which nucleon correlations or clustering are important. There is already evidence, from 1-GeV proton and alpha-particle studies, for binary clustering of nucleons (into "deuterons") in light nuclei and for clustering of nucleons in the periphery of medium and heavy nuclei into quasi-alpha particles. No unambiguous evidence yet exists to suggest that other than two-body forces are required within the nucleus. The new high-energy measurements will allow a direct estimate of the magnitude or limit on specific three-body or many-body interactions.

Scattering and interaction studies with both high- and low-energy pions are in their infancy but hold great promise as probes for internal nuclear structure. The meson factory now under construction at Los Alamos will open a new era in nuclear physics, an era that was only glimpsed before the demise of the Cosmotron.

A MICROSCOPIC LABORATORY

As noted above, the nucleus is the only many-body system in which all the known natural forces act and in consequence provides an unrivalled microscopic laboratory for the examination of fundamental conservation and symmetry principles.

The most familiar example of such utilization concerns the conservation of parity in weak interactions. In 1956 T. D. Lee and C. N. Yang recognized that despite extensive studies on nuclear beta decay no experimental data relevant to the question of parity conservation existed. They suggested certain crucial experiments and immediately thereafter C. S. Wu and her collaborators demonstrated conclusively, from the angular distribution of decay electrons from aligned Co^{60} nuclei, that parity conservation was strongly violated in weak interactions.

It was noted that the culprit in the weak interaction might well be the neutrino if it had definite helicity of -1, or in other words moved as a left-handed screw. This fundamental conjecture was tested experimentally by Maurice Goldhaber, Lee Grodzins and Andrew Sunyar in 1958 in the K-capture decay of metastable Eu^{152} to Sm^{152}, followed by a 961-keV deëxcitation gamma transition, and proved completely correct.

Extensive measurement on strong interactions has demonstrated that the breakdown of parity conservation in these interactions is very much smaller than in weak interactions—so much so in fact that it has eluded detection as other than an upper limit until the 1967 measurements of V. M. Lobashov and his collaborators in Leningrad. From circular polarization of selected gamma transitions in Ta^{181} and Lu^{175} it has been found that the strength, F, of the parity-violating strong interaction is $(2 \pm 4) \times 10^{-7}$.

Recent studies on the nucleon–nucleon system have shown a definite charge dependence of the parity non-violating part of the strong interaction. For example, the singlet scattering lengths are -16.75 ± 0.15, -16.4 ± 1.9 and -23.679 ± 0.028 fermis, respectively, for the proton–proton, neutron–neutron, and neutron–proton systems. Correction for magnetic effects can account for about 1 fermi of the 7-fermi discrepancy, and the remainder is interpreted as representing a 4% difference between the proton–proton and the neutron–proton interaction strengths. There is, as yet, no firm evidence for any difference between the forces between like nucleons. These results are qualitatively consistent with the 3% mass difference between the charged and neutral pions, and a dominant one-pion exchange character for the nuclear force, but quantitatively this mass difference accounts for only one half of the scattering-length discrepancy.

Returning briefly to the weak interaction, one of the outstanding fundamental questions is that concerning the relative magnitudes of the lepton-conserving and nonconserving parts of the interaction. The most direct experimental attack on this problem is by way of nuclear double-beta decay. During 1967–1968 Wu and her collaborators have been studying the double-beta decay of Ca^{48}, under much improved conditions, and their current lifetime lower limit of 10^{21} years corresponds to an upper limit on the nonlepton-conserving weak-interaction amplitude of 10^{-3}. Continuing measurements will either force this limit lower or perhaps establish the existence of a nonlepton-conserving component.

Tests for time-reversal invariance in physical processes have been suggested in many areas of nuclear physics, and during the past decade several have been attempted. Perhaps the best known are those involving the electron–neutrino correlation in the decay of polarized neutrons, first studied by John Robson and collaborators in 1960, and those involving the phase difference between interfering electromagnetic multipoles in nuclear gamma-deëxcitation transitions. In the latter terms, time-reversal invariance implied phase differences of exactly 0 or 180 deg between the interfering multipoles. Until late 1967 the uncertainty in these phase differences was ± 5 deg. In new measurements on Ru^{99}, however, Ottmar Kistner has shown that the phase difference (at least in this instance) between interfering M1 and E2 multipoles is 180 deg to within ± 0.15 deg, establishing a much more stringent upper limit on the possible amplitude of time-reversal noninvariant components.

As a final example of use of the nucleus as a microscopic laboratory we consider the possibility of the long-term temporal variation of the protonic charge e. In 1937 P. A. M. Dirac suggested that e^2 might vary directly with cosmological time t. Recent detailed examination by Freeman Dyson of the beta decay of Re^{187} to Os^{187} has demonstrated that during the period since termination of nucleogenesis in our region, for instance 3×10^9 years, e^2 has remained constant by a factor of more than 300 beyond what the Dirac suggestion would have required. Further evidence against long-term variation of e^2 has been adduced by Asher Peres from the stability of heavy nuclei. Even a very small change in e^2 would shift the most stable $A = 238$ isobar from U^{238} to Pu^{238} or Cm^{238}. Nuclear physics is unique in providing temporal measures of adequate duration to examine such hypotheses.

CONCLUSIONS

Nuclear physics has reached a degree of maturity that permits the posing of sophisticated questions concerning nuclear structure and behavior. The broad outlines of the field are relatively known although surprises occur with refreshing regularity. Fortunately new techniques, both experimental and theoretical, have been developed that permit the search for answers to these questions. Many yet remain unanswered, and indeed each new development appears to open more new questions than close old ones; this is the mark of a healthy and on-going field.

Major new instrumentation has only recently become available in research centers around the world; the precision and quality of data obtainable with this instrumentation is roughly two orders of magnitude better than before. Major progress can be expected, as well as many surprises and new insights.

Only recently too has the function of the nucleus as a microscopic laboratory been exploited in fundamental physical studies; these will certainly increase in number and delicacy.

The soon-to-be-available very high-energy electron and proton accelerators designed for nuclear research will add a completely new facet to nuclear research and provide an array of probes transcending anything now available. Our attack on the nuclear many-body problem is well underway, but a long road yet remains for us to follow in the 20 years to come. □

TWENTY YEARS OF PHYSICS

ATOMS, MOLECULES AND ELECTRONS

By LEWIS M. BRANSCOMB

CAN WE EVEN REMEMBER atomic, molecular and electron physics 20 years ago? When fine-structure states of atomic hydrogen were still happily degenerate according to Dirac theory, and there was no conclusive demonstration to the contrary? When the dissociation energies of the simplest molecules such as nitrogen and carbon monoxide were unknown? When you could call an electron beam with 1-eV energy spread a "monoenergetic beam" and leave the audience smiling approvingly?

It would seem that only a few of us can claim a first-hand memory, because estimates show that this oldest field of "modern" physics has had remarkably rapid growth. The Novick subpanel (on atomic and molecular physics and quantum electronics) of George Pake's physics survey study found, in 1965, that the training in the US of new scientists in this field would double the numbers in three years if they all remained in the field. Estimates of the actual rate of international growth suggest a current doubling time of 3.5 years. *Physics Abstracts*, in its 1947 annual index, listed about 260 papers that appear to be covered by its current definition of "atomic and molecular physics." This figure represents about 7% of the total for that year. In 1967 I extrapolate 3780 papers in the field, or about 10% of the total.

What we didn't know

We knew 20 years ago how to write down the Hamiltonian for an atomic system, but we were essentially restricted to a central field or hydrogenic approximation. We knew negative ions existed, but only for atomic hydrogen did we know the binding energy. Hyperfine-structure studies had been made spectroscopically in the