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Physics in the Twentieth Century

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The spirit of modern science has its deep roots in the culture of antiquity, in Greece and in the Judeo-Christian tradition, but it came to life and started its exponential growth in the days of the Italian Renaissance. Since then, scientific knowledge and experience have accumulated at a steadily increasing pace until, in our century, the human mind has been challenged to some of its most penetrating insights into the workings of nature. A description of all these accomplishments is much too great a task to be dealt with within the framework of a brief article, and I must restrict myself to sketching this subject with a few short strokes—al fresco, as it were. Reviewing the development of physics in the 20th century is indeed a dazzling experience. Relativity, quantum theory, atomic physics, molecular physics, the physics of the solid state, nuclear physics, astrophysics, plasma physics, particle physics—all these are children of the 20th century.

There was a definite change in the character of physics at the turn of the century. The older physics was under the spell of the revelation of two fundamental forces of nature: gravity and electromagnetism. The development of classical mechanics, from Galileo and Newton to Lagrange and Hamilton, had shown that the same natural law, the law of gravity, was operative on earth and in the universe. Electrodynamics, a child of the 19th century, reared by Faraday, Maxwell, and Hertz, was the first extensive application of the field concept in physics. The electromagnetic field was recognized as an independent entity in space, and the decisive role of electric phenomena in matter was revealed. The recognition, in the 19th century, of the nature of heat as random motion was another of these lucid flashes of rational perception of what is going on in our environment. The development of kinetic theory and thermodynamics in the work of Carnot, Clausius, Helmholtz, Boltzmann, and Gibbs led to thinking in terms of the atomic and molecular structure of matter. The existence of such elementary units was known in the 19th century; estimates of their size and weight were not too inaccurate. But the properties of matter were not understood at that time; they were not deduced from more elementary concepts, they were measured and expressed in the form of specific constants of materials, such as elasticity, compressibility, specific heat, viscosity, conductivity of heat and electricity, and dielectric and diamagnetic constants. The books of Lord Rayleigh are perfect examples of a 19th-century physicist's view of nature. They give a full and elegant treatment of electric and magnetic fields and of classical wave phenomena of light and sound, together with the properties of solids, liquids, and gases as derived from a number of empirical constants.

The physicists of the 19th century were not unaware of the importance of interatomic forces for the determination of material properties. We remember Maxwell's study of the repulsive force between molecules of a gas. But there was no way of telling what the origin of these interatomic forces was, and how to account for their strength or absence, whatever the case may have been. The great variety among the properties of the different elements was not considered a topic for physicists; it was the task of the chemists to analyze and systematize them, as was done so successfully a hundred years ago by Mendeléeff in his periodic system of the elements. The specific features of the different species of atoms—their characteristic optical spectra and their chemical bonds—were known and cataloged by the chemists, but they were not considered a suitable subject for physics. The innate forms and ever-recurring qualities of the atomic species were things foreign to the conceptual structure of 19th-century physics. The electron had already been discovered by 1900, and it was obvious that electrons must be essential parts of the atomic structure, but classical physics could not give any clue as to the kind of structure one should expect within the atoms.

A Golden Age of Physics

In physics, the 20th century truly begins in the year 1900. This date is not an accident, it is the year of publication of Max Planck's famous paper on the quantum of action, the birth year of quantum theory. It is impressive to contemplate the rate of progress in physics in the first quarter of this century: Planck's quantum of action in 1900; Einstein's special relativity theory in 1905; Rutherford's discovery of atomic structure in 1911; Van Laue's scattering of x-rays from crystals in 1912; Bohr's quantum orbits and explanation of the hydrogen spectrum in 1913; Einstein's general relativity theory in 1916; Rutherford's first nuclear transformation in 1917; Bohr's explanation of the periodic table of the elements (*Aufbauprinzip*) in 1922; the

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discovery of quantum mechanics by de Broglie, Heisenberg, Schrödinger, and Born in the period 1924 to 1926; Pauli's discovery of the exclusion principle in 1925; Uhlenbeck and Goudsmit's discovery of the electron spin in 1927; Dirac's relativistic quantum mechanics in 1928; Heitler-London's theory of the chemical bond in 1927; and Bloch and Sommerfeld's theory of metallic conductivity in 1930. Let us stop here, although the progress by no means ended in 1930; it went on at this rate for at least another 10 years, before slowing down to the relatively slow pace of today.

Among the great systems of ideas which were created in that period, relativity theory—special and general—has a place somewhat different from the others. It was born in the 20th century as the brain child of one towering personality. It is a new conceptual framework for the unification of mechanics, electrodynamics, and gravity, which brought with it a new perception of space and time. This framework of ideas is, in some ways, the crown and synthesis of 19th-century physics, rather than a break with the classic tradition. Quantum theory, however, was such a break; it was a step into the unknown, into a world of phenomena that did not fit into the web of ideas of 19th-century physics. New ways of formulating, new ways of thinking had to be created in order to gain insight into the world of atoms and molecules, with its discrete energy states and characteristic patterns of spectra and chemical bonds.

The new ways of thinking were formulated and codified in the midst of the third decade of this century. The wave-particle duality was proposed by de Broglie in 1924, the equation for particle waves was conceived by Schrödinger in 1925. In these years the concepts of quantum mechanics were expressed and critically analyzed in Copenhagen under the leadership of Niels Bohr, with the help of ideas of Heisenberg, Kramers, Pauli, and Born. The ink of these papers was hardly dry when the new way of thinking began to provide explanations for almost all the atomic phenomena that had been puzzling physicists since they were discovered. The rules of quantization of Bohr and Sommerfeld, which seemed arbitrary when they were proposed, turned out to be logical consequences of quantum mechanics; atomic spectroscopy became a deductive science; Niels Bohr's semiempirical *Aufbauprinzip* emerged logically from quantum mechanics with the help of Pauli's exclusion principle. Mendeléeff's periodic table of atomic properties was easily explained. A few years later, the chemical bond was understood to be a quantum mechanical phenomenon; so was the structure of metals and of crystals. A variant of a famous Churchill statement can aptly be applied to this golden age of physics: "Never before have so few done so much in such a short time."

There are three characteristic features that quantum mechanics has brought to our view of the atomic world.

First, it has introduced a characteristic length and energy which dominate the atomic phenomena, endowing them with a scale and a measure. The combination of electrostatic attraction between the nucleus and the electron, on the one hand, and the typical quantum kinetic energy of a confined electron, on the other, define a length (the Bohr radius) and an energy (the Rydberg unit). The size of the atoms is determined by the length, which is the combination h^2/me^2 of a few fundamental constants, where e is the unit of charge, m is the electron mass, and h is the quantum of action. The Rydberg unit is given by the combination me^4/h^2. Thus atomic sizes and energies are basically determined and explained.

Second, quantum mechanics introduces a "morphic" trait, previously absent in physics. The electron wave functions represent special forms or patterns of simple symmetry, characteristic of the symmetry of the situation which the electron faces in the attractive field of the nucleus and of the other electrons. These patterns (see cover) are the fundamental shapes of which all things in our environment are made. They are directly determined from the fields of force which bind the electrons. They always appear, identical and unchanged, whenever the atom finds itself under the same conditions. The appearance of characteristic forms and patterns is closely connected with a new way of dealing with mechanical concepts in quantum mechanics. The position of an electron has only probabilistic meaning within a given electron pattern and the same holds for other mechanical attributes such as the momentum. This lack of definiteness, usually expressed in terms of uncertainty relations, is more than offset by the much more refined description of atomic reality and observation provided by quantum mechanics.

Also a concept of ideal identity has been introduced. Two atoms are either in the same quantum state, in which case they are identical, or in different quantum states in which case they are definitely nonidentical. The continuous transition between identical, almost identical, and different has disappeared. The identity has measurable physical consequences, such as the intensity change in the spectra of molecules composed of identical atoms.

The third characteristic feature of quantum mechanics is the use of quantum numbers for the characterization of quantum states. Quality is reduced to quantity: the number of electrons and the quantum numbers of a given state fully determine all properties of the atom in that state. Pythagorean ideas are reborn here: the spectrum of frequencies of an atom represents a characteristic series of values, the typical "chord" of that atom, as it were; the "harmonies of the spheres" reappear in the world of atoms. Kepler's speculation that the sizes of planetary orbits in the solar system constitute simple geometrical and numerical ratios proved to be wrong, but it is reborn in the electron orbits of the atom, as a direct consequence of quantum mechanics.

A fundamental problem of natural philosophy was solved by the discovery of laws which give rise to specific shapes and well-defined entities. Clearly, nature is basically made up of such entities, as our experience tells us every day. Materials have characteristic properties, iron remains the same iron after evaporation and recondensation. The specific properties of matter were first the concern of chemistry, not of physics; quantum mechanics explains these properties and thus has eliminated chemistry as a separate science. The infinitely varied but well-defined ways in which atoms aggregate to larger units are now within range of a rational interpretation in quantum mechanical terms. A theory of the molecular bond came into being in which electron wave patterns (orbitals) keep atomic nuclei together in the right arrangement. Since here one is again dealing with the interaction of nuclear charges and electrons, the same sizes and energies must appear as in atoms—sizes and energies that give rise to interatomic distances of a few Bohr radii and bonding energies of the order of electron volts.

Atomic aggregates consist of two kinds of particles—heavy nuclei and light electrons—which are bound to each other by mutual attraction. The interatomic distances are fixed by the size of the electron cloud, a length which can also be regarded as the amplitude of the zero-point oscillation of the electron. Because of the much greater mass, the zero-point oscillations of the nuclei in a molecule are much smaller than those of the electrons (the ratio is the square root of the mass ratio); hence in molecules and solids the nuclei form a rather well-localized skeleton, a fact which introduces a structural feature into chemistry and materials science, with all its architectonic consequences. The quantum mechanical description of atomic aggregates leads to an understanding of all the material properties and material constants on which classical physics had collected empirical information. In principle, all the constants mentioned above can be predicted and expressed in terms of the fundamental constants e, m, and h and the nuclear masses. For example, the resistance against compression that characterizes solid matter comes from the fact that a reduction in volume leads to an increase in the quantum kinetic energy of the electrons. This is what replaces the "hardness" of atoms in the classical frame of thought.

The well-defined structure of the nuclear framework in molecules is of special significance in macromolecules, which are long linear arrays of molecular groups. The enormous number of different orderings of these groups, each order being well defined and reasonably stable, is reflected in the numerous species of living systems in our flora and fauna and is due to an intricate copying and reproduction process, which has been unraveled during the last decade. So chemistry, materials science, and molecular biology are direct descendants of the quantum mechanics of electrons in the Coulomb field of atomic nuclei. The basic structures have a limited stability measurable in fractions of the characteristic energy unit, the Rydberg. Perturbations of a strength of a few electron volts would disrupt them. This is the tender world of chemistry and biology which is destroyed at temperatures corresponding to particle energies of more than a few electron volts, such as exist in most stars. Matter in the form in which we are accustomed to see it is a rare phenomenon in the universe.

A New World of Phenomena

The faint glow of radium in Madame Curie's hand was a telling indication of the existence of yet unknown phenomena in matter. It was apparent from radioactive processes that there must be energies much higher than a Rydberg unit within the atom. Rutherford made use of these processes to penetrate the structure of atoms, and, from anomalous scattering of alpha rays in atoms, discovered the atomic nucleus. Incredible as it may seem, it was only 6 years later (in 1917) that he used the same tool to study the composition of the nucleus and found that some of the constituents are protons. A new world of phenomena had been discovered. However, it was not until 15 years later, in the great year of physics, 1932, that the composition of the nucleus was disclosed. In that year Chadwick discovered the neutron, Fermi published his theory of radioactive beta decay, and Anderson and Neddermeyer discovered the positron. Each of these discoveries had far-reaching significance.

The existence of the positron demonstrated the validity and depth of Dirac's relativistic wave equation (1927), one of the most remarkable examples of the power of mathematical thinking. This equation—a marriage of quantum mechanics with relativity theory—demonstrated the necessity of the existence of an electron spin with its typical magnetic moment. In addition, the equation exhibits a fundamental symmetry corresponding to the existence of two types of matter, ordinary matter and antimatter, with equal properties but opposite charges and other characteristic quantum numbers. Matter and antimatter can be created in empty space if energy is available, and can be caused to revert to pure energy in the reverse process of annihilation. These unusual features had been anticipated theoretically from Dirac's equation before they were discovered in nature.

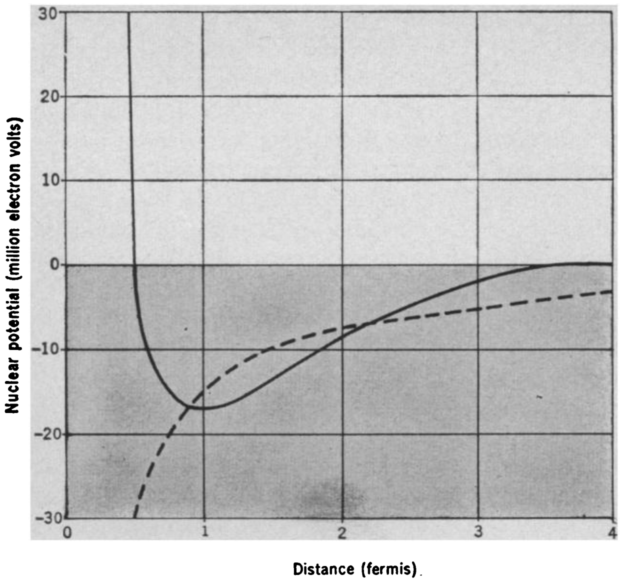
The discovery of the neutron as a constituent of the nucleus revealed the existence of a new force of nature. It pointed toward a strong nonelectric effect which keeps neutrons and protons tightly bound within the confines of the nucleus. Here was a manifestation of something new—a new force of nature without any analog in macroscopic physics. The "strong interactions" had been discovered.

Fermi's theory of the beta decay demonstrated the existence of another interaction between elementary particles. A neutron can transform itself into a proton with emission of a lepton pair—an electron and a neutrino. This transformation is effected by the so-called weak interaction—a fourth interaction supplementing gravitational, electromagnetic, and strong interactions. It is so weak that the time scale of its nuclear processes is of the order of seconds, days, or years.

Thus the year 1932 was the beginning of a new type of physics dealing with the structure of the nucleus and with its constituents, and working with hitherto unknown forces and interactions.

Let us return to the force between neutron and proton. Scattering experiments have revealed that this force has a rather complicated structure. It is short-ranged and attractive, except for small distances of less than a Fermi, when it becomes repulsive (see Fig. 1). Also it is strongly dependent on the relative spin orientation of the two particles and on the symmetry of the wave function. In this respect, and in its repulsive nature at small distances, it resembles the chemical force between two atoms, an analogy to which I return later. In estimating the strength of the attraction, let us compare it with the electrostatic attraction which would be present if the neutron and the proton had opposite electric charges g and $-g$. Of course, the nuclear attraction is short-range and changes to repulsion at small distances, but a qualitative comparison between the electrostatic attraction and the attractive part of the nuclear force is useful. It turns out that the nuclear attraction is roughly equivalent to an electric attraction between two opposite charges of magnitude $g \simeq 3\,e$. This information allows us to estimate the approximate size and energy of simple nuclear systems by applying the same quantum mechanical principles that were applied in the case of the atom. All we have to do is take the expressions for the Bohr radius and the Rydberg unit, replace e by g, and substitute the nuclear mass for the electron mass. We then obtain the nuclear Bohr radius $a_N = h^2/mg^2 \simeq 2 \times 10^{-13}$ cm, and the nuclear Rydberg $Ry_N = mg^4/2h^2 \simeq 3$ Mev. Nuclear systems are 10^{-5} times smaller than atomic systems, and the relevant energies are in the million-electron-volt region.

Once the nuclear force was established, quantum mechanics could be



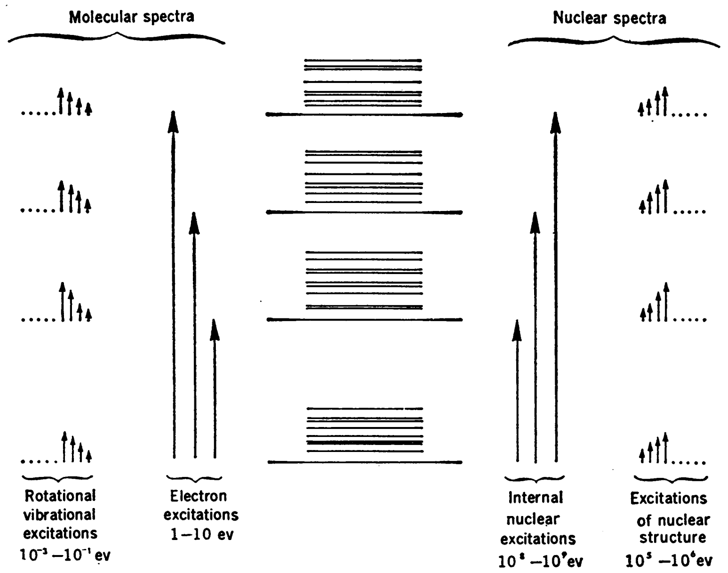


Fig. 1 (left). The potential of the force between two nucleons. The solid curve is an approximate rendition of this potential. The exact value depends on the relative spin direction of the nucleons and on the symmetry of the quantum state. The dashed curve indicates the electrostatic potential between two particles of opposite charge, 3.3 times the charge of the electron. [From *Scientific American*, with permission] Fig. 2 (right). Schematic sketch of a molecular spectrum and of a nuclear spectrum. The arrows at left indicate the nature and energies of the levels in molecules; those at right refer to nuclei.

applied to the nucleus as a system of neutrons and protons. We find in nuclear physics a repeat performance of atomic quantum mechanics, but with a different scale of units. Nuclear-energy-level spectra presented a structure similar to that of atomic spectra, with the same kind of quantum numbers. One significant addition appeared, however—the isotopic spin quantum number. It originates from the fact that the nuclear force does not distinguish neutrons from protons, so that, for nuclear conditions, one should consider the two particles to be two equivalent states of a single particle, the nucleon. Thus a situation arises that is formally similar to the two ordinary spin states of a fermion, and this analogy led Heisenberg to introduce the important concept of isotopic spin and its quantum numbers. The weak interactions provide a process for changing a neutron into a proton and vice versa, so that the spin analogy has also a dynamical sense. The nuclear system therefore is not an entity with fixed numbers of neutrons and protons; all that is fixed is the total number A of nucleons. All nuclei with equal A belong to the same quantum system, and one finds many typical similarities between quantum states of nuclei with equal A which differ only with respect to the number of neutrons that have been replaced by protons. Whereas transitions between atomic states are accompanied by the emission and absorption of light quanta (or by equivalent processes), nuclear transitions are accompanied not only by light radiation but also by weak interactions with emission of lepton pairs, in which case the charge of the system is no longer fixed but changes by one unit.

There are many striking parallels in atomic and nuclear structure. One is the periodicity of properties as a function of the atomic number A, arising from similarity of shell structure. The occupation numbers at which the shells are completed differ slightly because of differences in the nature of the average potential and because of the important role that spin orbit coupling plays in nuclei. The role of the noble gases, which have high stability and low reaction rates, is played in nuclear physics by those nuclei for which shells are completed. There exists a Mendeléeff table of periodic nuclear properties too. It is interesting to compare the dependence of certain properties on the number of protons in atoms and in nuclei—properties such as excitation and binding energies, or atomic volumes and nuclear quadrupole moments. Both, atoms and nuclei, show the same kind of periodicity, and the influence of shell structure is manifest.

A nuclear chemistry analogous to atomic chemistry exists, but there is an essential difference. In atoms and molecules, some of the constituents, the atomic nuclei, are well localized; they stay apart from each other and form the skeleton of molecules. This is not the case in nuclear structure. There each constituent is distributed over the whole nuclear volume. Hence, if two nuclei react with each other in a collision, they merge completely. Two oxygen nuclei form a sulfur nucleus and not a O_2 molecule. There is no particle whose zero-point oscillation is small as compared to the object; hence we do not find the variety of forms and the complexity of phenomena that we find in atomic chemistry. Furthermore, there is a limitation on the number of nucleons that can be merged into one unit, because of the electrostatic repulsion of protons.

The Internal Structure of the Nucleon

The analogy between atoms and nuclei is perhaps not thoroughly justified. It is probably more correct to compare nuclei with molecules, where the nucleons play the role of the atoms. Why? The force between nucleons is complicated, in its dependence both on the distance and on other properties. That force is much more like the chemical force between atoms, with its repulsive character at small distances, its minimum of potential in between, and its dependence on the symmetry of the wave function. It is tempting to assume that, in analogy to the chemical force, the nuclear force is not a fundamental force such as the electrostatic attraction; it may be a derived effect of a more basic phenomenon residing within the nucleon, a residue of something much more powerful and simpler, just as the chemical force is a residue of the Coulomb attraction between electrons and nuclei within the atom.

Modern particle physics has discovered much evidence for an internal structure of the nucleon, but it has not yet been able to interpret it. The most important evidence is the fact that the nucleon seemingly changes its character when it is bombarded with beams of energetic particles. It can be excited to a large number of quantum states. These states form a level spectrum which represents a third spectroscopy in which excitation energies are measured in billions of electron volts, not in millions of electron volts as in nuclei, or in electron volts as in atoms. This level spectrum shows regularities similar to those of the other spectra, and the same quantum numbers appear, plus a new one introduced by Gell-Mann and Nishijima, the hypercharge or strangeness. Here again transitions between the states occur with emission or absorption of light quanta and lepton pairs, but a new form of energy exchange was found: the absorption or emission of mesons.

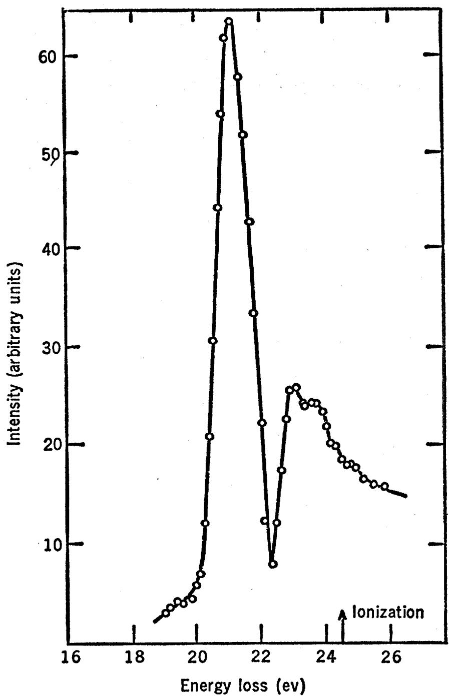


Fig. 3. Intensity of inelastically scattered electrons (energy, 120 electron volts) from helium atoms, as a function of the energy loss. The maxima show the first excited states of helium. [From Mott and Massey, *Theory of Atomic Collisions* (Oxford Univ. Press, New York, 1952)]

The analogy between nuclei and molecules is enhanced by the character of the spectrum of nuclei, if one considers not only the excitations of the proton-neutron system but also the internal excitations of the nucleons within the nucleus. One obtains a spectrum in which nuclear excitations are added to each internal nucleon excitation. The spectra of hypernuclei, as it were, are included in the nuclear spectrum. This spectrum is strongly reminiscent of molecular spectra (see Fig. 2), in which the rotational-vibrational structure is added to the electronic excitations. There is a quantitative difference, however. In a certain sense the nuclear force is less effective than the chemical force, as shown by the fact that the binding of the deuteron is so weak that it would dissociate even if it were rotating with one quantum of angular momentum. The nuclear force is barely strong enough to concentrate the wave function of the deuteron in the ground state sufficiently within the range of the force for binding to ensue. The bonds of diatomic molecules, however, are able to withstand the centrifugal force of 20 to 40 units of angular momentum. The same contrast is seen in the fact that the binding energy of a nucleon within the nucleus is much smaller than its internal excitation energies, whereas in molecules these two energies—molecular binding and atomic excitation—are comparable. Probably it is more appropriate to compare the nuclear force with the van der Waals force between closed-shell atoms. Nuclear matter would then correspond to superfluid helium, an analogy which goes surprisingly far in explaining the relatively independent motion of nucleons within the nucleus (the shell model) and some typical properties of the spectra connected with a phenomenon corresponding to the energy gap of a superfluid.

Let us go back to the search for the internal structure of the nucleon. This is one of the most challenging frontiers of modern physics. The problem of the nature and structure of the nucleon must be solved if we are to obtain answers to many fundamental questions regarding the basic reasons why matter has the properties we observe and regarding the origin of matter in the history of the universe. Most probably, new insights will be obtained, by this research, into the meaning of commonly used concepts such as particle, field, mass, interaction, and charge. The task is difficult on the experimental as well as the theoretical front, and progress is slow. An encouraging example, however, of the tremendous strides physics has made during this century in penetrating the structure of matter is the development of experiments on inelastic electron scattering.

Franck and Hertz in 1914 demonstrated the existence of excited states in atoms in their famous experiment which showed that the energy losses of scattered electrons equal the different excitation energies. Figure 3 shows these peaks at those specific energies for electrons scattered from helium atoms. The energy losses are of the order of electron volts. Figure 4 shows results of the same experiment performed with nuclei; one finds the same characteristic peaks, but here we are dealing with millions of electron volts. Figure 5 shows the results of a recent experiment on inelastic scattering of 16-Gev electrons at the proton; here the peaks in the energy loss correspond to the excitation of the proton itself, which is of the order of several hundred million electron volts—the same type of phenomenon as that observed by Franck and Hertz, but in an energy range 10^8 times larger!

The existence of excited states certainly points to some internal dynamics of the nucleon. The presently known spectrum of these states exhibits certain regularities which are vaguely related to those of a system consisting of three kinds of particles with half-integer spin, sometimes referred to as "quarks," "dions," or "stratons." One is tempted, therefore, to consider the nucleon to be made up of three of those subparticles. In addition, the regularities in the spectrum of mesons—they also have been observed in many quantum states that form a spectrum—point toward the hypothesis that a meson is made up of a quark and its antiparticle. In this hypothetical picture the mesons are the quantum states of a quark-antiquark system, in analogy to positronium, which is an electron-positron system. Such systems are forms of pure energy; they can be created by, and annihilated into, other forms of energy. Hence it is a suitable picture for a meson which is absorbed or emitted in transitions between excited states of the nucleon.

Quarks have not been observed in nature. If they really existed they would have some unusual properties, such as an electric charge one-third or two-thirds that of the electron unit, and probably some unusual statistics, different from the expected Fermi statistics. All we can say today is that cer-

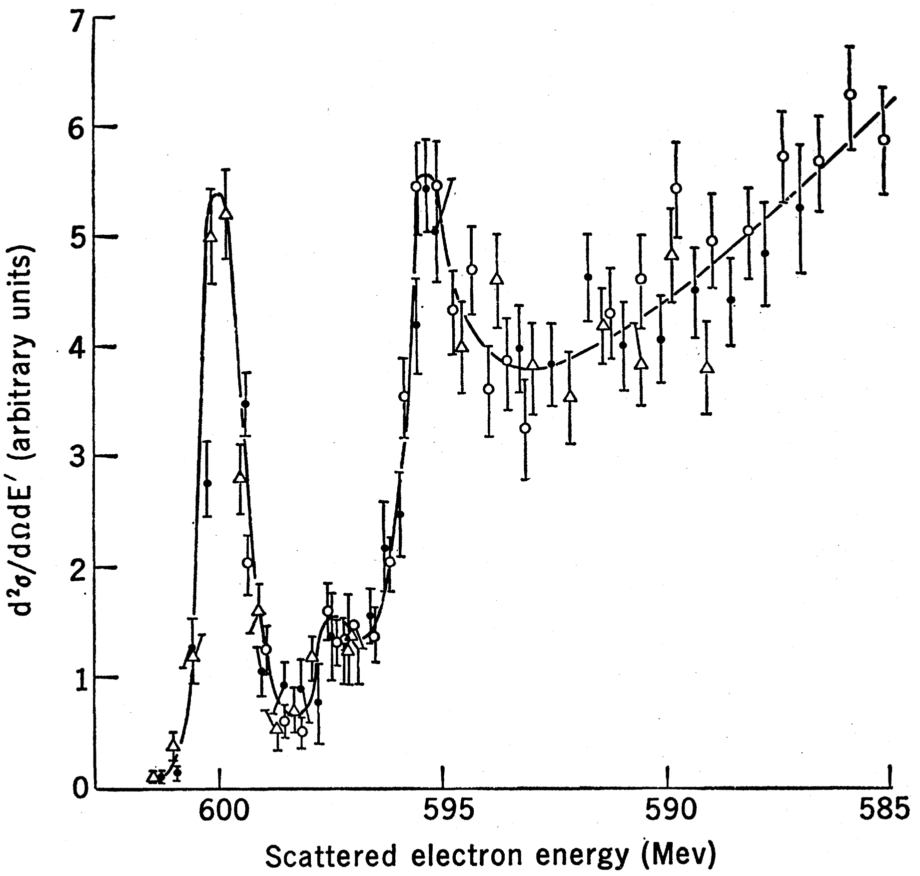


Fig. 4. Intensity of inelastically scattered electrons (energy, 600 Mev) from lead nuclei (Pb^{208}), as a function of the energy of the scattered electrons. The quantity plotted is the differential cross section per unit energy and solid angle at a scattering angle of 31°. The first peak shows the elastically scattered electrons, the next peaks show excitations of the nucleus. [From experiments by H. Kendall and J. Friedmann at Stanford Linear Accelerator Center, Stanford, California]

tain observations can be explained by assuming their existence. They would be bound together by an extremely strong, yet unknown, force, which might turn out to be the fundamental strong interaction, whose residual effects give rise to the nuclear forces. If they did exist, the physics of nucleons and mesons would be a third application of quantum mechanics on an even higher energy scale, after successful applications to atomic and nuclear problems. However, the situation would be different in many respects; our present view of quarks as constituents is probably an inadmissible use of an oversimplified picture. There is one important difference between the world of atomic and nuclear systems on the one hand and of excited nucleons and mesons on the other. In atoms and nuclei the excitation energies are very small as compared to the mass energy of the constituents; hence, the existence of antiparticles is irrelevant to the structure of these systems. In the world of nucleons and mesons, however, the excitation energies are comparable to, and sometimes larger than, the rest mass of the system. The relevant energies are of the order of the mass energies of the particles involved. As a consequence, pairs of particles and antiparticles are present within the system and contribute importantly to its structure. Hence the number of constituents of such systems may be quite undetermined; this is a new and essential feature of these systems. Today we have no systematic way of dealing with such situations.

There is also the question of an internal structure of the electron itself, which has not yet been faced. The most puzzling aspect of this question is the existence of the heavy electron or muon, a particle which, seemingly, is in every respect identical with the electron except for its mass, which is 200 times greater. The muon has a finite lifetime; it changes into a neutrino with the emission of a lepton pair (an electron plus a neutrino). It may be that the four known leptons—electron, muon, and two types of neutrinos—represent the beginning of a more complicated lepton spectrum. Although today the electromagnetic properties of the electron are extremely well described by the almost perfect theory of quantum electrodynamics, there remain grave questions regarding the nature of the electron: the reason for the apparent uniqueness of the elementary charge; the existence of the heavy electron; the source of the electron mass; and, last but not least, the nature of weak interactions, with their puzzling violations of established symmetries, such as right- and left-handedness and matter-antimatter symmetry.

Modern particle physics has led to the discovery of many unexpected phenomena. Theoretical understanding does not yet go very far, although theoretical physicists have contributed many ideas, models, and analogies in order to correlate and systematize the wealth of experimental material. There is as yet no Rutherford of particle physics, and no Niels Bohr. The lack of success is not due to any lack of intellectual effort, but the great insight into what goes on within a so-called elementary particle is not yet in hand.

"Extensive" Developments

So far I have sketched the development of our knowledge of the structure of matter in the 20th century, from atomic physics to modern particle physics. It is not only in this intensive direction toward smaller sizes, higher energies, and phenomena and laws hidden deep within the units of matter that science develops. There is also an "extensive" direction of development, in which knowledge of the basic laws and properties of matter is applied to the understanding of broader fields of inquiry.

Much has been learned and understood since the great breakthrough of quantum mechanics in the third decade of this century. An enormous amount of new insight has been gained into the properties of matter in its varied forms and states of aggregation. The amount of new knowledge is so great that I cannot hope to do justice to it within the frame of this article, which emphasizes fundamental research. I will restrict myself to a few scattered examples. Modern solid-state physics can give a detailed account of the behavior of metals, semiconductors, and crystals of all kinds. In particular, the behavior of solid matter at very low temperature revealed phenomena, such as superconductivity, which, for a long time, defied all explanation. But these phenomena, together with the superfluidity of certain liquids at low temperature, turned out to be understandable and derivable from the basic assumptions about the quantum nature of atomic dynamics. It was a long time before adequate concepts were found which made it possible to formulate the main features of the quantum behavior of systems with many constituents. Once such concepts were formed, they contributed to an understanding not only of the strange behavior of bulk matter at low temperatures but also of some features of the behavior of heavy nuclei, and they helped even in elucidating some problems of quantum electrodynamics and other field theories. The applicability of new concepts in many fields of physics is one of the gratifying developments which emphasize the unity of physics. This is even more apparent in the development of new instrumental methods in experimental physics. The great progress of microwave techniques has advanced all fields, from solid-state physics to elementary-particle physics. The development of our knowledge of materials such as semiconductors gave rise to new and improved particle-detection devices, and beams of elementary particles are the finest tools for the study of interatomic fields in liquids and solids. The strongly coherent light beams which are produced today in lasers and masers have their uses in all fields of physics.

New vacuum techniques, microwave devices, and strong magnetic fields made it possible to study matter in its plasma form—that is, a form of matter at high temperatures and low pressure where most electrons are no longer in their atomic quantum orbits. This state of matter is very common in the universe, in the interior of stars as well as in the expanses of space. The behavior of the plasma state is defined by very simple laws: the electromagnetic interaction between nuclei and electrons. Quantum effects are negligible because of the high excitation. Hence we are dealing with the classical physics of electrons and nuclei. Surprisingly, the resulting phenomena are more complex than those in quantum physics. Superposition principle and quantum stability are absent, and we face strong nonlinear effects and many instabilities.

Modern Astrophysics

An account of physics in the 20th century would be very incomplete without some mention of astrophysics. It is a science born in this century. It is the frontier of physics at extremely large distances, in contrast to particle physics, which is the frontier of extremely small distances. There is good reason to believe that the two are intimately related. Two major insights have shaped this branch of science: (i) recognition that nuclear reactions are the source of stellar energy, and (ii) the discovery of the expanding universe.

The first discovery has shown that nuclear reactions are infinitely more important for the production of energy than ordinary chemical reactions. However, nuclear processes do not occur on earth, except in the case of those few radioactive elements which are the last embers left over from the great supernova explosion in which our terrestrial matter was produced. In order to study nuclear processes, we had to reproduce them in our laboratories. It was no mean feat for man to recreate, on earth, processes which in nature are found only in the center of stars or in big star explosions, and to make technical use of them, even though some of these uses have been destructive ones.

The second discovery, the expansion of the universe, is mysterious but of fundamental significance. A new time and space scale appears. It is the time in which the universe has expanded to its present state, an interval of approximately 10^{10} years. We are very far from knowing what the universe was like at the beginning of this interval, but one fact is sure: the matter of our present universe was in a very different state at that time. The time interval also defines a length (the distance that light travels during that interval); it is the radius of the present universe, from beyond which no message can ever reach us. It defines a maximum size—about 10^{10} light years—in which our world is embedded.

The 20th century is, for the universe, what the 16th century was for the earth, when Magellan's ships sailed around the planet and showed that it has a finite surface. We have learned in this century that there is a finite universe with which we can be in contact, and we almost fathomed its depth when stellar objects were seen with a red shift of the order of unity.

Modern astrophysics has brought a new aspect to physics: the historical

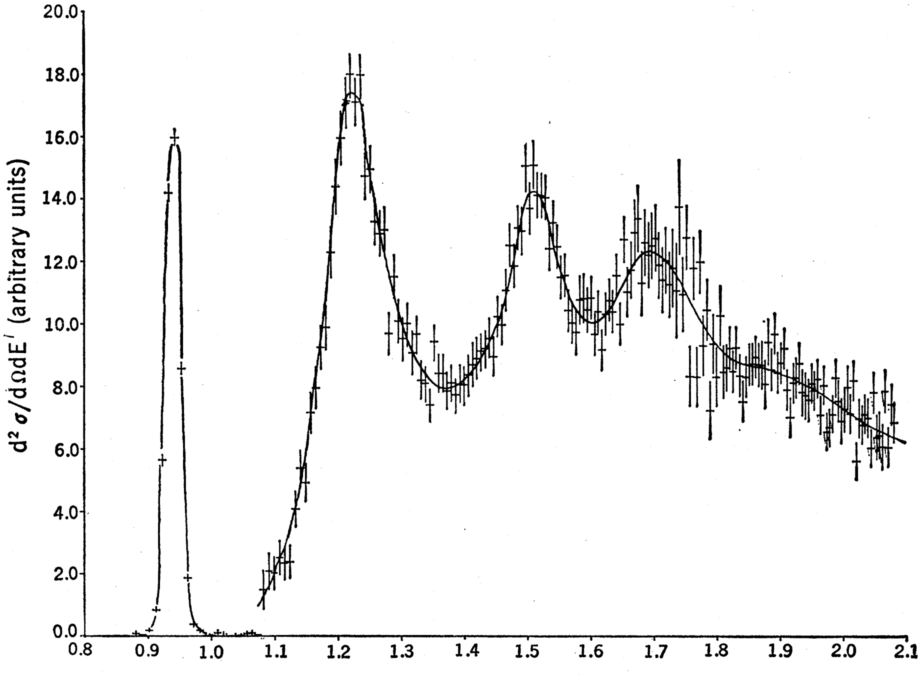


Fig. 5. Intensity of inelastically scattered electrons (energy, 16 Gev) from the protons, as a function of the internal energy of the scattered protons. The quantity plotted is the same as in Fig. 4; the scattering angle is 6°. The first peak shows the elastic scattering (reduced by a factor of 10); the next peaks are excitations of the proton. [From experiments by H. Kendall and J. Friedmann at Stanford Linear Accelerator Center, Stanford, California]

perspective. Previously, physics was the science of things as they are; astrophysics deals with the development of stars and galaxies, with the formation of the elements, with the expanding universe. There are many unsolved questions in this history, many phenomena, such as quasars, which are unexplained, but part of the history is fairly well understood. It is the part in which stars are formed from a hydrogen cloud, elements are formed by synthesis from hydrogen, and stars are developing through different states, some ending as cold chunks of solid matter, others ending in tremendous explosions which we observe as supernovas, sometimes leaving behind fast-spinning neutron stars.

One of these explosions occurred in the year A.D. 1054 and left behind the famous Crab Nebula, in which we see the expanding remnants of the explosion with a pulsar in the center. This explosion must have been a very conspicuous phenomenon, in its first days surpassing the planet Venus in brightness. So different from today's attitudes was the mental attitude in Europe at that time that nobody found this phenomenon worth recording. No records whatsoever are found in contemporary European chronicles, whereas the Chinese have left us meticulous quantitative descriptions of the apparition and its steady decline. What a telling demonstration of the tremendous change in European thinking that took place in the Renaissance!

The kinetic energies produced when large stars contract after their nuclear fuel is exhausted are such that individual protons reach energies of the order of several hundred million electron volts, not far from the energy of their rest mass. Therefore high-energy physics will come into play at these stages of development, and all the newly discovered phenomena of nucleon excitation and meson production will take place on a large scale, just as nuclear reactions take place on a large scale in the center of ordinary stars. Perhaps it is significant that such energies are reached when the gravitational energy of a particle becomes of the order of its mass. This is the so-called Schwartzschild limit, at which the gravitational field becomes critically large and the local space is heavily distorted. This may point to a connection between high-energy physics and gravitational phenomena.

The cosmological aspects of matter reveal a certain insignificance of electronic quantum physics in the universe. Only rarely is matter in a state where the quantum properties of electrons around nuclei are of relevance; for the most part, matter is too hot or too dilute. But it is at those special spots where quantum orbits can be formed that nature developed its atoms, its aggregates, its macromolecules, and its living objects. It is there that the greatest adventure of the universe takes place—that nature in the form of man begins to understand itself.

Employment Status of Recent Recipients of the Doctorate

Doctoral graduates in science and engineering have found professional employment despite a tightening job market.

Office of Scientific Personnel, National Research Council

In articles (*1*) and letters (*2*) published in scientific and professional journals, fears that Ph.D.'s may be in oversupply have recently been expressed. The authors of these articles and letters report that recipients of doctoral degrees are finding it increasingly difficult to obtain professional employment and that some are unemployed. "Is this country now producing more scientists than it can place in suitable scientific jobs?" asks one reporter (*3*). Echoes of these worries have reached a wider audience through newspapers (*4*) and magazines (*5*). Concern has not been limited to the employment prospects for new Ph.D.'s, but it has been especially acute in regard to this younger group.

Evidence cited for supposed unemployment of recipients of the doctorate is largely anecdotal and circumstantial rather than comprehensive and direct. Academic departments in some disciplines report that recent doctoral graduates have not been able to obtain suitable employment. The examples are scattered, however, and the number of authenticated cases of lasting unemployment is small. Dissertation advisers write letters to many colleagues, rather than to a few as in earlier years, in an effort to place their doctoral students in satisfying jobs. Graduate students, who had expected to be besieged by prospective employers, feel compelled to write large numbers of letters of application for jobs. Small academic departments that, a few years ago, were delighted to hear from a single well-qualified applicant for a faculty position now say they can choose from among many applicants from good universities. The ratio of employers to job seekers in the hiring halls of professional societies and college placement offices has shifted from 2 or 3 to fractional values during the last 2 years. Recruitment advertising by employers has diminished. All these developments indicate a tightening job market for Ph.D.'s, but they are not in themselves firm evidence of actual unemployment.

Reports and rumors of unemployment among Ph.D.'s have been accompanied, however, by changes in both demand and supply that have lent them credence. Actual and threatened reductions in federal support of research in universities have diminished research opportunities and have limited the growth of many departments on the larger campuses (*6*). The rate of increase of un-

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