basic elements required for such simulation are only in the process of being identified.

It is tempting to find in the investigation of the webs of the orb-weavers a solution for the problem of studying animal behavior with the methodological stringency of the laboratory but without restricting or oversimplifying the behavioral repertory (*34*). Unlike most laboratory animals, *Araneus* need be taught nothing nor be in any way impeded in its pursuit of survival. In its own good time it produces a record of a significant portion of its behavioral capacity, in a form which is readily measured and tested. Of course, mating and manner of seizing and devouring prey are behavioral events which cannot be studied by web evaluation. In other traditional areas of behavioral concern, such as the operation of sensory and learning functions, the restricted adaptive capacities and the highly specialized sensory range of the invertebrate spider may be advantages rather than handicaps.

The kind of record provided by the orb-web-builder is, unfortunately, not a common phenomenon in behavioral study, and it would be of questionable usefulness to propose similar investigations with other animals. The generalization which seems appropriate is one in terms of functions. The spider and its web compose a relatively clear system, an instance of a complex but measurable biological operation. Successful reconstruction of it would probably be significant as a model for the operation of other behavioral systems of whatever complexity.

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Nuclear Physics: A Status Report

The development of nuclear physics, its present position, and prospects for the future are reviewed.

A. Zucker and D. A. Bromley

Rapid development in the sciences makes it especially desirable to stop occasionally to examine a particular field in some detail. It may be worth while, then, to consider nuclear physics, to review its development, to assess its present position and its relationship with other sciences and with technology, and perhaps even to attempt to foresee dimly its future course.

Traditionally, the specialists in any vital field look on the present moment as unusually crucial: discoveries of far-reaching consequence and deep significance in unraveling the mysteries of their subject are just over the horizon. The outsider, on the other hand, remembers the great discoveries which usually occur at the inception of a new science. He considers further developments as refinements which have only slightly changed the essential situation. Just where a science is going, and why, is rarely clear to him. Our purpose in this article is to review nuclear physics, to give some of the flavor of the art, and perhaps to show why, to its practitioners, it is so exciting.

The birth of nuclear physics can properly be dated from the discovery of the nucleus by Rutherford in 1911. During the next 20 years the size, density, mass, and charge of the nucleus were investigated crudely. It was not until the discovery of the neutron and its identification, along with the proton, as one of the fundamental constituents of nuclear matter, by Chadwick in 1932, that the study of the nucleus began in earnest.

It was far from obvious, a priori, that the quantum concepts which had been developed to replace Newtonian mechanics in correlating and describing atomic phenomena would have relevance in the nucleus. (Indeed one of the most important discoveries in nuclear physics in subsequent years has been that quantum mechanics survives this scale change of 10^5 entirely unscathed). It was recognized that the strong forces acting in the nucleus

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were necessarily of much shorter range and greater strength than the electrostatic forces of the atom. It was tacitly assumed that discovery of the characteristics of the basic force between nucleons awaited further experimental study, and that even if these characteristics were fully known, no adequate mathematical approach existed which would permit *ab initio* the calculation of nuclear properties, except in the very restricted case of two-body systems or in the unphysical case of assumed infinite nuclear matter, in which no account can be taken of the proton charge.

Thus from the very beginning it was recognized that recourse to models was inevitable. Although the exact solution of the problem, as just noted, is beyond our grasp, parts of it are accessible to experimental study as the ground and excited nuclear states. To correlate the information concerning these partial solutions, a framework must be generated from a mathematical model approximating the exact nuclear case, but amenable to solution.

Nuclear Models

The physicist has a powerful weapon in his arsenal which he unleashes in such situations: analogy. Indeed, we find that the first nuclear model, the so-called potential model, was proposed by Wigner in analogy with the atom. In this view the nucleons are moving in a potential well which results, in some unspecified but self-consistent fashion, from all the nucleon-nucleon interactions present. A characteristic prediction of this model is a small number of widely spaced, excited states. But very soon it was found that the nucleus has many closely spaced, sharp states, and the potential model fell into disuse. However, this model was the direct forerunner of the shell model that has proved so fruitful in its modern guise.

As soon as very sharp energy levels were observed in the capture of neutrons and protons by nuclei, a process by which new nuclear species are formed, Bohr, and almost simultaneously Breit and Wigner, suggested that there must exist many degrees of internal freedom in a nucleus. These are excited by rapid interchange of energy between an incident nucleon and the nucleons in the target. The sharpness of the level reflects, because of the uncertainty principle, the long time required to concentrate enough energy on a nucleon or group of nucleons, through statistical exchanges of energy, to make the penetration of the barrier in the decaying reaction exit channel possible. This approach provided not only a new model of the nucleus but also the first model for a nuclear reaction. It is variously known as the compound nucleus model, statistical model, or Bohr model. It treats a nuclear reaction as proceeding in two well-defined, independent steps, (i) formation and (ii) decay; the two steps are separated by a relatively long-lived but little-known compound nucleus.

The quantitative aspects of sharp resonances in nuclear reactions which excite the sharp nuclear levels were explored by Breit and Wigner. The Breit-Wigner formula, one of the most useful developments of nuclear physics, describes successfully the resonance behavior of many nuclear interactions. It is, in fact, the underlying equation in almost all low-energy nuclear physics. It has also successfully bridged the gap to high-energy physics, describes successfully the reso-of mesonic resonances, providing yet another example of the remarkable continuity in physics: a formula based on atomic physics, applied with great success to nuclear physics for many years, and found to be equally valuable in high-energy physics. In energy, its application has spanned nine orders of magnitude, from electron volts to thousands of millions of electron volts, or Gev's.

A possible analogy between the two assumptions about the compound nucleus—(i) the nucleon mean free path is much smaller than the nuclear radius and (ii) the formation and decay of the compound nucleus are separate processes—and the known characteristics of a droplet of liquid led to the liquid-drop nuclear model, which had its greatest success at the hands of Bohr and Wheeler in 1939, when they described and elucidated the mechanism of nuclear fission. The concepts of this model are also basic to the convenient semiempirical mass formulas which permit extrapolation of nuclear masses, with considerable precision, from the known nuclei near the valley of beta stability to the interesting and short-lived neutron- and proton-deficient species. In view of the premises on which it is based, the liquid-drop model is capable of reproducing only slowly changing parameters as the atomic number of the nucleus changes. From the outset it was evident that nuclear behavior was much too rich in systematic phenomena to be encompassed within such a framework.

Although primitive, these early models carried in them the underlying structure of modern nuclear physics.

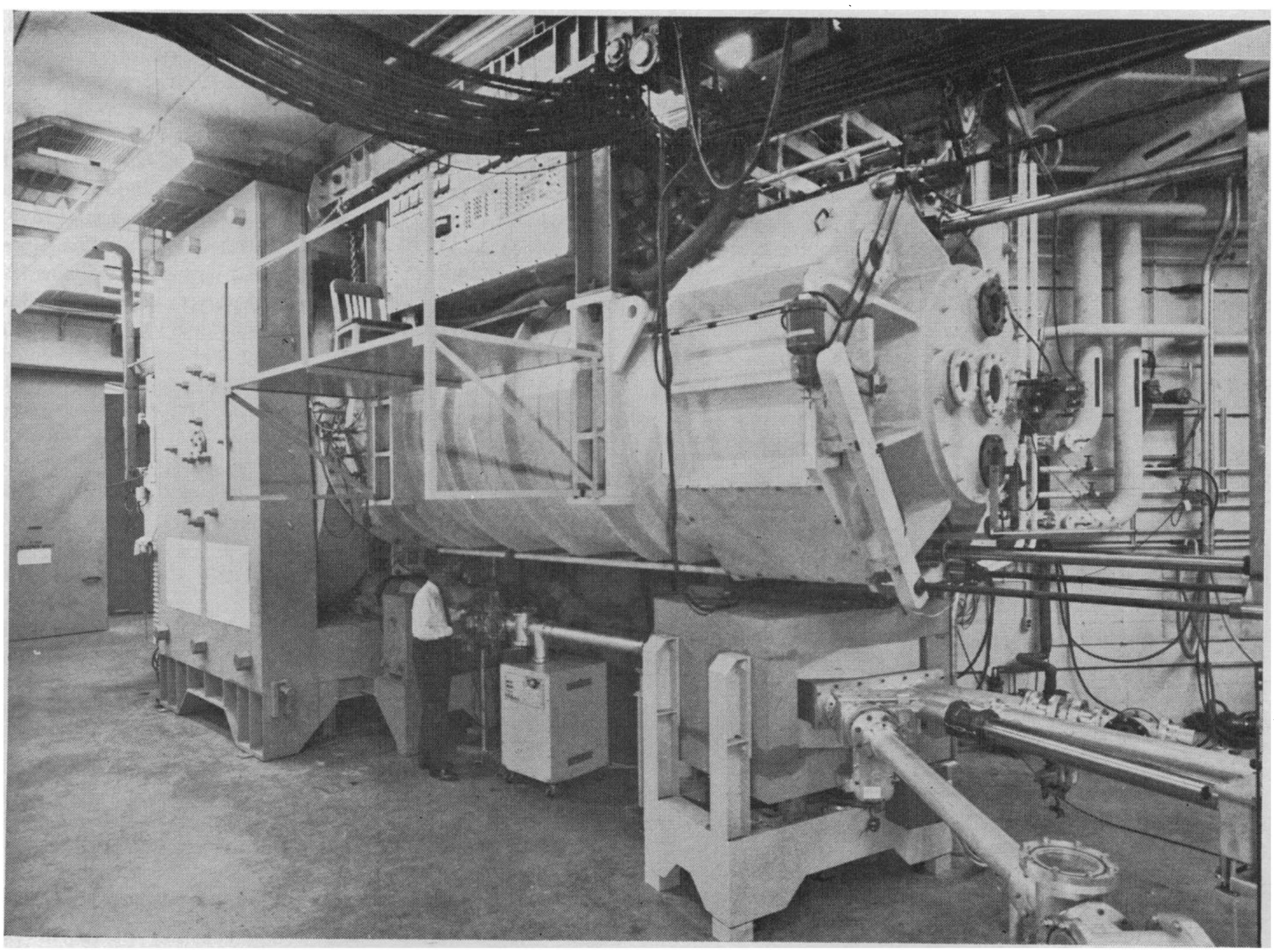
At the same time, a completely different and far-reaching theoretical development was brought forth by Yukawa. Reasoning by analogy with the better known quantum mechanical system, the atom, Yukawa suggested that a field particle analogous to the photon, or quantum of the electromagnetic field, was required to explain the apparent characteristics of the nuclear force field. This field particle was shown by Yukawa to have finite mass and was subsequently demonstrated to be the pi meson. Again, at roughly the same time, it was recognized that the relative slowness of nuclear betadecay was the signature of a force much weaker than either the electromagnetic force or the nuclear force. Basic insight into the characteristics of this "weak" interaction followed Fermi's pioneering theoretical treatment, carried out in analogy with electromagnetic theory, and Pauli's deduction of the existence of a massless field particle, the neutrino. We thus see that, in the 1930's, theoretical attacks on the nucleus provided tremendous new insights into the structure of matter. These investigations are the clear antecedents of modern-day elementary particle physics.

During World War II, study of the nucleus gave way to applied research. Fission and the nuclear chain reaction were shown to be capable of providing mankind with enormous energies for war or peace. Other techniques also advanced mightily during the war and in the immediate postwar years. Among them were new developments in radio-frequency and vacuum engineering, so vital to accelerators, and the construction of digital computers essential to treatment of any complicated entity, such as the nucleus.

Starting about 1950, renewed attacks were made on the mysterious nucleus. It was more than a coincidence that nuclei with 2, 8, 20, 50, 82, and 126 neutrons or protons had very unusual properties. These properties are reflected by anomalously large numbers of stable isotopes, by a systematic variation of electric and magnetic moments, by anomalously low neutron capture cross sections, and by variations in nuclear masses. The occurrence of these characteristic numbers, now atavistically called "magic numbers," is reminiscent of the closed electron shells of the noble gases in atomic physics. The shell structure of the nucleus was implicit in Wigner's original potential model; however, all attempts to reproduce the observed nuclear numbers in analogy with the closure of electronic shells failed until, in 1949, it was realized simultaneously by Mayer and Haxel, Jensen, and Suess that the secret lay in a strong spin-orbit-interaction term.

In other words an important—for the shell model, a fundamental—cause of order in the nucleus is the interaction of the spin of the neutron or proton in the nucleus with the magnetic field produced by the circular motion of the particle's own orbit. This again was nothing very new; it had been observed for electrons in atoms long before. However, because of the short-range nuclear interactions, the doublet ordering in the nucleus was found to be inverted relative to that in the atom; in the nucleus, the state of maximum angular momentum now lies lowest in energy. In this simplest model, it is assumed that all even numbers of neutrons and protons pair sequentially to give a spherically symmetric configuration to the system, resulting in a potential which the last, unpaired nucleon experiences. In consequence, this model predicts spherical equilibrium shapes for all nuclei, zero spins for all nuclei with an even number of nucleons and, for nuclei with an odd number of nucleons, spins entirely attributable to the last, extra-core, unpaired nucleon. During the early 1950's this simple shell model was used with impressive success in correlating the large mass of experimental data on nuclear spins and magnetic moments and on the occurrence of isomeric islands and the location of the magic numbers.

Central to the shell model is the assumption that the nucleon mean free path is large compared with the nuclear radius; otherwise the concepts of shells and orbits have dubious significance. The simultaneous success of liquid-drop and shell models in explaining and correlating different facets of nuclear behavior while resting on diametrically opposed assumptions posed a serious paradox. Weisskopf then noted that a nucleon, in traversing a nucleus, necessarily exchanges energy and momentum with other nucleons with which it collides by pro-



The Oak Ridge isochronous cyclotron. The 200-ton magnet is at left, the variable-frequency radio-frequency system at right, and below it, the pipes through which the beam is guided to several experimental stations. The new isochronous cyclotrons provide beams of protons, deuterons, alpha particles, and heavy ions in the 20- to 100-Mev range for nuclear structure research. [Oak Ridge National Laboratory] moting them to different quantum states. He further noted that the states accessible by this process are already occupied, so that in accordance with the Pauli principle such collisions in the motion of a shell-model nucleon do not in fact occur. At higher energies it is possible to excite target nucleons to previously unoccupied states, and thus to transfer both energy and momentum to the intrinsic motion of the system.

As more evidence accumulated on excited states of the nuclei, it became evident that the assumptions of the original concepts of the shell model were too simple and that account had to be taken of the fact that all nucleons outside of the magic-number closed shell interact with one another with so-called residual interactions in addition to the central potential. In this independent-particle or intermediate-coupling shell model, the relative importance of central and spin orbit forces played a dominant role; the observed coupling changes from the Russell-Saunders $l \cdot s$ coupling characteristic of the atom, in the lightest nuclei, to $j \cdot j$ coupling in medium and heavy nuclei. The more realistic shell model successfully correlated many of the data which had eluded the original simple model, but it did so at the cost of an enormous increase in computational labor. Even with modern digital computers, actual calculations have been limited to systems with less than five nucleons outside the closed shell, and in such cases the order of the matrices to be diagonalized may reach 1000×1000 in dimension.

None of these shell models was successful in reproducing measured nuclear binding energies. As more and better information on nuclear electric quadrupole moments became available, an even more striking failure of the shell models appeared. Not only were these moments in some cases larger by several orders of magnitude than the moments that could be predicted by the shell models, but they also showed a strikingly systematic behavior: a positive sign and increasing magnitude for nuclei immediately following a shell closure, a switch to negative sign in mid-shell, a decrease, and passage through zero at the next shell closure. This behavior was extremely suggestive of nonspherical core deformations away from closed shells, with prolate and oblate shapes giving positive and negative moments, respectively. Such a model clearly has elements in common with the Bohr-Wheeler liquid drop; it was suggested first by Rainwater and later developed extensively and with great success by A. Bohr and his collaborators in Copenhagen.

Identification of characteristic rotational and vibrational spectra in nuclei throughout the periodic table, with excitation energies given by $(\hbar^2/2I) \cdot J(J+1)$ and by $\hbar w(N + \frac{1}{2})$, in regions of static and dynamic deformations, respectively, has provided unambiguous evidence for these models. So has the observation of the predicted enhancements of electric quadrupole transitions linking members of these rotational and vibrational bands.

If we combine the idea of a hydrodynamic deformable core with the shell model idea of the single nucleon in motion, the result is the so-called unified model proposed and exploited by the Copenhagen school. This model represents one of the most powerful approaches to the correlation of nuclear data.

The unification of single-particle and collective aspects of nuclear behavior was initially an *ad hoc* one, but pioneering work by Elliott and others has led to a fundamental understanding of this unification. Elliott was led to this problem by the observation that, in some light nuclei where both calculations are feasible, the calculated predictions of the shell and the collective models often were in closer accord with each other than with experimental data. Elliott was able to demonstrate that by selecting proper linear combinations of spherical-shell-model wave functions it was possible to obtain almost exactly the rotational wave functions of the collective model.

Recent developments have demonstrated that almost all aspects of nuclear behavior are reconcilable within the framework of a generalized shell model of individual nucleons moving in well-defined orbits. These orbits, however, are not those of the simple spherical shell model but those appropriate to a self-consistent potential which can assume different shapes, including, for example, that of a deformed sphere (spheroid).

A fundamental attack on nuclear physics has been in progress since 1952, under the general title of Brueckner theory. Brueckner and his associates start with the shell model, but instead of treating the nucleon-nucleon force only in first order, as has been customary, they take this force to all orders. The theory thus concentrates on treating interactions of nucleon pairs in great detail and demonstrates how the effects of weak mixing from a wide range of distant configurations may be approximated by replacing the nucleon-nucleon potential appropriate for the interaction of free nucleons with one of modified form within the nucleus, whose strength is taken as one of the model parameters and is substantially different from that of the free potential. Like earlier models, this one ignores all correlations higher than two-body ones. The importance of such correlations remains one of the fundamental open questions in nuclear theory. The Brueckner theory is plagued with extreme calculational complexity; however, the nuclear radii and binding energies currently obtained for closed-shell nuclei, by recently evolved techniques for including the higher-order effects, are in remarkable accord with experiment.

Our discussion thus far has been largely oriented toward models and thus reflects the major activities in the field. It must be emphasized, however, that to restrict these activities to the pursuit of model predictions or ambiguities would rapidly result in a sterile situation. Perhaps the majority of the exciting findings in nuclear research, as indeed in any other science, have come from pure flights of imagination or experiments carried out from sheer curiosity rather than from calculations dictated by models. Only in this way are completely new frontiers glimpsed and explored. One of the ubiquitous problems of the nuclear physicist is the maintenance of a proper balance between the two types of research.

Much of our earliest information concerning the nucleus resulted from the study of alpha and beta radioactive decay, and such studies still play a very significant role in providing large amounts of nuclear data. Nevertheless, we estimate that between 80 and 90 percent of our current information about nuclei is derived from scattering and reaction studies made possible by projectile beams accelerated to energies from a few to hundreds of millions of electron volts; these beams have replaced the natural alpha particles with which the nucleus itself was discovered.

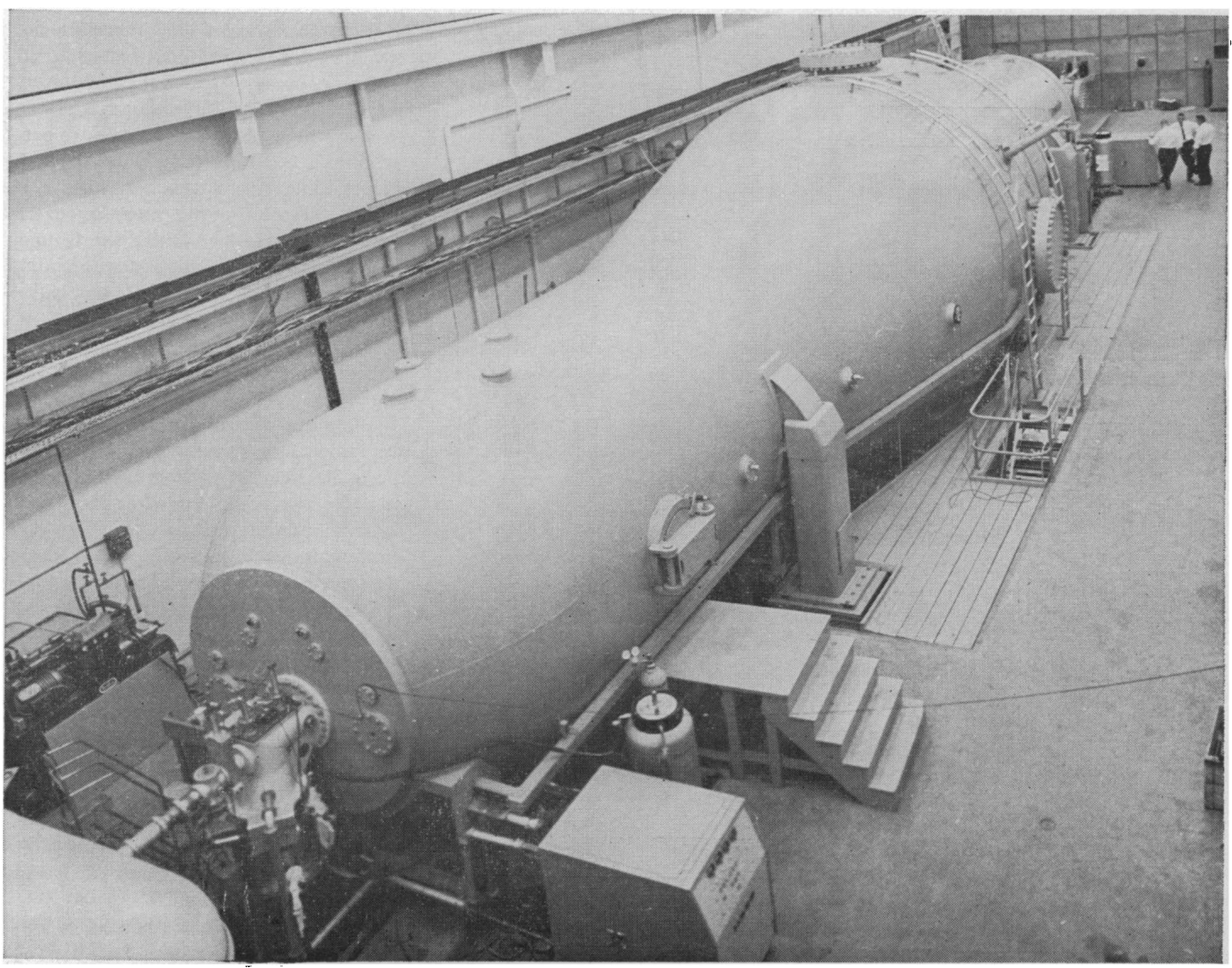
Nuclear Reactions

If we are going to make use of information from nuclear reactions and scattering, we must first understand the reaction process itself. Unfortunately, this poses a problem which appears to be almost as difficult as the nuclear problem we set out to unravel in the first place. We now have separate models or calculational approximations which allow us to understand the reaction process, but as much theoretical and experimental effort must be devoted to this as to the underlying problem of the nucleus itself.

At low energies, simple electrostatic effects dominate the situation for charged, although clearly not for neutral, projectiles. Added to the electrostatic effects are effects caused by nuclear resonances of compound states. When the nuclear states are well separated, at low energies and in light nuclei, the interference between the electrostatic and the resonant amplitudes provides a powerful probe for determining the characteristics of these states. As the separation of the resonance decreases with increasing energy, increasing target mass, or both, such analysis of scattering data becomes impractical.

For these conditions, where many levels are encompassed in the energy width of the incident beam, Feshbach, Porter, and Weisskopf developed the cloudy crystal ball interaction model, in analogy with the interaction of light with a target region characterized by a complex index of refraction, to include both scattering and absorption phenomena. Because little is specified beyond the limits of the target region and the complex interaction potential, this so-called optical model does not attempt to make detailed predictions about any process other than the formation phase of the compound system. It does, however, describe in detail the diffraction, refraction, and absorption of the incident projectile wave by the target.

The optical model provides an excellent parameterization of the physical phenomena involved. The parameters change smoothly, and in reasonable fashion, with changing energy or atomic number. With this model one can predict with fair accuracy the angular pattern for the scattering of various projectiles from nuclei, as well as the probability that the projectile will be absorbed by the nucleus on which it impinges.



General view of a Model MP Van de Graaff accelerator under construction by High Voltage Engineering Corporation for installation at Yale, the University of Minnesota, Chalk River, (Canada), the University of Rochester, and Heidelberg. This accelerator extends the range of precisely defined proton energies to over 20 Mev and makes all nuclei, for the first time, accessible to precision studies. [Photo International, Boston, Mass.]

Ground State
Reaction Data
Mass-Spectrometer Data

$_{62}Sm^{149}_{87}$

Ground State

J	7/2	App.1	Abundance	13.83%	App.2
μ	− 0.7	App.1	σ	66,000	App.3
|q|	< 0.72	App.1			

Reaction Data

Levels $Sm^{149}(\alpha,\alpha'\gamma)$ E_α = 6 55H64
No γ with E_γ < 0.6 scin

Mass-Spectrometer Data

S_n 5.9 *3* Sm^{149}-Sm^{148} 57J18

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57J18 W.H.Johnson,Jr., A.O.Nier, Phys.Rev. 105, 1014.

App.1 See green appendix sheets to be included with subsequent sets.

App.2 See yellow appendix sheets.

App.3 See pink appendix sheets to be included with subsequent sets.

$_{62}Sm^{149}_{87}$

Ground State
Ground-State Decay
Reaction Data
Mass-Spectrometer Data

$_{62}Sm^{149}_{87}$

Ground State

J	7/2	App.1	Abundance	13.83%	App.2
μ	-0.7	App.1	σ_{nA}	41,500	App.3
|q|	<0.72	App.1			

Ground-State Decay

$T_{1/2}(\alpha)$ 4 x 10^{14} y 2 Counted for 400 h 60Ka23
> 1 x 10^{15} y Counted for 78 h 61Ma5

α 1.84 5 ic 60Ka23
Not observed 61Ma5

Compiler's Note: The presently available data on nuclear masses can be used to predict an alpha decay energy of 1.9 2

Reaction Data

Resonance $Sm^{148}(n)$ tfl 58B12
E_0(eV)
94.3 *26*

Reaction γ $Sm^{149}(\alpha,\alpha'\gamma)$ scin
0.650 *20* B(E2)↑= 0.21 E_α = 17 60Na13

No γ with E_γ < 0.6 E_α = 6 55H64

Level $Sm^{149}(\gamma,\gamma)$ Eu^{149} source 62Jh4
0.022 $T_{1/2}$ ≥ 2.8 ns
resonance fluorescence

$Sm^{(149)}(\gamma,\gamma)$
0.022 Γ ≤ 6 x 10^{-7} eV Möss 62Al13
$T_{1/2}$ ≥ 0.7 ns

Reaction Data continued

Levels Sm^{148}(d,p) VdG, s 62Ke4

Level	I*	Level	I*	Level	I*
g.s.	1				
0.022?					
0.280	0.38	1.910	0.02	2.830	0.13
0.350	0.23	1.943	0.27	2.858	
0.398	1.31	1.975	0.10	2.891	
0.535	0.08	1.999	0.10	2.923	0.13
0.566	0.04	2.024	0.09	2.949	0.22
0.640	0.03	2.059	0.24	2.968	0.18
0.675	0.52	2.101	0.23	2.995	0.18
0.700		2.137	0.10	3.015	0.24
0.712		2.159	0.04	3.073	0.13
0.842		2.191	0.06	3.094	0.19
0.881		2.210	0.14	3.160	0.10
0.928		2.242	0.19	3.194	0.13
0.956		2.264	0.09	3.218	0.16
1.013		2.280	0.07	3.257	2.71
1.084		2.295	0.07	3.303	0.42
1.125		2.332	0.06	3.324	0.18
1.158	0.15	2.358	0.11	3.377	0.17
1.190	0.34	2.377	0.05	3.393	0.17
1.200	0.12	2.387	0.19	3.419	0.10
1.280		2.418	0.10	3.436	0.20
1.316	0.16	2.442	0.15	3.461	0.15
1.385	0.07	2.494		3.478	0.13
1.465	0.38	2.508		3.533	0.21
1.484		2.534	0.17	3.545	0.20
1.556	0.10	2.568	0.16	3.575	0.22
1.579	0.08	2.590	0.26	3.595	0.12
1.621	0.03	2.622	0.12	3.623	
1.662	0.24	2.640	0.18	3.636	
1.678		2.671	0.14	3.661	
1.705	0.03	2.711	0.12	3.687	
1.752	0.36	2.723	0.09	3.700	
1.782	0.17	2.737	0.14	3.734	
1.816	0.28	2.762	0.24	3.765	
1.881	0.09	2.797	0.19	3.806	

*Relative proton-group intensity at 60°

Q Sm^{148}(d,p)
g.s. Q = -3.648 *12* 62Ke4

$Sm^{149}(\gamma,n)$
Observed threshold energy of 6.45 *16* does not lead to g.s. but probably to the 0.551 level in Sm^{148} 60Ge1

The observed threshold is 6.91 *8* 57B164

Mass-Spectrometer Data

S_n 5.9 *3* Sm^{149}-Sm^{148} 57J18

5-2-21 (Dec. 1962) Sm^{149}-1 Replacement for 58-12-11 Sm^{149} completed

Nuclear data sheets for ^{149}Sm, as published (top) in 1958 and (bottom) in 1962. Over 100 energy levels were identified in the intervening 4 years. This development is not an isolated case but is fairly typical of the information explosion in nuclear physics.

This, however, has not been the only use made of the optical model. In examining much more general reactions with quite different initial and final nuclei—for example, after transfer of one or more nucleons between the projectile and the target—account must be taken of the short-range transfer mechanism as well as of the interaction between the projectile and the target as they approach at larger impact parameters, and between the product and residual nuclei as they recede from one another after the interaction. Prior to the interaction the situation is essentially identical with that in scattering. Under time reversal the final state can be interpreted as the scattering of the product on the residual nucleus at appropriate energies and angles. In consequence it has become customary to take all these longer-range effects into account by using optical model wave functions. In effect, these wave functions represent the plane wave functions distorted by the presence of electrostatic and nuclear forces. These distorted-wave calculations have played, and continue to play, a very important role in permitting extraction of nuclear spectroscopic data from reaction measurements, for they permit attention to be focused on the specifically short-range nuclear interaction unobscured by extraneous scattering perturbations.

Present Status

We have chosen to outline the developments in nuclear physics for the past 30 years by describing nuclear models. We could, instead, have done it by describing a succession of experiments, or we could even have described the progress of nuclear physics in terms of the development of experimental techniques, particle detectors, and accelerators. But the models, we believe, give a fairly coherent picture of the progress of nuclear physics until we come to very recent times. The historical approach fails as the time perspective is foreshortened and it becomes less clear just which theoretical approach or experimental line of research will prove to be the main stream. We shall now take stock of what we know about nuclei, how well we know it, and how our information may lead us to further insights. In addition, we shall show what we do not know, or better, what we now think it would be extremely useful to know.

We turn first to measurements of mass, size, and electric and magnetic moments—the macroscopic properties of the nucleus, if such a term may be applied to an object of nuclear dimensions.

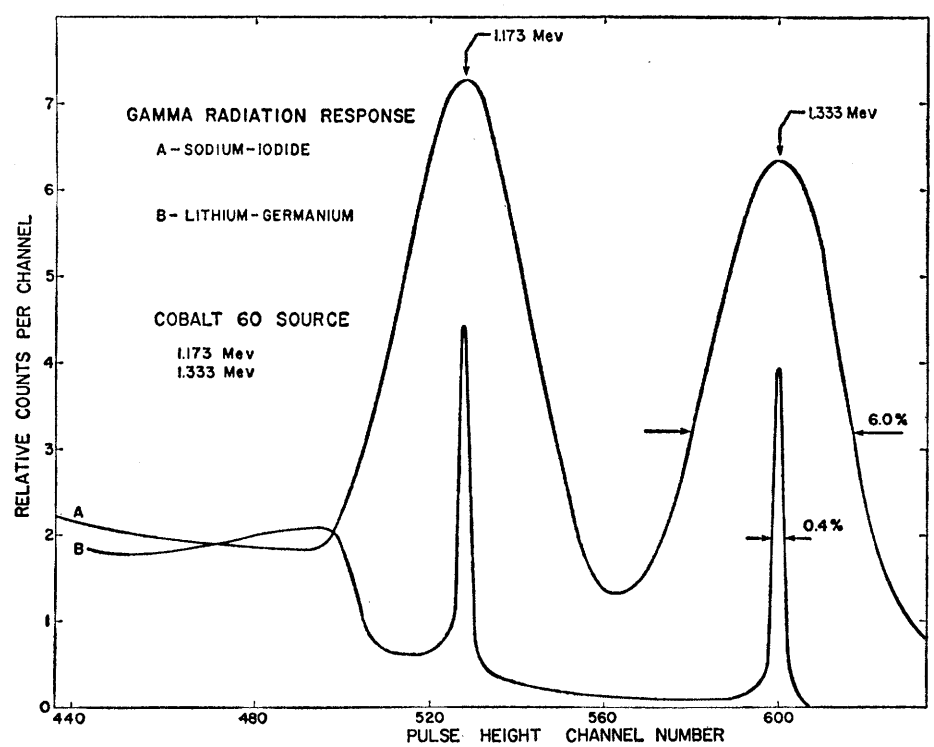
Accurate measurements of nuclear masses are available throughout the periodic table. The masses of light nuclei are known, to about 10^{-3} millimass units (1.66×10^{-30} g) or better, both from mass spectrometric measurements and from energy balance in nuclear reactions. From $A = 60$ upward (A is the atomic number), masses are less precisely known, and for some of the more difficult radioactive nuclides we must rely on empirical mass formulas which are usually good only to a few tenths of a millimass unit. We note here that the most fundamental nuclear masses, those of a proton or neutron, cannot as yet be derived from any fundamental principle, and that the difference in mass between the neutron and the proton is not fully understood. On the other hand, given these two masses and a rather simple interaction between the neutron and the proton, the mass of the deuteron may be calculated quite rigorously. For masses larger than 2, however, we must rely on calculations based on nuclear models.

The "size" of a nucleus has two related aspects. The elastic scattering of high-energy electrons now gives very reliable values of the charge radius of the nucleus. From this evidence a nucleus appears to be a uniformly charged sphere of radius $R_{el} \cong 1.2$ $A^{\frac{1}{3}}$ fermis (1 fermi = 10^{-13} cm). If we are, on the other hand, interested in the extent of the nuclear force associated with a nucleus, we find, from a variety of experiments, that $R_N \cong$ 1.5 $A^{\frac{1}{3}}$ fermis. In other words, the nuclear force extends beyond the charged sphere of the nucleus, but it then drops to zero in a fermi or two, in contrast to the electric or gravitational forces, which decrease slowly with the inverse square of the distance. The variation of nuclear density as we traverse the nuclear surface is currently the subject of intensive study, particularly in nuclear reactions involving bombardment with heavy projectiles such as carbon or nitrogen ions, and with high-energy protons whose spins are aligned in a certain direction (polarized).

Until recently, high-energy accelerating facilities ($\geqq$ 100 Mev) were almost exclusively directed toward investigation of mesonic problems. As some of these accelerators have been bypassed by the march to ever higher energies, it has been possible to use them for nuclear physics. This opens up an exciting and potentially rich field for exploration: not only is the projectile wavelength small enough to probe for individual nucleons deep in the nuclear interior, but also the impulse approximation, which suggests that the target nucleon is examined essentially in its original unperturbed state because of the short interaction time, is expected to be valid. In studies on the (p, $2p$) reaction, for example, it has been possible to extract protons from shells deep within the target nucleus, to measure their binding energies and angular momenta, and thus to provide striking confirmation for the correctness of the concepts of the shell model. Measurements with meson beams, both pions and muons, promise a powerful attack on the problems of nuclear correlations, momentum distributions, and spatial distributions in nuclei.

We now turn to more microscopic nuclear properties. The solutions to the nuclear equations of motion, as in any quantum mechanical system, are available to us as the energy levels of the system. The past decade has witnessed an almost explosive increase in the information concerning the location and characteristics of energy levels for nuclei throughout the periodic table.

The density of these levels increases rapidly with both the excitation energy and the atomic number, as more nuclear configurations or internal degrees of freedom become accessible. Most of our detailed nuclear spectroscopic information has been derived from study of isolated levels at relatively low excitation energies (less than 10 Mev in light nuclei, less than 1 Mev in heavy nuclei). At higher energies it has been established that the level density increases roughly exponentially with excitation; statistical and thermodynamic techniques generally have proved to be useful in correlating data on high-density overlapping levels. In all this spectroscopic work, the theoretical techniques evolved for use in atomic and molecular studies have been widely exploited and extended. They in turn are now finding initial application to the spectroscopy of the strongly interacting, subnuclear particles. This generality of application is simply a further manifestation of the broad validity of quan-



Relative response to Co^{60} gamma radiation for a sodium iodide crystal (7.6 cm diameter $\times$ 7.6 cm) scintillation spectrometer and a lithium-germanium semiconductor (1.8 cm diameter $\times$ 0.8 cm) spectrometer. Although the much higher intrinsic energy resolution of the lithium-germanium spectrometer is attained at considerable sacrifice of efficiency, the development of these detectors is one of the recent instrumental advances of greatest potential in precision nuclear spectroscopy.

tum mechanical principles through all atomic, molecular, nuclear, and subnuclear systems.

As was suggested in the earlier discussion of nuclear models, impressive progress has been made in understanding the microscopic structure and behavior of nuclei. In the past, as in the early phases of any new field, individual investigators or groups tended to evolve or invent models which emphasized one specific aspect of nuclear behavior, sometimes unfortunately to the exclusion of other, equally striking phenomena. One of the most significant developments in nuclear physics in recent years is the identification of all these varied, and often apparently contradictory, models as special cases or caricatures of a single, much more encompassing, generalized shell model.

It has been suggested that, in consequence, all that remains to be done is a general working out of our present understanding along relatively well defined pathways. Nothing could be farther from the current situation. Modern nuclear physics is often compared with atomic physics in the decade before the work of Bohr. Perhaps a closer analogy is with the situation in classical astronomy prior to Kepler. Although excellent empirical data were available to him, without the concept of gravitation, large admixtures of demonology and associated metaphysics were required in Kepler's natural philosophy. Only with Newtonian insights into the nature of the gravitational force did the mechanics of the solar system reach its present place as a triumph of the human intellect.

As in all vital fields of investigation, in nuclear physics the unknown far transcends the known. We believe, however, that we have reached a stage in our conquest of the nucleus where we can pose crucial questions concerning the fundamental bases for nuclear behavior.

We have already mentioned that the nucleon-nucleon force is not yet known in sufficient detail. An important related question is that of charge independence of the nuclear forces. For many years it was considered certain that the neutron and the proton are identical particles so far as nuclear effects are concerned, and that the fact that one is neutral and the other is charged causes only trivial and readily explainable differences in behavior. Very precise recent experiments lead us now to question this tenet, and efforts to explain the difference and use it in building nuclear matter will provide a severe test of nuclear theory. In fact, this difference, if verified, will seriously affect our understanding of the nature of elementary nuclear constituents such as the neutron and proton and their place in the scheme of so-called strongly interacting or elementary particles.

Even were the interaction between two isolated nucleons completely known, it is far from obvious that this same interaction would hold inside nuclear matter. The importance of higher than two-body interactions—that is, interactions in which three, or more, nucleons interact coherently—is almost completely unknown, and these higher-order effects have customarily been ignored, with a posteriori justification. New information here can only come from detailed study of the more complex nuclear phenomena.

We also know that the nucleons are not at rest in the nucleus. In fact, they move with very high velocity; the average energy of a neutron or a proton inside the nucleus is surmised to be about 20 Mev. We have already obtained striking confirmation of the physical existence of the outer orbits postulated in the shell models. Using high-energy protons as probes, we can hope to investigate the degree to which these orbits retain their identity and character deep inside the nucleus. We have only rough ideas concerning the nucleon momentum distributions in nuclei; further insight will come from these experiments with protons and also from experiments with electrons and mesons. Use of these particles will make it possible to vary the energy and the momentum in the system independently. A fast proton may deliver high momentum and relatively little energy to the target nucleus before escaping, whereas capture of a stopped π^- meson delivers some 140 Mev of energy and essentially no momentum. Comparison of electron- and photon-induced reactions will make it possible to disentangle the effects of the distribution of charge and magnetic moment within the nucleus.

We have mentioned that the nuclear surface is currently the subject of intensive experimental and theoretical research. The importance of this kind of work is apparent when we recall that a nucleus is mostly surface. Fifty percent of the nuclear matter can be considered as lying in the surface region. The degree to which this matter exists as nucleons in discrete orbits or as local agglomerations into clusters, such as deuterons on alpha particles, has not yet been established. Further work on nuclear molecules or inverse-fission such as that recently established in the $^{12}C + {}^{12}C$ system will shed new light on surface behavior. It awaits the precise beams of heavy projectiles that will soon be available from the new and much larger electrostatic accelerators. Measurements made with meson beams also provide information on such granularity of the nuclear surface.

Central to continuing progress in nuclear physics will be our ability to obtain answers to the multitude of questions concerning nuclear structure and interactions which are posed by our rapidly improving theoretical understanding of the nuclear system. In a fortunate coincidence, this burgeoning of theoretical insight has been paralleled by major technical improvements in experimental nuclear physics. New accelerators, new detectors, and new data-handling systems combine to permit an increase, by an order of magnitude, in the precision of nuclear data. In the past, in any scientific field, such conditions have led not only to evolution but also to revolution in our understanding of the phenomena involved; nuclear physicists are convinced that this will hold true in the future, and that measurements of greatly improved quality and increased precision will provide the bases for striking future progress.

Even more general questions can be raised at this point. We have talked mainly about the nuclear force, which is very strong and which actually serves to contain the nucleons within the confines of a very small space. But we know that there are at least three other forces in nature: gravitational, electromagnetic, and the so-called weak force that operates in beta decay. True, the other three forces are weak in comparison with the nuclear force, but there remains an open question whether these four forces are in any way related. If they are, a thorough and painstaking study of the nucleus may reveal the relationship and open yet another vista on our ever more complex universe. The nucleus is the only stable system where we find all four forces acting simultaneously.

There is also the intriguing possibility that there may be a "fifth force" or, for that matter, several other forces lying hidden, just waiting to be discovered.

Since its beginning, nuclear physics has greatly extended man's intellectual horizons. Many of the theoretical techniques developed for use in nuclear physics have found extensive utilization throughout the sciences. The nucleus is a rich source of physical phenomena. Discovery of these phenomena taxes to the full our experimental prowess, just as their exploration and correlation tax to the full our theoretical prowess.

Impact of Nuclear Physics

A measure of the value of a science is the extent to which it influences other sciences, the extent to which it furthers man's material well-being through technology, and the extent to which it contributes to the intellectual storehouse of mankind. To take examples in physics, the discovery of universal gravitation set the philosophical tone which for three centuries dominated Western thought. The development of thermodynamics and also the discovery of electromagnetic induction have changed the living conditions of all humanity and have made many other sciences possible, even in principle.

Nuclear physics rates high on this score; characteristically it seems not only to be useful for technological applications, which are just beginning, but to be of the greatest importance to the development of many quite unrelated sciences. Foremost among such developments is the production of radioactive tracers, which has completely altered the biological sciences and has also played an important role in such varied disciplines as archeology, metallurgy, chemistry, and criminology. Soon after the successful operation of the first reactor, Fermi was asked wherein, in his opinion, lay the greatest promise to mankind which might be derived from his work. It lay in "the use of tracers," he replied, "which will revolutionize all sciences." He was, quite likely, right, as usual.

Nuclear physics has contributed in a fundamental and far-reaching way to cosmology. At last a clear picture is emerging of the detailed manner in which the elements are formed. Excellent agreement between (i) the observed abundances of the elements and their observed isotopic constituents and (ii) theoretical calculations based on observed cross sections for neutron capture, and on other details of nuclear reactions, has been achieved. Similarly, the source of the sun's energy has long been explained on the basis of rather esoteric nuclear reactions. New and mysterious objects such as the quasars (extremely intense energy sources in the universe) are being discovered in ever-increasing number as the result of our explorations of space. Here, also, nuclear physics functions as the handmaiden of astronomy.

Investigations in the structure of matter are significantly helped by the existence of nuclear reactors, specifically of slow neutrons for diffraction studies. A dramatic example is furnished by the fact that the structure of salt was elucidated in 1912 by von Laue with x-rays, and it took 51 years to decipher the stereo structure of sucrose by the diffraction of thermal neutrons. Surely the mapping of much more complex structures—proteins or viruses—by neutron diffraction must lie somewhere just beyond the technological horizon.

Other examples abound of instances where nuclear physics has touched and fructified another science. For instance, the Mössbauer effect has been of the greatest value to the study of the solid state. Again, the development of very sophisticated, and sometimes extremely complex, instrumentation for nuclear physics has paid dividends in the development of automation, in medicine, and in anthropology.

We cannot leave this subject without a brief mention of tremendous changes nuclear physics has initiated in our technology. It has created a new source of power, which is expected to provide, in another 35 years, 45 percent of the total power used in the United States. It has created the promise of bountiful fresh water from the oceans. It may well revolutionize the cultivation and distribution of food, if current very promising leads in fertilizer production and food sterilization by nuclear methods prove rewarding. Undoubtedly it will contribute widely to terrestrial and space transportation in the future.

Conclusion

We have tried to give a brief account of the past and the present of nuclear physics. It is truly a large field. On an energy scale it deals at one end with Auger transitions involving a few electron volts, at the other end with weapons whose energy content is measured in megatons of TNT. On scales of space and time it ranges from the galactic to the subnuclear. It is a field exciting and valuable as an end in itself; at the same time, its findings permeate all sciences and may hold the key to the future of mankind. It is a large field, and small; provincial, exceptionally specialized, and, at the same time, universal. It is fair to ask, Where it is going?

We could answer this question with many details, with descriptions of new, promising lines of research. We could answer it by listing puzzles, both theoretical and experimental, which bedevil the nuclear physicists, or by describing new research, too difficult for our present tools, which must be done before the puzzle of the nucleus is solved. But we will do none of these things. Instead, let us just state that nuclear physics is only one window on the subatomic world. Our tools, principally quantum mechanics, were devised to explain phenomena on an *atomic* scale, 10^5 times as large and 10^6 times as slow. It is astonishing that this approach has worked as well as it has on the nuclear scale. We thus look on the future of nuclear physics from two points of view. First, we have to continue our painstaking and ever more exact investigation of nuclear structure, of the nuclear force. But second, we must bear in mind that solution of nuclear questions may reveal deeper truths—universal truths about fundamental interactions and even perhaps a new corpus of theory to supersede and include current physical concepts as a special case. This has been the history of physics, and it is not likely to change.