THREE STEPS IN THE STRUCTURE OF MATTER

For atoms and nuclei, classification schemes provided the key to the underlying structure. Will the same be true for elementary particles?

Victor F. Weisskopf

ORDER WAS BROUGHT to the chaos of the elements 100 years ago when Dimitri Ivanovich Mendeleyev arranged them in the periodic table. The riddle presented by the regularities in this table remained unsolved for 52 years, until Niels Bohr published his famous "Aufbauprinzip," based on the quantum theory of the atom. Physical experimentation penetrated deeper into the structure of matter and revealed the properties of atomic nuclei. Similar periodicities were found when these nuclei were arranged according to the number of protons and neutrons. These regularities found their explanation in the shell model of the nucleus that was introduced in 1951 by J. Hans D. Jensen, Marie Goeppert-Mayer, Otto Haxel and Hans E. Suess. In the last two decades the proton and the neutron themselves were exposed to high-energy beams and many new short-lived entities were discovered. Recently Murray Gell-Mann, Kazuhiko Nishijima and Yuval Ne'eman discerned some order in the seemingly chaotic list of new "particles," but the explanation of this order is still outstanding.

Here are three stages of penetration into the nature of matter—the first concerning the structure of the electron shell of the atom, the second dealing with the structure of the nucleus as a system of neutrons and protons and the third aiming at the structure of the elementary particles. Interesting similarities and striking contrasts exist among these three fields of research, each of which has opened up a new world of phenomena.

ATOMS

In the 19th century physics and chemistry were separate disciplines. Chemistry dealt with "unphysical" concepts such as indivisible atoms with definite, unchanging characteristic shapes and qualities—concepts that had no place in contemporary classical physics. The physics of that period dealt with continuously variable qualities of solids, liquids, and gases, which were governed by constants such as elasticity coefficients, viscosities, dielectric properties, conductivities, and so forth. Physics was not able to explain the actual values of these constants; its aim was to find the consequences in the behavior of matter for a given arbitrary set of values.

The physics of the 19th century had no way to deal with the atom and its properties. True enough, the electron was discovered, and its important role within the atom was suspected in the works of J. J. Thomson, Hendrik A. Lorentz and their contemporaries. However, the two physical magnitudes associated with the electron—its charge e and its mass m—do not determine a length nor an energy. One needed the quantum of action h,

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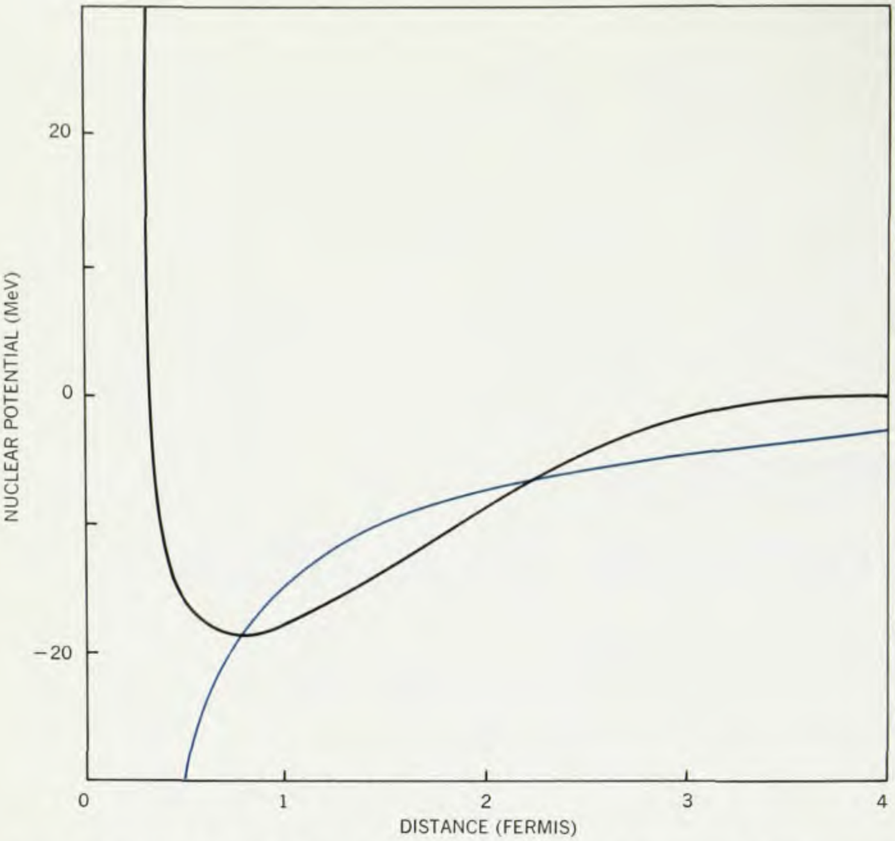


NUCLEAR FORCE IS REPULSIVE below about one fermi, attractive above. Coulomb force corresponding to opposite charges of 3*e* has the potential curve shown in color. Shape of nuclear potential resembles that of molecular potential. —FIG. 1

which was introduced by Max Planck's great contribution in 1900.

The year 1900 signified not only a change of century but a change in physics that culminated in a "physicalization" of the chemical concepts. Quantum mechanics, the child of the 20th century, proved to be a basis for a rational understanding of chemical phenomena such as the stability of atoms, their sizes and excitation energies. It gave rise to atomic units of length and energy, the Bohr radius and the Rydberg, resulting from a balance between the Coulomb attraction of electrons by atomic nuclei and the quantum mechanical zero-point energy of electrons in a confined region of space. It introduced into physics a "morphic" element: The fundamental equations of quantum mechanics determine the characteristic shapes and patterns that reflect the intrinsic symmetry of the atomic or molecular situation.

Quantum mechanics also gave a physical explanation of the spatial arrangements of chemical bonds. The observed stability and unchangeability of chemical properties were found to be consequences of the existence of discrete and well defined quantum states. Chemical ideas and concepts turned out to be contained in quantum physics, and chemistry has ceased to be a separate science.

Bohr's intuition

The quantum theory of the atom was the basis for Niels Bohr's explanation of Mendeleyev's periodic system of elements. But how could Bohr anticipate the correct explanation in 1921, before the formulation of quantum mechanics and—even more surprising—before the formulation of the exclusion principle by Wolfgang Pauli in 1925?

Bohr constructed his atoms one at a time by adding one electron after the other to the elements. So great was his force of intuition that he divined the rule that not more than two electrons can be placed in one orbit. Bohr read this fact from the properties of atomic spectra; he saw it in his mind's eye when studying the Mendeleyev periodicities. Trying hard to understand the double occupancy of orbits, he talked about "a disinclination to accept more electrons with the same quantum numbers." He speculated that "electrons with the same *m* and *k* are possible only if they form a harmonious interplay."

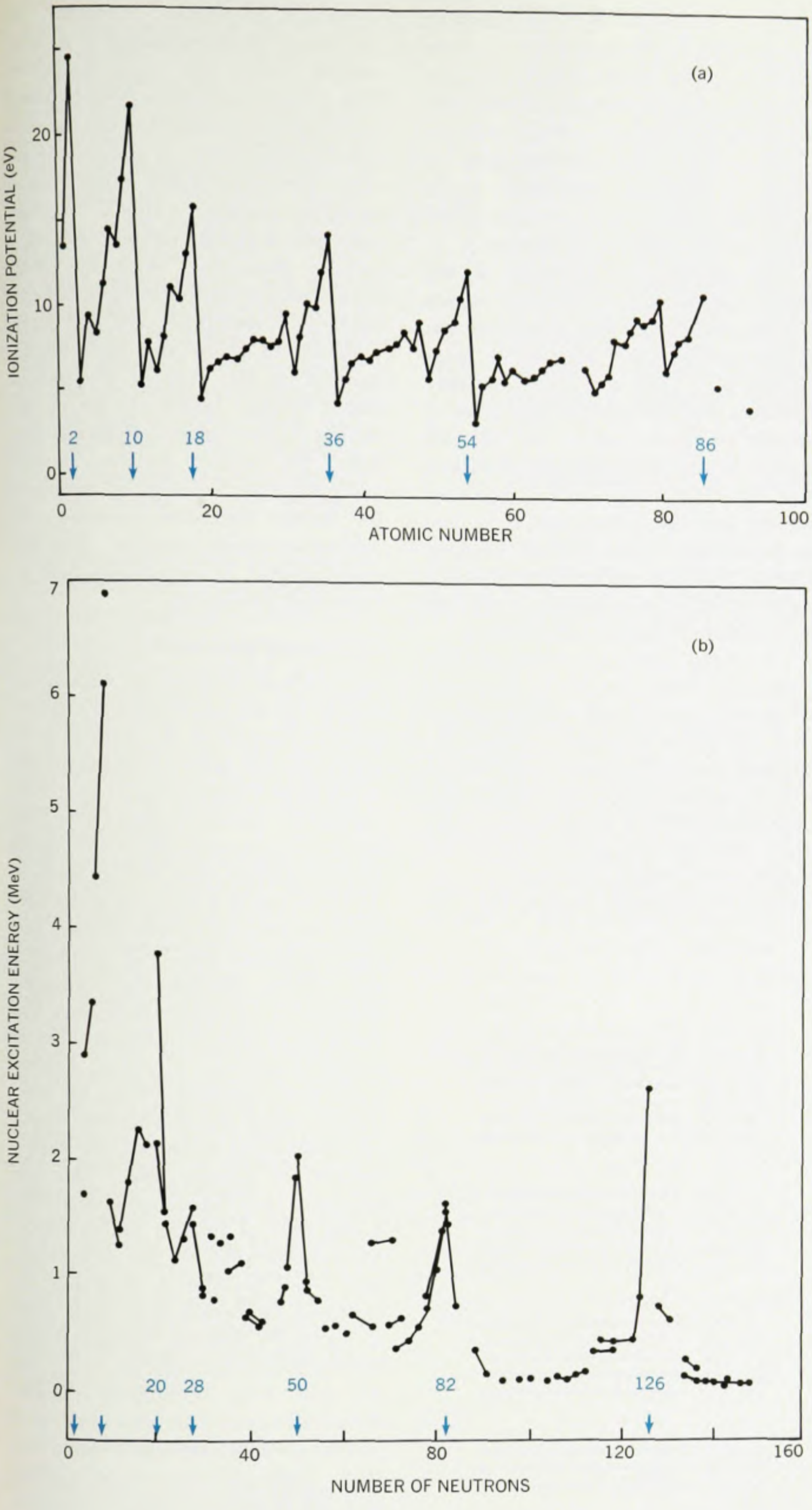
Pauli, the great critic and puritan, did not like this attempt at an explanation. He sensed already in 1921 that a major principle was hidden in these regularities. As an interesting testimony to Pauli's attitude, I quote some remarks that I found scribbled on the margins of a book in the Pauli library at CERN. The book contains Bohr's famous paper on the "Aufbauprinzip." During his discussion of the adding of the 11th electron to the closed shell of ten electrons, Bohr remarks: "We must expect that the 11th electron goes into the third orbit." ("Wir müssen erwarten dass das 11. Elektron (Na) in die 3. Bahn geht.") Pauli, obviously annoyed by this statement, writes hastily in the margin with two exclamation marks, "No reason to expect anything; you concluded it from the spectra!!" ("Wir müssen es nicht *erwarten* aber wir wissen es aus den Spectren!!")

Four years later, after careful analysis of atomic spectra and of the Zeeman effect at high fields, Pauli was able to formulate clearly his exclusion principle, which put Bohr's explanation of the periodic system of elements on a firm basis. Fifteen years later, in 1940, Pauli was able to prove that the exclusion principle for particles with half-integral spins is not an additional new principle but follows necessarily from the structure of relativistic wave equations.

With the development of quantum mechanics, the concepts of chemistry were no longer "unphysical." An important step toward the unity of science was taken. The various interactions among atoms that were once expressed in terms of chemical forces—van der Waals's forces, adhesion, viscosity, electricity, capillarity—were all reduced to one well known natural interaction, the electrostatic attraction between electrons and nuclei. The effects of this attraction are determined according to the circumstances by the laws of quantum mechanics.

Fundamental numbers

The quantum mechanics of atoms and molecules is governed by two fundamental numbers whose small values are essential for the character of the observed phenomena—the fine-structure constant, $e^2/\hbar c$, and the mass ratio between electron and nucleon, m/M. If $e^2/\hbar c$ were near unity or larger,



SIMILAR PERIODICITIES IN ATOMS AND NUCLEI are evident in plots of (a) *atomic ionization energies* compared with (b) nuclear excitation energies. Largest energies occur for inert gases and magic nuclei (colored arrows), both of which correspond to closed shells. Nuclear excitations are shown for first excited levels in even–even nuclei; the solid lines connect all nuclei that have the same proton number. —FIG. 2

atomic mechanics would be dominated by relativistic effects. For example, electron–positron pairs would then be important constituents of atoms.

If the mass ratio, m/M, which is responsible for molecular structure, were not small, physics and chemistry would be completely different. The average distance between nuclei in a molecule is determined by the size of the electron orbital, a length that can be considered as the amplitude of the zero-point motion of electrons. The nuclei are subject to the same force as the electrons (Newton's third law) but their zero-point motion is reduced by a factor $(m/M)^{1/2}$; for this reason they are well localized within the molecule. They form a nuclear skeleton that makes possible the immense variety of molecular architecture, including crystals and macromolecules. If the mass of the proton were of the same order as the electron mass, there would be no chemistry, no solid bodies and, in the last instance, no life and no minds to consider the problem.

The reason for this difference of mass is still unknown. It certainly is connected with the existence of strong interactions between nucleons, and it is one of the central problems of modern particle physics. As long as we do not understand the origin of the heavy mass of nucleons and the small mass of electrons, and the value of the electric charge measured in units of $\hbar c$, we cannot claim to understand the basic reasons why the world around us is the way we observe it.

NUCLEI

Our world of chemistry and biology can only exist in an environment where energy exchanges between particles are not too violent and where enough energy is available to initiate nonviolent changes in molecular structure. These benign conditions are available on earth because of the safe distance of 10^{13} cm from a star and of the protective cover of the atmosphere. Most of the matter in this universe exists under very different conditions. In the center of the stars, for example, the world of nuclear processes is of prime importance. In this realm, the second ordering principle is relevant. On the surface of the earth, nuclear processes are practically nonexistent; the energies available are not sufficient to initiate them. We find only rare cases of such processes, the natural radioactive elements, which are remnants of a distant past when terrestrial matter probably was ejected by a supernova explosion.

The nuclear force

To study nuclear phenomena in our laboratories we have to produce them with particle accelerators. These studies have been highly rewarding because they have uncovered the existence of a world so different and yet so analogous to our atomic and molecular environment. First of all, a new force was discovered that acts between the nucleons. This complicated force is shown in figure 1. Repulsive at distances less than 10^{-13} cm (1 fermi), it becomes attractive in the region between one and several fermis and goes exponentially to zero at larger distances. The details of the force depend on the relative spins and symmetry of the quantum states of the two particles.

In contrast to the electric force, the nuclear force has no macroscopic realisation. A macroscopic electric field is produced by concentrating many electric charges within a given volume. The fields of the charges reach far outside the volume and add up to a large field. This can not be done with a nuclear-force field because its range is not much larger than the closest distance within which nucleons can be brought together.

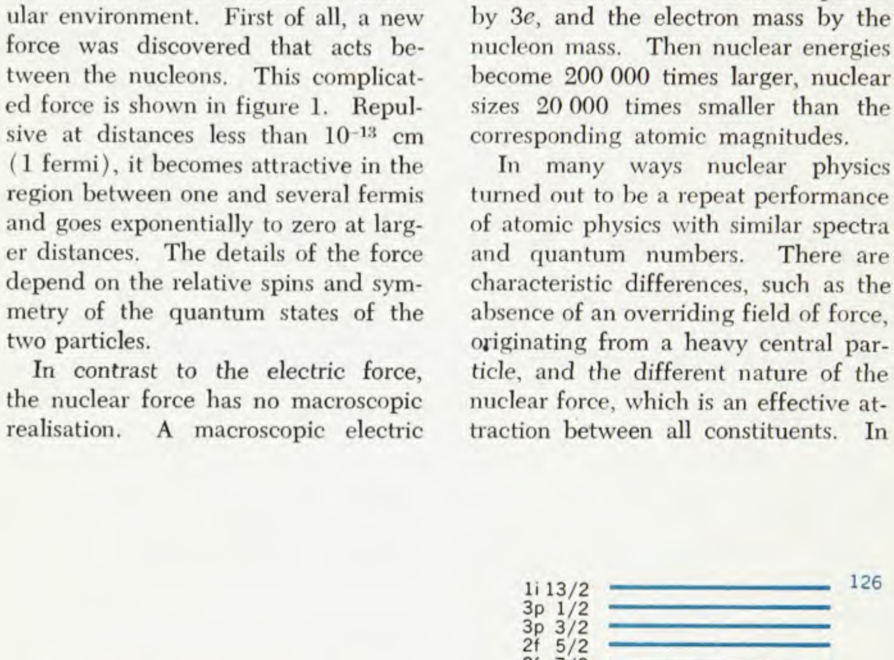
The approximate strength of the nuclear force in the attractive region is comparable to the attraction between two opposite charges of magnitude $3e$. With this value we may estimate that the energies and sizes of simple nuclei are given by the well known expressions for the Rydberg and the Bohr radius with e replaced by $3e$, and the electron mass by the nucleon mass. Then nuclear energies become 200 000 times larger, nuclear sizes 20 000 times smaller than the corresponding atomic magnitudes.

In many ways nuclear physics turned out to be a repeat performance of atomic physics with similar spectra and quantum numbers. There are characteristic differences, such as the absence of an overriding field of force, originating from a heavy central particle, and the different nature of the nuclear force, which is an effective attraction between all constituents. In quantum mechanics, however, the symmetry of the situation is a determining factor for many properties. The average attractive field to which each nucleon is subjected has the same spherical symmetry in atoms as in nuclei. Hence we obtain similar sets of quantum numbers, a similar "Aufbau" principle, a similar periodic system of nuclear properties, when the nuclei are ordered according to the number of protons or neutrons. We find nuclei with closed shells and high binding energies at the ends of the periods. These "magic" nuclei are the nuclear analog of inert gases. Figure 2 illustrates the analogy between nuclear and atomic periodicities by comparing the atomic ionization energies with nuclear excitation energies. The general character is similar, but there are important deviations.

Contrasting properties

The analogy between the nuclear and atomic spectra breaks down on several points. First of all, the order of levels in the average potential of the nucleus is different from the order in a Coulomb field. Because the nuclear force has no singularity in the center, the 2s level is higher than the 1p level, as shown in figure 3, whereas in the Coulomb field the order is reversed. Secondly, a strong spin–orbit coupling in the nucleus changes the occupation numbers of successive shells such that the ends of periods occur at different particle numbers. Moreover, because there is a repulsion among the electrons in atoms and an attraction among all constituents in nuclei, we have a reversal of Hund's rule. This rule maintains that the atomic ground state is the state of highest multiplicity of the configuration in the last incomplete shell because in that state the electrons stay apart from each other. In nuclei, by contrast, the ground state has the lowest multiplicity, being zero for any even occupation number. Hence all nuclei with even numbers of protons Z and neutrons N have zero spin. Only odd occupation numbers give rise to nonzero angular momenta.

A further difference is the existence of two types of nuclear constituents—neutrons and protons—of almost equal mass. The equivalence of these two types with respect to the nuclear force results in an approximate degeneracy of quantum levels that differ by replacing neutrons by protons. The degeneracy is broken only by the weaker electric effects coming from the pro-



DIFFERENCES IN ORDER OF ENERGY LEVELS result from differences in atomic and nuclear forces. Absence of singularity in nuclear force inverts order of 2s and 1p levels; spin–orbit coupling changes occupation numbers of successive shells, labeled in color. Scale indicates only order, not value of energy. —FIG. 3

ton charge. This degeneracy gives rise to a new symmetry and a new quantum number, the isotopic spin, that governs nuclear spectra.

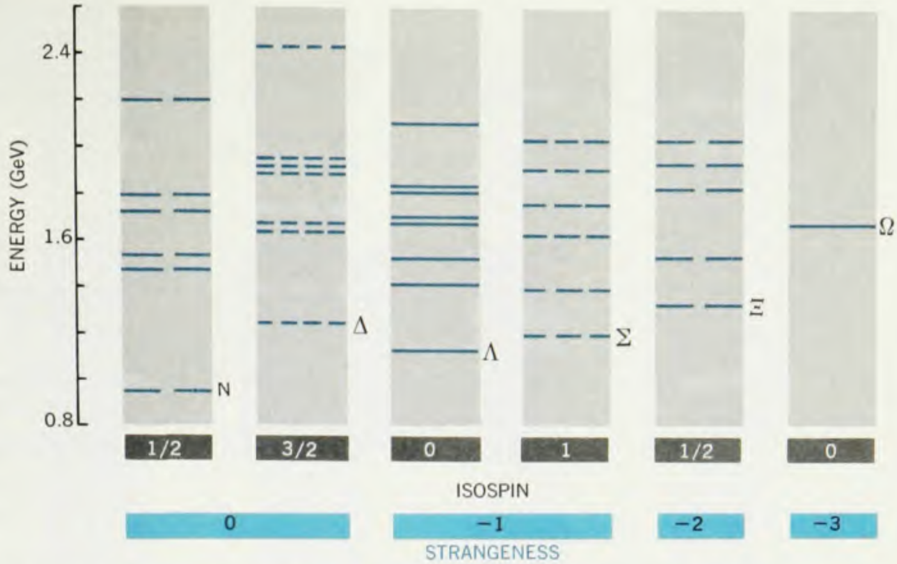
Another consequence of equal mass among constituents is the absence of any special localization or well defined center within the nucleus. Hence when two nuclei merge in a nuclear reaction, the product is not a "molecule" but a new nucleus. For example, two merging oxygen nuclei give a sulfur nucleus. No skeleton or superstructure is formed. In this sense, the possibilities of creating new structures by combination is much poorer with nuclei than with atoms. However, the energy released in nuclear mergers is 10^6 times larger than in chemical reactions.

There is an upper limit to the number of nucleons that can be joined because of the increasingly disruptive effect of the Coulomb repulsion. Possibly some special shell effect may extend this limit further than the presently known transuranic elements. Also, on a larger scale, the gravitational attraction would help keep nucleons together, as in the recently discovered neutron stars.

Another new feature appears in the nuclear world. Transitions between quantum states from higher to lower energy take place not only by emission of light quanta as in atoms but also by emission of lepton pairs—electrons and neutrinos. These emissions are manifestations of the mysterious weak interaction; they exhibit surprising properties, such as a violation of the right–left symmetry. They permit transitions between states of different total charge. Hence all nuclei with the same number of nucleons belong to the same quantum system irrespective of the charge. The nuclear system will arrive at its ground state by undergoing successive transitions until it contains the number of protons that minimizes the energy.

NUCLEONS AND MESONS

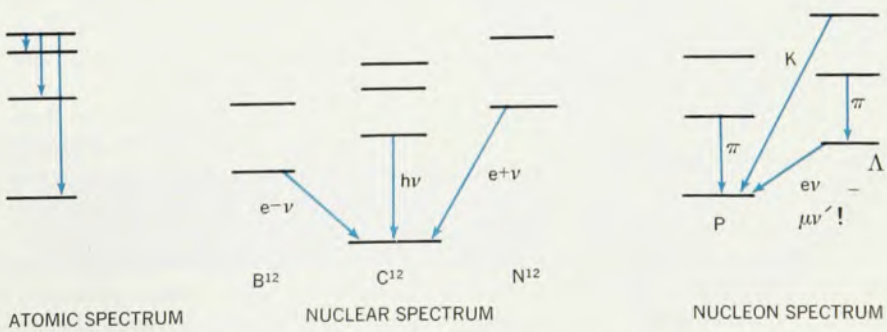
The third step in the recognition of the nature of matter was the penetration into the structure of the nucleon itself. The nucleon turned out to change its state when bombarded with particle beams of energies larger than several hundred MeV. The nucleon assumes short-lived "excited" quantum states, from which it returns to its ground state (neutron, proton) with the emission of the energy difference in various forms. In the spectrum of these "excited" states, shown in figure 4, the energy differences are of the order of 10^8 eV, about 1 000 times larger than excitation energies of nuclei. When these phenomena were discovered, the excited states were not yet put in this well ordered array. One state after the other was found and considered to be a new elementary particle.



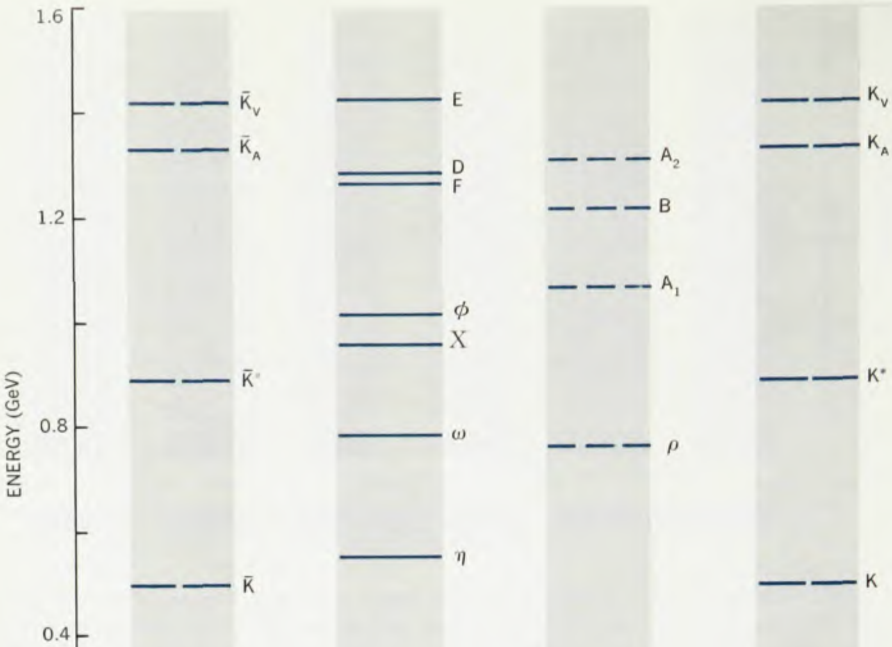
MANY "ELEMENTARY" PARTICLES were found to be excited states of the nucleon with energies 1000 times greater than nuclear excitations. They fall into groups characterized by values of quantum numbers such as isospin and strangeness. Number of dashes at each level indicates the multiplicity of charge states. —FIG. 4

After careful study of the excitation energies, quantum numbers and emission products, Murray Gell-Mann, Kazuhiko Nishijima, Yuval Ne'eman and many others unraveled the apparent chaos of large numbers of elementary particles and put order into it by introducing a new quantum number, "strangeness" or hypercharge, and a group-theoretical classification, SU3. The new particles—named with Greek letters such as Δ, Σ, Ξ and Ω—were recognized as excited states of the nucleon that fall into distinct groups according to the values of certain quantum numbers. Some of these quantum numbers, such as angular momentum and isotopic spin, were known from atomic and nuclear physics but the quantum of hypercharge was making its first appearance.

This new realm of phenomena revealed not only a new quantum number but also new forms of energy emitted or absorbed in transitions between quantum states. In addition to light quanta and electron–neutrino pairs, which are emitted in atomic and nuclear systems, a new lepton pair—the muon–neutrino pair—appears in these transitions. The muon is a heavy electron about 200 times heavier than the ordinary one. But



FIELD QUANTA EMITTED in three types of spectra. Light quanta (electric interaction), lepton pairs (weak interaction) and mesons (strong interaction) characterize atomic, nuclear and nucleon transitions, respectively. —FIG. 5



MESONS ARE CLASSIFIED in manner similar to nucleon spectrum. Both are characteristic of composite structure, as proposed by the quark model. —FIG. 6

the really new forms of energy emitted and absorbed are the mesons. Figure 5 gives examples of the three types of field quanta and the interactions in which they occur.

There are many types of mesons, some carrying spin, charge or hypercharge. The large array of different mesons can be classified and grouped according to the same quantum numbers used for the nucleon spectrum; they form a spectrum of mesons, as shown in figure 6. Indeed, in a change of a nucleon state, the difference in quantum numbers is delivered or removed in the acts of meson absorption or emission. Thus the classification according to quantum numbers also brought order into the chaos of meson states.

Nuclei are like molecules?

Are the three spectroscopies—atomic, nuclear, nucleon—three equal steps in a development towards smaller entities? There is some doubt about this. It may be more appropriate to consider only two systems, the atom and the nucleon, and then to consider also the levels of combined systems, such as molecules in the first case and nuclei in the second. We then would face atomic and molecular spectra on the one hand, and nucleonic and nuclear spectra on the other. Then the nuclear spectra are but extensions of the nucleon spectrum in the same sense that molecular spectra are extensions of atomic spectra. The nucleons in a nucleus play the role of atoms in a molecule, and the nuclear forces, the role of the chemical forces. This analogy is reinforced by the similarities between the nuclear and chemical forces. Both of them are attractive at larger distances and strongly repulsive at short ones; they both depend on the relative spins and the symmetry of the partners.

The analogy is striking if one considers the wider excitation spectrum of a nucleus, which includes not only the excitation of the proton–neutron system but also the internal excitations of the nucleons as given by the third spectroscopy. One then obtains a spectrum by adding the nuclear excitations to the internal nucleon excitations that is strongly reminiscent of molecular spectra, as seen in figure 7.

In a certain sense the nuclear force is less effective than the chemical force. For example, the binding of the deuteron is so weak that it would dissociate even if rotating with one quantum of angular momentum. By contrast, the bonds of diatomic molecules are able to withstand the centrifugal force of 20 to 40 units of angular momentum. As a similar contrast, the binding energy of a nucleon within the nucleus is much smaller than its internal excitation energies, whereas in molecules these two energies are comparable. Probably it is more apt to compare the nuclear force with the van der Waals's force between closed-shell atoms. Nuclear matter would then correspond to superfluid helium, an analogy that goes surprisingly far in explaining the relatively independent motion of nucleons within the nucleus (shell model) and some typical properties of the spectra.

We are tempted to assume from the rather complicated form of the nuclear force that it is not as fundamental as, say, the electrostatic attraction. It may be an effect derived from a more basic phenomenon residing within the nucleons, a consequence of something much more powerful and simple, in the same way that the chemical force is a consequence of the simple electrostatic interaction.

Quark model

Let us return to the excited states of the nucleons and the mesons. In contrast to the atomic and nuclear realm, the order found in this third spectroscopy so far is empirical. It can not be explained or derived from the internal dynamics of the system because this

SUPERPOSITION OF NUCLEAR EXCITATIONS (black arrows) on internal nucleon excitations (colored arrows) results in spectrum similar to molecular spectrum, where rotational-vibrational (black) are added to electron excitations (color). Perhaps the nuclear force, like the molecular force, is not basic but derived from a simpler and more fundamental force. *—FIG. 7*

dynamics is largely unknown. One intriguing feature of this order is that the spectra of the nucleons and of mesons exhibit certain features that point toward a composite structure. The nucleon spectrum has some of the characteristic properties of a three-particle system, where each particle is a member of a typical triplet of some subparticles of half-integral spin. The meson spectrum looks like a spectrum of a pair of those particles, or rather, of a particle and its antiparticle.

Although this so-called "quark model" can explain a large amount of phenomena connected with excited nucleons and mesons, it is beset with many logical difficulties. Unlike the world of atoms and nuclei, the excitation energies of mesons and nucleons are of the same order (sometimes even larger) as the mass energy of the system in the ground state. If the relevant energies in these systems are in that range, pairs of particles and antiparticles will be present or virtually present in any interaction process. As yet, we have no systematic way of dealing with this new feature.

Unsolved puzzle

The structure of nucleons and mesons is still largely unknown. We do not know what determines the forces between them nor why the energy of the nucleon ground state bears its particular relation to the electron mass, a relation that was decisive for the properties of matter we see around us. We can not claim to understand chemistry without understanding why protons and neutrons are as heavy as they are.

We are just beginning to learn how to speak about these objects and their interactions. Dispersion relations, current algebra and Regge poles are ways and means to put the observed facts into a logical framework, compatible with the rules of relativity and quantum fields. Most probably we will need much higher beam energies before we can find out what is going on "inside" these structures. At present, all we do is let them collide and find out how they interact and in what quantum states they fly apart. It is like trying to guess the structure of atoms by studying "low-energy" atomic collisions, namely, those collisions that excite the atoms but do not take them apart. It would be a difficult, and perhaps futile, operation.

The spectrum of excited nuclear and meson states was discovered less than ten years ago. Considering that it took 52 years to explain the periodic table of atoms, we should not be despondent over our present inability to explain the spectra of elementary particles. □