10 September 1965, Volume 149, Number 3689

SCIENCE

Quantum Theory and Elementary Particles

Recent discoveries, including new symmetries, have carried the search for elementary particles to a new level.

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All these things being considered, it seems probable to me that God in the beginning formed Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with such other Properties, and in such Proportion to Space, as most conduced to the End for which he formed them; and that these primitive Particles being Solids, are incomparably harder than any porous Bodies compounded of them; even so very hard, as never to wear or break in pieces; no ordinary Power being able to divide what God himself made in the first Creation. While the Particles continue entire, they may compose Bodies of one and the same Nature and Texture in all Ages: But should they wear away, or break in pieces, the Nature of Things depending on them would be changed. Water and Earth, composed of old worn Particles and Fragments of Particles, would not be of the same Nature and Texture now, with Water and Earth composed of entire Particles in the Beginning. And therefore, that Nature may be lasting, the Changes of corporeal Things are to be placed only in the various Separations and new Associations and Motions of these permanent Particles.

—NEWTON (*1*)

In this well-known and justly famous statement, Newton recognizes the logical necessity of elementary particles in order to explain the existence of materials with well-defined properties, such as "Water" or "Earth," metal or mineral, liquid or gas, and with characteristic and ever-recurring qualities. Matter must be composed of some entities on which those qualities are based, entities which today are called atoms or molecules. Newton faces a problem, however: the elementary constituents of matter must possess specific properties that do not change with time; they should not "wear off in use," they should be immune to any rough treatment. He solves this problem by assuming that they are "incomparably hard" and indestructible by any ordinary power. But today we know that this is not so. Atoms can be broken by a very ordinary power, for example by lighting a match, but still they possess an intrinsic shape. They regenerate themselves whenever the original conditions are reestablished. What Newton ascribes to the "first Creation" happens everywhere and at any time. We find well-defined shapes without permanence of the unit itself.

Today we know what Newton did not know, that this is based upon quantum mechanics; it is based upon a very simple idea, namely that energy is connected with symmetry and shape. Quantum mechanics requires that the states of lowest energy exhibit simple shapes, which are determined by the inherent symmetry of the internal conditions within the system. It is this symmetry which is the shape-giving agent. In the atomic world, there are two symmetries which are decisive. One is the symmetry of space, rotational and translational, and the other is the symmetry of permutation, the identity of electrons.

The space symmetry determines the character and shape of the atomic states. It admits scalar waves with one component, spinor waves with two components, and so on. The shape of the states follows from the spherical symmetry of the nuclear Coulomb field: the states of lowest energy must be simple spherical harmonics.

The permutation symmetry admits two alternatives: the quantum state may be symmetric or antisymmetric with respect to an exchange of particles. Nature chose the second alternative for electrons, which gives rise to the Pauli principle. We know today that the spinor character of electron waves is a necessary consequence of this. This is where the large variety of atomic shapes comes from, since electrons are forced into higher and different forms when the lower ones are occupied. In many ways, the Pauli principle replaces the classical concept of impenetrability or hardness. Two identical particles, obeying the principle, can never be brought to the same place. It is therefore reasonable to reserve the term "particle" for the entities which obey the Pauli principle.

The spectrum of atomic energy levels reflects the basic symmetries. They produce characteristic groups of levels—the multiplets—whose multiplicity, wave form, and other properties are determined by the symmetry. We arrive in that way at a classification scheme of atomic levels by means of the spin and angular-momentum quantum numbers.

It is important to keep in mind that these symmetries do not determine all properties of the quantum states. They determine the general shape and many other features, such as the structure of the level spectrum and details regard-

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ing transition probabilities. They do *not* give the size or the energies of the quantum states. These properties are determined by the strength and by the nature of the forces with which the particles are bound within the system. The symmetries alone are not sufficient for a complete description of a system; a knowledge of the dynamic conditions is required.

Quantum Mechanics and "Permanent Particles"

Let us now return to Newton's remarks. Does quantum mechanics of atomic structure fully remove the difficulty which Newton brought forward? It leads to an essential insight into the origin of fundamental shapes in nature: intrinsic shape and ever-recurring properties of atoms are possible without the atoms' being incomparably hard. But Newton would not have been completely satisfied with this answer, because our conclusions are based upon the existence of other particles, electrons and nuclei, which themselves possess intrinsic properties, such as mass, charge, spin, and magnetic moment. So the question obviously is raised again on a new level. Are the atomic constituents incomparably hard? Is there an ordinary power that can take them apart?

As far as the nuclei are concerned, the answer is known. Nuclei can be taken apart by ordinary power; they consist of protons and neutrons. The intrinsic shapes and forms of nuclei are determined by the same symmetries as the atomic shapes. This is why nuclear physics is similar in so many ways to atomic physics, for instance with respect to shell structure and multiplet structure of the spectra. But nuclear quantum states are dominated by an additional symmetry: nuclear forces are independent of the nature of the nucleon, whether it is a neutron or a proton. This dichotomy is analogous to the dichotomy of the two spin directions and, therefore, this additional symmetry takes the form of an invariance with regard to rotations of a symbolic spin, the isotopic spin. Hence nuclear quantum states have one more characteristic quantum number, which makes it possible to group nuclear levels into super-multiplets reflecting this new symmetry.

The isotopic symmetry brings in a new feature: the multiplets contain states of different charge: isobaric nuclei of different charge belong to the same spectrum and can be considered as states of the same system. Another new feature should be mentioned here, too: in the atom, transitions between states of the spectrum are accompanied by the emission or absorption of light quanta, at least in isolated systems. In the nucleus we find a new way of going from an excited state to a lower state, namely by the emission of a lepton pair, a pair consisting of an electron and a neutrino. Such transitions occur, of course, between states of different charge. Apart from this and the additional symmetry, nuclear structure and dynamics resemble closely the structure and dynamics of atoms.

Here again we must keep in mind

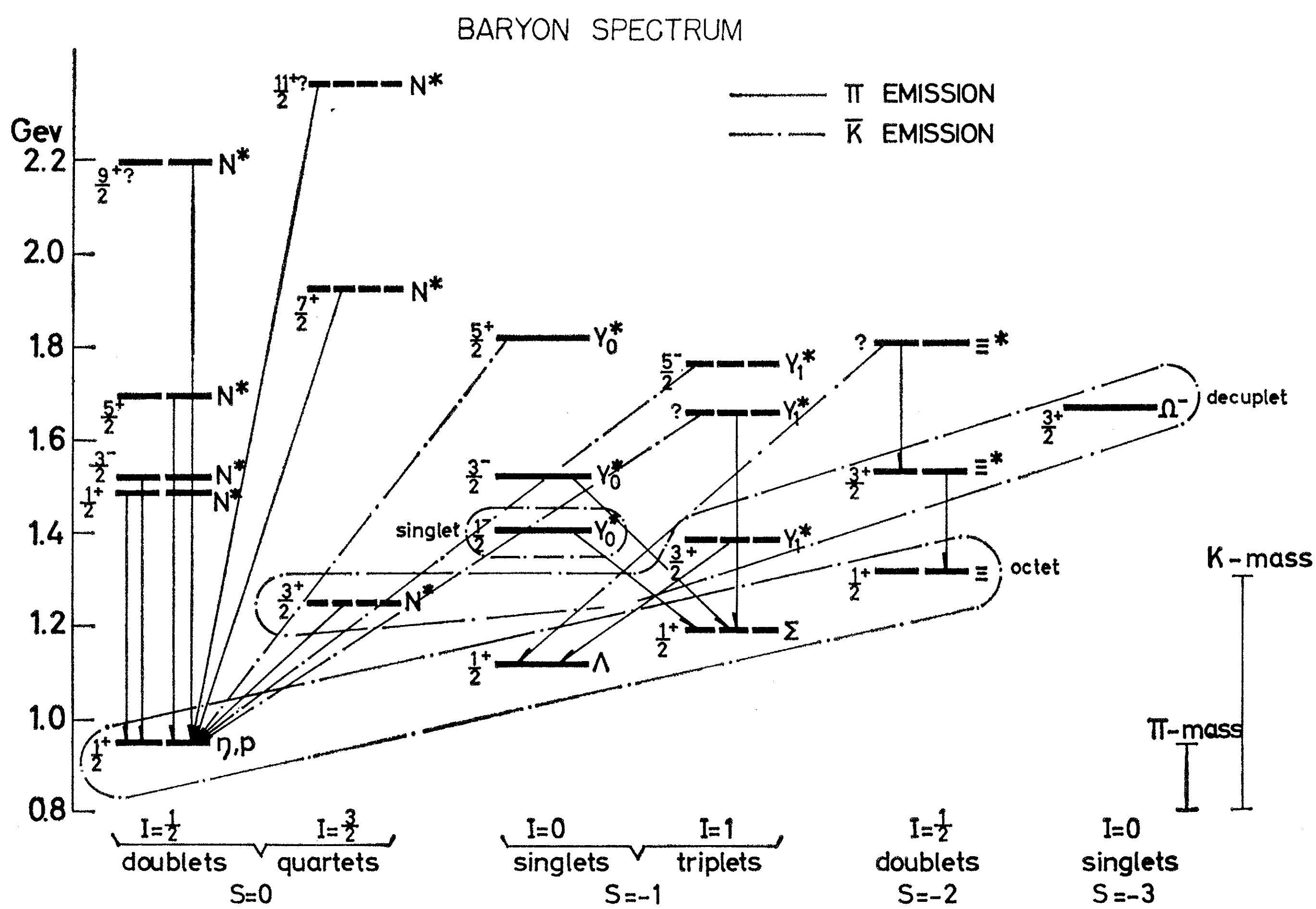

Fig. 1. Spectrum of the energy states of the baryon. The isotopic spin *I* and the strangeness *S* are given at the bottom, the angular spin and parity are given at the left of the level, the symbol at the right. The isotopic multiplicity, the transitions by meson emission, and some SU(3) multiplets are indicated.

that symmetries determine only the shape of the quantum states and their groupings into multiplets. The actual size of the states and the characteristic energies are determined by the relevant forces. It is, therefore, of interest to compare atomic with nuclear sizes and energies. The atom is held together by an electric force whose potential is given by e^2/r with $e^2/hc = 1/137$, e being the electronic charge, r the distance from the center of the field, h Planck's constant, and c the velocity of light. From this it follows that atomic sizes are of the order of a Bohr radius $a = h^2/me^2$ and atomic energies of the order of the Rydberg $R_y = me^4/h^2$, with m being the electron mass. The nucleus is held together by a nuclear force whose potential is somewhat more complicated, but whose most relevant contribution has the Yukawa form

$$(g^2/r)[\exp(-r/r_0)]$$

where $g^2/hc = 0.08$ and r_0 is the range of nuclear forces. If, for a moment, we set the exponential factor equal to unity, we get the same kind of potential as in atoms and would expect the size of nuclei to be of the order of a "nuclear Bohr radius" $a_N = h^2/Mg^2 = 2.5 \times 10^{-13}$ cm where M is the nucleon mass, and nuclear energies to be of the order of a "nuclear Rydberg" $R_N = Mg^4/h^2 = 6$ Mev. These values do indeed give a good orientation as to the sizes and energies of nuclear phenomena. The fact that a_N is of the same order as the range of nuclear forces is a justification for the omission of the exponential factor in the Yukawa force.

The Baryon

Would Newton have been satisfied at this point? Not completely; the number of elementary particles is essentially reduced to three: proton, neutron, electron. (We do not count the light quantum among particles, since it is the quantum of the electromagnetic field and obeys Bose statistics. The neutrino is excluded because it never appears as a constituent of matter.) But the existence of these particles still remains an assumption: they have "God-given" properties and may have to be "incomparably hard" so as not to change their properties when in use.

Let us first look at the situation regarding the proton and the neutron. So far nobody has taken a nucleon apart. The Rutherford of this stage is not yet known. It seems probable, however, that the nucleon is not "incomparably hard" either. Indications of an internal structure are clearly present; there exists a spectrum of excited states of the nucleon. These are not usually called excited states, but the observed phenomena can hardly be interpreted differently. What do we observe? When the nucleon is exposed to any kind of high-energy beams, it is transformed into short-lived states of higher energy, which are known under various names, such as "hyperons" or "resonances." The name "baryon" will be used for the entity which appears in the form of proton or neutron, or in the form of its excited states. In the spectrum of baryon states (see Fig. 1), the proton and the neutron figure as the ground states—they form a ground-state doublet. Exactly speaking, the neutron also is an excited state of the proton. All other states can be reached by supplying the nucleon in the ground state with the necessary excitation energy in one form or another. Some of the excited states have different charges from the ground state; some have different strangeness or hypercharge—a new property which turns up for the first time in these phenomena. The excited states return to the ground state in one or several steps, with the emission of π mesons, K mesons, light quanta, or electron-neutrino (lepton) pairs.

The charged mesons and the lepton pairs are charge carriers and therefore are emitted when there is a charge difference between excited and ground state; the K mesons are also strangeness carriers and are emitted when the strangeness changes. The K meson carries a positive unit of strangeness, the anti-K meson ($\bar{K}$) carries a negative unit.

In atoms, transitions between quantum states take place mostly by light emission or absorption; that is, by coupling with the electromagnetic field. In atomic nuclei we find, in addition to light emission, lepton-pair emissions (electron-neutrino pairs), which are produced by weak interaction coupling with the lepton field. In the baryon spectrum we find, in addition to those two kinds of emissions, transitions with meson emission, which is transacted by the strong interaction of nucleons with a meson field. All three couplings are active in any of the three cases. But the energy differences between atomic states are too small to allow the emission of lepton pairs, for which an energy of at least 0.51 Mev is needed because one of the leptons must be an electron; the differences between nuclear states are large enough for lepton-pair emission (β radioactivity) but too small for the emission of mesons, the smallest of which has a mass of about 140 Mev. In the spectrum of the baryon, however, the transitions are paid for in a new currency—the mesons—although the ordinary currency—light quanta and lepton pairs—is not excluded.

Let us quote a few examples of transition between nucleon states: the simplest example is the emission of a π meson in the transition from the first excited baryon state, a multiplet with the isotopic and ordinary spin of 3/2. This state has the same strangeness as the ground state; the transition is therefore accompanied by the emission of a π meson. The charge of the emitted π meson depends on the charge difference between the two combining states (see Fig. 2). Another example would be the transition from a highly excited state of strangeness different from that of the ground state: there a K meson would be emitted, in order to carry away the difference in strangeness. An odd situation occurs with the lower excited states of dif-

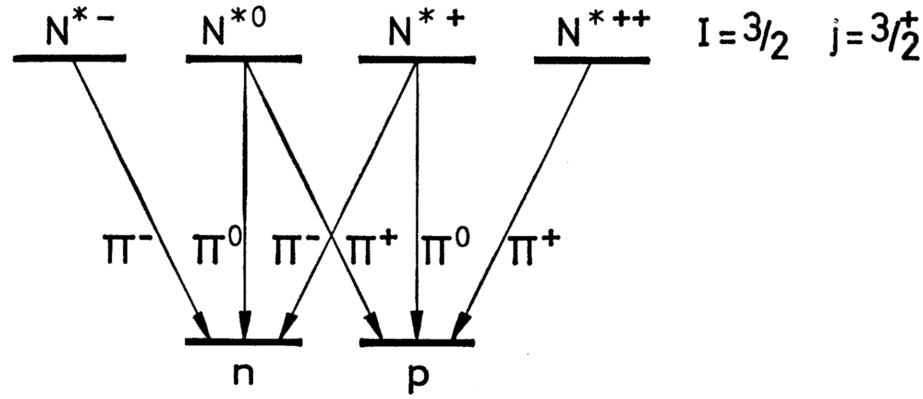

Fig. 2. Transitions between the (3/2,3/2) state and the ground state of the baryon. I, isotopic spin; j, ordinary spin.

ferent strangeness such as the ones designated by the symbols Σ, Λ, and Ξ. They cannot de-excite by K emission into the ground state, because the mass of the K meson is higher than the energy difference. These states, therefore, would be stable if the conservation of strangeness were an exact law (as the conservation of ordinary charge is). In fact, however, strangeness is conserved in all interactions except the weak interaction. Therefore, there exist very slow transitions from those states to the ground state with emission of π mesons or lepton pairs, mediated by weak interactions. Hence, the lowest states with strangeness different from zero are metastable and decay slowly into the only real stable state, which is the proton.

The excitation of these metastable states takes place mostly in a two-step process: first the nucleon is excited into one of the higher states, without change of strangeness, by proton collision or pion absorption; then a transition to a state of different hypercharge takes place, with the emission of a K meson. This is called associated production, since the end product consists of two entities of opposite strangeness: an excited baryon and a K meson.

The Boson Spectrum

Experiments with high-energy accelerators have revealed not only a spectrum of excited states of the nucleon, but also a second spectrum: the spectrum of mesons, or boson spectrum (see Fig. 3). A careful analysis of the mesons produced by high-energy collisions has revealed that the π meson and the K meson are not the only forms in which mesons appear. There exists a series of excited states referred to by various letters: ρ meson, ω meson, η meson, and so on, of which the π^- and the K meson are the lowest states. In fact, neither the π^- nor the K meson itself is really stable. Both decay by weak interactions into leptons. Hence they should be considered as true ground states of the meson spectrum only if the weak interactions are neglected.

In transitions from an excited state to a lower one, also, the energy difference is emitted mostly in forms of mesons. For example, the so-called ρ meson decays into two π mesons. We can interpret this as a transition from the ρ meson state to the lower π meson state, with the emission of another π meson. Figure 3 shows the most important meson quantum states known today and indicates their quantum numbers. Here, as in the baryon spectrum,

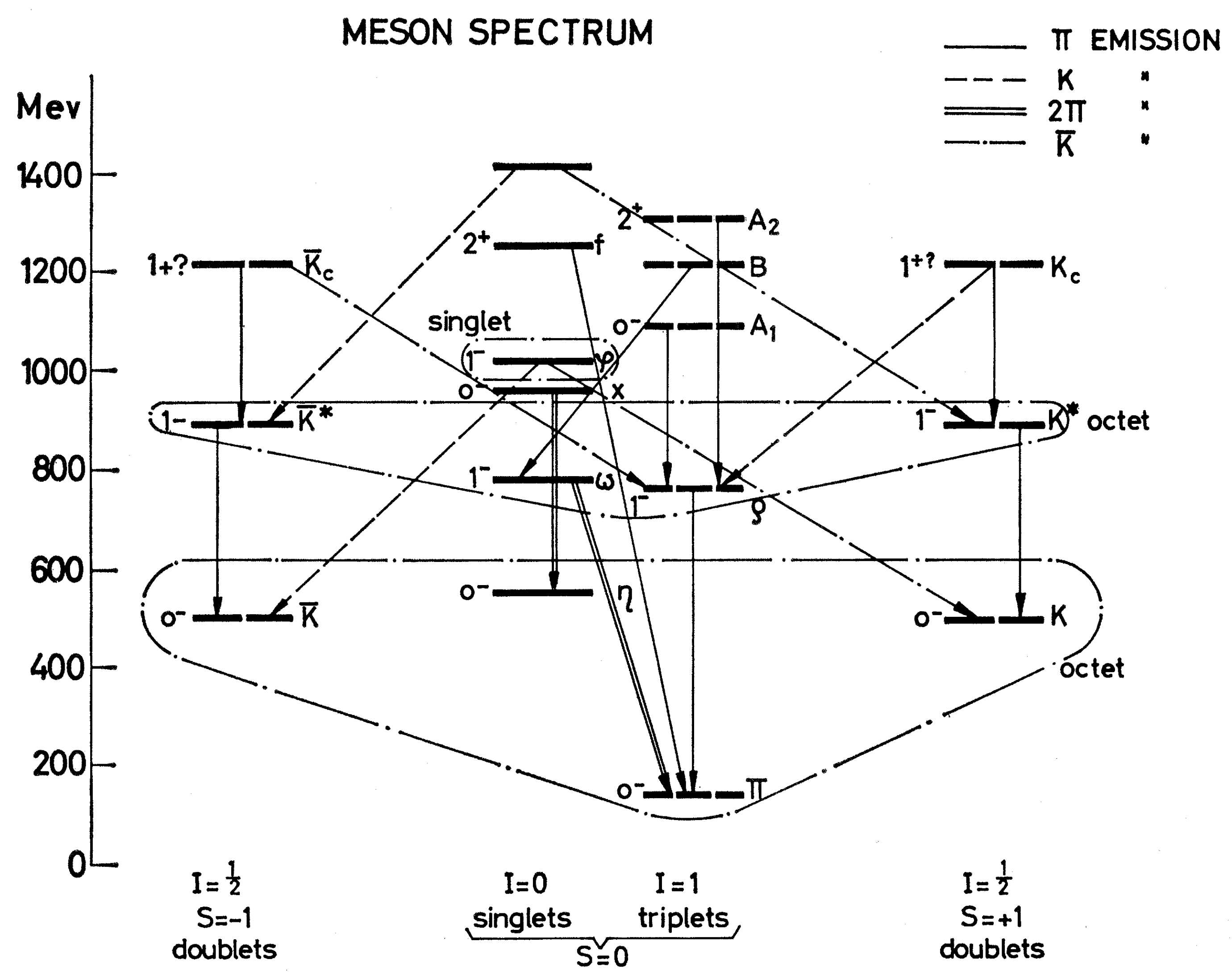

Fig. 3. Spectrum of the energy states of the meson. Isotopic spin I and strangeness S are given at the bottom, angular spin and parity at the left of the level, the symbol at the right. The isotopic multiplicity, the transitions by meson emission, and some SU(3) multiplets are indicated.

we find the same quantum numbers as in nuclear spectra—ordinary and isotopic spin and parity—and also the new strangeness quantum number.

The existence of such excited meson states is perhaps not so surprising as one might think. Let us consider the situation from the point of view of the analogy between light quanta and mesons. Both entities are quanta of a field; the quantum of the electromagnetic field with its source (the charge) is determined by the small constant $e^2/hc = 1/137$; it is a weak coupling. The coupling of the nuclear field to its source (the nucleons) is very much stronger. The corresponding magnitude G^2/hc is about 15. This is much larger than the magnitude $g^2/hc \approx 0.08$ which was used in estimating the strength of nuclear forces within nuclei; the nuclear forces have the peculiar property of being quite weak between nucleons whose relative momentum is nonrelativistic, as it is in the case of motion within nuclei. For that special situation the relevant coupling is reduced by a factor $g^2/G^2 = (m_\pi/2M)$, where m_π is the pion mass and M is the nucleon mass. It has its large value, however, under general conditions such as those for fields acting between particles of high relative momentum or between particles and antiparticles.

It is because of this circumstance that we can have a theory of nuclear structure based upon relatively weakly interacting proton-neutron systems without recurrence to the higher baryon states. If the relevant interaction constant in nuclear structure were as large as G, the nuclear excitations would be of the order of the baryon excitations; nuclear physics and elementary particle physics would be as closely related as meson physics and baryon physics.

A very strong coupling between field and source would have a number of consequences, some of which can be understood by extrapolation from electrodynamics. It is known, for example, that two light quanta interact weakly with each other. If the coupling constant were larger than unity, however, the interaction would become large and would be comparable with energy of the quanta. It would not be surprising, then, to find states in which several field quanta are bundled together. Such bundles are perhaps an appropriate description of the nature of excited meson states. There remains a question why no meson with rest mass zero exists in analogy to the light quantum. Is this also a consequence of strong interaction, or is there an essential difference between electromagnetic and mesonic fields? This is a most interesting problem which at present is left in complete darkness.

The above-mentioned interaction of light quanta comes from the fact that the two quanta can form virtual electron-positron pairs. Since the coupling constant between nucleons and mesons is large, the virtual pair states would play a much more important role in meson states. In fact, it would not be unreasonable to consider the meson states as states of the baryon-antibaryon system. There cannot be an essential difference between a bundle of field quanta and a state of the baryon-antibaryon system, since the former can produce the latter and vice versa. Because of the strong interaction, any such bundle will contain a considerable fraction of baryon-antibaryon pairs of equal spin and symmetry.

Baryons Guarantee Stability

Not only mesons but also baryons should really be considered as surrounded by virtual baryon-antibaryon pairs. After all, the strong meson field in the neighborhood of the baryon must also give rise to virtual pairs. The physical baryon and the physical meson are in fact extremely complicated systems which can be described as mixtures of many different states: they contain any number of baryon pairs and meson bundles, compatible with the quantum numbers. The basic difference between the baryon and the boson states lies in the total number B of baryons present. The baryon spectrum contains all states of matter in which this number is unity (the antibaryons are counted negative), the boson spectrum contains the states with $B = 0$.

The spectrum of states with $B > 1$ would contain the spectra of nuclei with a nucleon number $A = B$ and also the spectra of the isobaric hypernuclei. Such a spectrum would have a coarse and a fine structure. The fine structures are the ordinary nuclear and hypernuclear spectra which are built upon a coarse structure resulting from one or more nucleons' being in an excited state.

Here we recognize the reason why, in the meson spectrum, even the lowest states are metastable and decay by weak interaction into lepton pairs, whereas the ground state of the baryon spectrum—the proton—is really stable, and so are the ground states of all spectra with $B > 1$. The baryon number B is a quantity which is conserved in all interactions; hence only mesons can disappear by disintegrating into leptons; baryons must remain forever, a guarantee for the stability of our world.

When looking in this way at the baryons and mesons, one might be prompted to say that a meson is nothing but a given state of a baryon-antibaryon system or that any given state of the baryon is nothing but a combination of another baryon state and a few mesons. In other words, any of these states can be thought to be a combination of others. An ambitious attempt to get a self-consistent description of a group of particles in this way is known under the name of "bootstrap method"; one requires that the masses and interaction constants should be such that one obtains self-consistent results in any of the possible combinations.

The complex nature of the physical baryon or meson is used today for the explanation of interaction processes by picking out a particular feature of the mixed surrounding of the particles which may be essential for certain interactions. For example, a collision in which one unit of charge or strangeness is transferred from one particle to the other is then described as the exchange of one meson carrying these properties. Such semi-quantitative methods succeed from time to time in explaining a few characteristic experimental features. One tries to single out a typical Feynman diagram which symbolizes one of the many possible interaction mechanisms, ascribing to it greater importance than to all other possible ones. This is known under the name of "peripheral processes."

The two new spectra, the baryon spectrum and the boson spectrum, are not yet understood. They seem to indicate some internal structure of these entities, in the same sense as the atomic and the nuclear spectrum are reflections of the internal dynamics of the atom and the nucleus. In the latter cases, however, we know the dynamics; we know that the atomic spectra represent the quantum states of electron motion in the Coulomb field and that the nuclear spectra represent the quantum

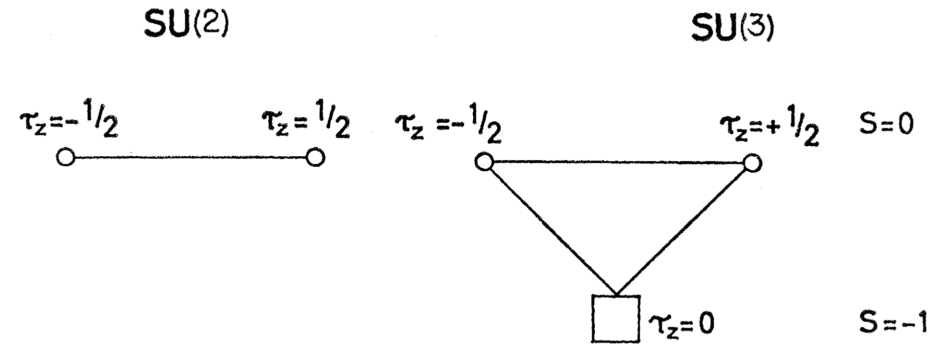

Fig. 4. (Left) The two basic states of SU(2) having a z-component of the isotopic spin $\tau_z = 1/2$ and $-1/2$. (Right) The three basic states of SU(3) consisting of a basic SU(2) pair and a third state with $S = -1$ and $\tau_z = 0$.

states of the nuclear motion under their mutual attraction. This knowledge allows us to establish the rules of symmetry which determine the relevant quantum numbers and the corresponding multiplets. It also allows us—in principle, at least—to calculate the energies, sizes, and other properties of the quantum states.

The situation is different with regard to the baryon and boson spectra. We have no definite idea yet as to their dynamic basis. We cannot, therefore, predict any symmetry rules for them. However, empirical inspection of the spectra definitely reveals multiplet structures, which indicate the validity or approximate validity of certain symmetries in a yet unknown dynamics. What are these symmetries? First of all, one is able to ascribe to each state a total angular momentum J leading to the usual $(2J + 1)$-fold degeneracy. This is obviously a reflection of the rotational symmetry of the situation and a consequence of the validity of our fundamental quantum-mechanical concepts. The decay patterns of unstable configurations exhibit the same geometrical shapes in simple spherical harmonics—which are the typical form elements of this symmetry. In fact, one has more occasion here than in the study of atomic or nuclear spectra to determine the angular momentum directly by the geometrical shape. This is because in high-energy processes particles are produced more often in polarized states than at lower energy.

It is less obvious that there are also isotopic-spin multiplets, the characteristic groups of levels of almost equal energy which differ only in electric charge. The ground-state doublet (neutron-proton) is one example; the three π mesons, π^+, π^-, π^0, are another. It seems that the charge independence found in nuclear structure carries over into the baryon and boson structures. (Or, rather, the observed charge independence in the baryon and meson structures is the basic fact, from which it would follow that interactions between nucleons and hence nuclear structure are also independent of charge.) The most interesting observation, however, is the presence of an additional symmetry: it has to do with the hypercharge or strangeness. As mentioned before, each quantum state of the nucleon and of the boson can be ascribed a strangeness quantum number. Evidently, the strangeness quantum number plays an important part in the ordering of these states. Is there any way in which it reflects a new symmetry?

SU(3) Symmetry

This new symmetry has recently been discovered and is known as SU(3) symmetry. The SU(3) group which underlies this new symmetry is a generalization of the SU(2) group. The latter is the "special unitary group" based on two fundamental states and is well known as the group which underlies the ordinary spin or the isotopic spin formalism. It is based on the "dichotomy" of two fundamental states—for example, the proton-neutron pair—and analyzes the properties of nuclear systems, derived from the invariance to an exchange between that basic pair. It is well known that this formalism leads to a multiplet structure of the spectrum. We have, of course, the basic proton-neutron doublet (isotopic spin ½); furthermore, a system of two nucleons gives rise to singlets and triplets of isotopic spin 0 and 1, a system of three nucleons gives rise to doublets and quartets of isotopic spin ½ and 3/2, and so on.

The SU(3) group starts with a "trichotomy" of three states; two of these represent a basic isotopic doublet with zero strangeness; the third is an entity whose isotopic spin is zero, but it carries a unit of strangeness which is usually assumed to be negative (see Fig. 4). Obviously, in the first attempts in this direction, the proton, the neutron, and the hyperon were considered to be the basic states of this fundamental triplet. Soon it turned out that the situation is, in fact, more complex and more interesting.

Let us look at the baryon spectrum. Here we find isotopic spins $I = 1/2$ and 3/2 with strangeness $S = 0$, we find $I = 0$ and 1 with $S = -1$, and $I = 1/2$ with $S = -2$, and $I = 0$ with $S = -3$ (see Fig. 5). What does this mean? It points toward the fact that the baryons behave as if they were combinations of three entities which are members of a basic trichotomy. These entities have received the ugly name of "quarks." (Let us not be confused by the fact that the number "three" is involved in two different ways: first, the "quark" exists in three basic states; second, the baryon is supposed to be a combination of three quarks.) Let us see how it works. There are three kinds of quarks: a pair of isotopic spin $I = 1/2$ with $S = 0$, and a third one with $I = 0$ but $S = -1$. What kind of baryons can we build if each baryon must be a combination of three quarks? If all three are of the ($I = 1/2$, $S = 0$) kind, we get systems with $I = 1/2$ or 3/2 but $S = 0$; if two are of the ($I = 1/2$, $S = 0$) kind and one of the ($I = 0$, $S = -1$) kind, we get systems with $I = 0$ or 1 and $S = -1$; if two are of the ($I = 0$, $S = -1$) kind, we get $I = 1/2$ and $S = -2$; if all three are of the ($I = 0$, $S = -1$) kind, we get $I = 0$ and $S = -3$. This is exactly what we find in the baryon spectrum.

Let us now look at the boson spectrum. Here we observe the following characteristics: (i) a symmetry with regard to positive and negative strangeness, any particle in one group having its antiparticle in the other; (ii) the fact that the $S = 0$ bosons are their own antiparticles; (iii) only $I = 1/2$ for $|S| = 1$. This points to the fact that the bosons behave as if they were combinations of one quark and one antiquark. If the two quarks are of the type ($I = 1/2$, $S = 0$), such a combination would yield entities with $I = 0$, or 1, and $S = 0$, and they would be their own antiparticles. If one quark is of the second type ($I = 0$, $S = -1$), one gets a meson of isotopic spin ½ with $S = +1$ or -1, depending upon whether the quark or the antiquark is of the second type. The $S = +1$ and $S = -1$ combinations then are each other's antiparticles.

A more quantitative exploitation of these ideas resulted in even more surprising agreements with the observed facts. If one assumes, for example, that the dynamic conditions which hold these hypothetical quarks together are invariant to an interchange of one of the three types of quark by another, then one can derive a super-multiplet structure for the levels of a three-quark system and of a quark-antiquark system. The formalism shows that the former system gives rise to singlets, octets, and decuplets, and the latter system to singlets and octets. For example, a baryon octet would consist of the proton, the neutron, the three Σ's, the Λ, and the two Ξ's. The decuplet would consist of the ten observed baryon states of angular momentum 3/2. One of the boson octets would consist of the three pions, the two kaons, the two antikaons, and the η meson (see Figs. 1 and 2).

The assumption of complete equivalence of the three types of quarks would lead to the result that the members of these multiplets have all the same mass. In fact, this is not so; they differ in energy by far more than the members of isotopic spin multiplets which, in fact, are subgroups of the SU(3) multiplets. However, the energy split within these multiplets follows a regular pattern, and it is just the pattern predicted by the SU(3) formalism for the case in which a weak force existed which breaks the symmetry.

Roughly speaking, this split can be reproduced by the simple, symmetry-breaking assumption that the quark which carries strangeness is heavier than the other two. It would explain the general tendency of mass to increase with increasing absolute values of strangeness. Finer considerations make it possible also to reproduce the mass splits between multiplet members of equal strangeness. The accuracy with which these predictions are fulfilled is most striking and has led to the prediction and subsequent discovery of the baryon state of strangeness -3, the famous Λ particle. The predictions of approximate SU(3) symmetry are not only confined to energy splits; it is also possible to predict certain quantitative relations between members of one multiplet with regard to other properties, such as magnetic moments, and transition probabilities. Also these predictions seem to be on the whole well fulfilled.

SU(6) Symmetry

Recently, theoretical physicists tried to combine not only isotopic spin and strangeness into a fundamental triplet, but to include also the dichotomy of ordinary spin. The quarks are considered as particles with spin ½; instead of the three basic states of the quark, there are then six basic states, since each one may have the ordinary spin directed up or down. If the conditions are assumed to be invariant also to the direction of the ordinary spin, one obtains the so-called SU(6) symmetry. The consequence of this wider symmetry is surprisingly well fulfilled. One finds, for example, that the quark-antiquark multiplets should exist for angular spin 0 and 1, and that the system of three quarks should have the total angular spin either ½ or 3/2, the decuplet appearing only with the second alternative. This is just what one finds in nature. In addition, most interesting predictions can be made in regard to magnetic moments; for the first time the ratio 3/2 between the proton and the neutron moment has been explained by a theory.

A remarkable aspect of this SU(6) symmetry is the amalgamation in one symmetry of both the angular and the isotopic spin. This may lead to a deeper insight into the fundamental role of the spinor concept in our description of particles. So far, however, it has led to a number of difficulties. They come from the fact that the angular spin is inextricably connected with the orbital angular momentum. Remember that the angular momentum of a relativistic particle consists of spin and orbital parts which are combined in a different way in the so-called "large" and in the "small" components. Only in the nonrelativistic limit can one speak of a pure angular spin dichotomy. There is, of course, no such thing as an orbital momentum in the isotopic spin space. The analogy of isotopic spin and angular spin, which is based upon the dichotomy of basic states, breaks down under relativistic conditions.

The successes of the new symmetries when applied to the description of elementary-particle states are quite impressive. It seems that the states of

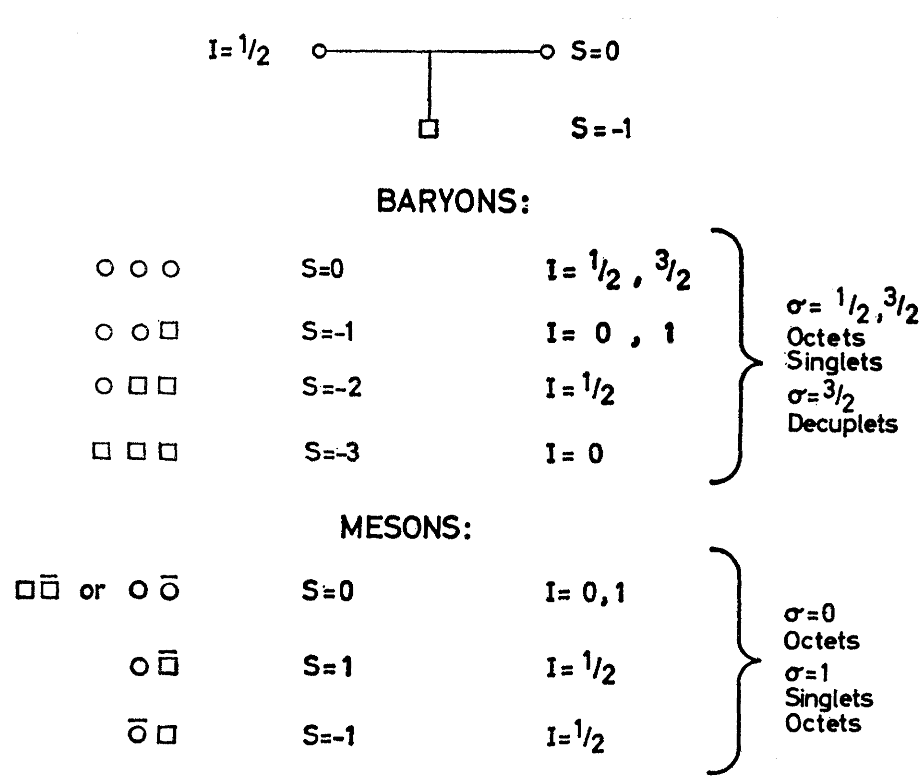

Fig. 5. The combinations of three basic "quark" states and the combinations of a pair of quark-antiquark states. The resulting strangeness S, isotopic spin I, and angular spin σ are indicated.

the baryon and of the meson are arranged according to an orderly principle which we now begin to understand. They are grouped into multiplets, which are characteristic of three-particle systems or of particle-antiparticle systems made of some simple hypothetical units. However, this does not by any means imply that the baryon and meson are really made up of quarks in the same way as atoms are made up of nuclei and electrons. The triplet of quarks is used only for the purpose of constructing the somewhat more complicated multiplets observed in the spectra. The following analogy may help to understand the situation: the light quantum carries a spin of 1; the simplest possible spin, however, is ½, and a spin of 1 can be considered as arising from a combination of two entities of spin ½. But it does not necessarily follow from this that the light quantum must be a system of two particles of spin ½.

There are some conclusions which one can draw from the existence of those SU(3) or SU(6) multiplets. We ignore today the internal dynamics of mesons and baryons, but it seems obvious that the conditions which govern that dynamics must be approximately invariant to those transformations which correspond to the replacing of one type of quark by another. This is the logical content of the observed SU(3) or SU(6) invariance. The approximate nature of this invariance is significant: the observed regularities in the split of the multiplets are typical of a violation, but of a *small* violation, of invariance. Although the actual energy differences are considerable—they amount to several hundred million electron volts—the ratios of the splits are such as one would find if they were caused by a weak interaction. This suggests that there are two "forces" acting within these entities: one that is SU(6) invariant and extremely strong, the relevant energies being much higher than a billion (10^9) electron volts; and another which is not SU(6) invariant but considerably weaker, and which is responsible for the split of the multiplets.

Hence the discovery of the new invariances in no way solves the problem of the structure of nucleons and mesons. On the contrary, it shows that the problem is much more difficult than it appeared. The dynamics responsible for the internal structure seems to involve energies very much higher than the ones with which we work today. It is true that the spectrum begins to make sense to us; however, it turns out that it is nothing but a fine structure of the ground state of the real thing. Most of the excited states so far discovered are closely related to each other; they are members of the same multiplet, which means that they are essentially the same state looked at in a different direction of an abstract space. This is why we find simple relations between their observed properties.

When the nucleon revealed its presently known spectrum, we may have hoped to have before us the essential ingredients for the understanding of its structure, just as the Balmer formula of the hydrogen spectrum gave Bohr the clue for its dynamics. Now it seems that what we know today reveals only the effects of a weaker and probably less important part of the dynamics. The effects of the main part might be hidden behind much higher energies. We saw a peak and thought it was the top of the mountain; when we climbed it we found ourselves facing the real top shrouded in dark clouds.

The Question of the Electron

Thus Newton's question is not yet answered. We still ignore the basis for the unchanging properties of the nucleon. But more shape-giving symmetries have been found and we may be on the way to a deeper understanding of the reasons for the existence of the nucleon. However, we still owe Newton an answer as to the electron. The properties of the electron seem to be simpler in many ways, since it does not participate directly in the interplay of the newly discovered world of baryons and mesons. It interacts with the rest of the world only via the electric field and the weak interactions. But very little can be said to satisfy Newton's and our own curiosity with regard to the reasons why the electron has the properties which we observe. It is true, we understand better than ever the relations of the electron with the electromagnetic field. Quantum electrodynamics allows us to calculate all phenomena of this type with seemingly arbitrary accuracy. But this perfection is brought by abandoning any claims for understanding the charge and mass of the electron. They are "renormalized" to their experimental values. Being unable to explain them, we are still forced by ignorance to assume that these essential features are given to us *ab initio*. To make things worse, nature has provided us with a second kind of electron, the muon, which as far as we now know differs from the ordinary one only in its mass. The reasons for this duplicity are still totally obscure.

Weak Interactions

Even more mysterious are the roles played by the two electrons in the weak interaction. It is established today that all known particles interact by a universal weak interaction. The most characteristic feature of any interaction process is that it is connected with an exchange of charge. When the electron interacts with a nucleon, it transfers its charge to the nucleon and assumes its uncharged state: it becomes a neutrino. The most common form of this process is a beta-decay in which, say, a proton becomes a neutron and a positron-neutrino pair is emitted. Here the emission of a positron is equivalent to an absorption of an electron; hence the process corresponds to an encounter of an "incoming" electron with a proton, during which their charges are exchanged. The heavy electron behaves exactly like its lighter counterpart with respect to the weak interactions. It also possesses an uncharged form, the neutretto or muon-neutrino, which now has been definitely proved to be different from the electron-neutrino.

So far, not the slightest indication has been found of an internal structure of leptons. The electromagnetic interactions of both kinds of electron have not yet revealed any deviation from a point charge, and nothing like a spectrum of lepton states exists, except for the two forms, the charged and the uncharged one.

The second striking feature of weak interaction is its violation of parity equivalence. Left-handed and right-handed processes are not equivalent. In fact, both kinds of neutrinos always appear with a spin opposed to their motion (left-handed screws). Until quite recently, this asymmetry was mitigated by the fact that antiparticles show exactly the opposite properties in their weak interactions; antineutrinos,

Table 1. The four interactions and their symmetries.

Interaction	Symmetry					
	Translation and rotation	Charge, Baryon conservation	Parity conservation	Strangeness conservation	Isotopic spin conservation	SU(6)
Weak	X	X				
Electromagnetism	X	X	X	X		
Strong	X	X	X	X	X	
Very strong	X	X	X	X	X	X

for example, show up as right-handed screws; hence, weak interaction processes preserve an invariance if a left-right inversion is connected with particle-antiparticle transformation (CP invariance). Lately, however, even this invariance has been put in doubt by experiments on K meson decays.

Baryons are subject to weak interactions in all quantum states. Strangeness or isotopic spin are not conserved in these interactions. It was most interesting to observe that the weak interactions with higher quantum states of the baryon are closely related to the weak interactions of the proton and the neutron. These relations bear out again the equivalence of the different baryon states on the basis of SU(6) symmetry.

The weak interaction presents us with another fundamental problem: our present understanding of interaction processes requires a field for the transmission of interaction, such as the electromagnetic field or the meson field. Does such a field exist for weak interactions? A recent search for the corresponding field quantum had negative results. Does this mean that the mass of the quantum is higher than the limit which could have been found with today's accelerators (about two proton masses), or that our ordinary field concepts do not apply to the weak ineractions?

Summary

Let us try to summarize what we can answer today to Newton's question for the reasons of the unchanging properties of nature. The characteristic and well-defined structures of atoms and nuclei are based upon the symmetry of quantum states of these composite units. But the stability of their constituents is still poorly understood. There are two types of entities which we encounter here: they go under the names leptons and hadrons. The leptons include the two electrons in their charged and uncharged form, and the hadrons include all baryons and mesons. To our knowledge, these entities are subject to mutual interactions of four different types which we enumerate in the order of their strength: gravity, weak interactions, electromagnetism, and strong interactions. We leave out gravity from our considerations since its role in the world of elementary particles is completely unknown.

Weak interactions exist between all of these entities, leptons and hadrons alike; electromagnetic interactions are found between all particles carrying charges or magnetic moments; strong interactions exist only in the case of hadrons. Today we do not know whether the hadrons have an internal structure; hence it is not clear whether the strong interactions should be considered as acting between hadrons or as acting between the constituents of hadrons.

The symmetries of these interactions determine many of the properties of the units and therefore are the essential shape-giving factors. It is most interesting that the number of symmetries increases with the strength of interaction. All of the interactions are subject to the translational and rotational symmetry of the space in which they are imbedded. This is a symmetry which appears to us as quite natural. The laws of conservation of energy, momentum, and angular momentum are a direct consequence of these symmetries. All interactions are subject also to two further conservation laws, which are not so well understood at present: the charge conservation, and the conservation of baryon and lepton number. Parity and strangeness, however, are not conserved by the weak interactions; they are conserved only by the electromagnetic interaction, and those stronger than it; isotopic spin conservation holds only for the strong interactions; SU(6) symmetry is valid for the strong interactions, but there exists a relatively weaker part of these interactions which violates it (see Table 1).

The stronger the interaction, the more symmetries exist. Is this remarkable fact significant for the ultimate explanation of the existence of elementary particles? It may be, for instance, that a certain number of symmetry principles imposes a unique dynamics, which then determines the properties of its fundamental units. It may also be that hadrons and leptons are not the ultimate structures at all; the hadrons may be composite structures of particles such as the quarks. If this were the case, the proton and the neutron would be a sort of "molecule" made up of fundamental particles; the nuclear force between the nucleons would be a kind of Van de Waals force, an indirect effect of much stronger interactions within the "molecule." Then the fundamental problem of elementary particles would reappear at a higher level when it is asked: why do quarks exist? Most probably, however, the actual solution of the problem will take a new and wholly unexpected form.

It is fit to close these remarks with another prophetic statement of Newton, the timeliness of which is almost uncanny:

> Now the smallest Particles of Matter may cohere by the strongest Attractions, and compose bigger Particles of weaker Virtue; and many of these may cohere and compose bigger Particles whose Virtue is still weaker, and so on for divers Successions, until the Progression end in the biggest Particles on which the Operations in Chymistry, and the Colours of natural Bodies depend, and which by cohering compose Bodies of a sensible Magnitude.
>
> There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out (*2*).

References and Note

This article contains no references to the literature except for the references to Newton. The task of establishing a complete list of all sources for so many excellent ideas proved to be too difficult. The only mitigating circumstance which the author can claim for this serious shortcoming is the fact that none of the ideas presented here are his own.

1. I. Newton, *Opticks*, I. B. Cohen, Ed. (Dover, New York, 1952), p. 400.
2. ———, *ibid.*, p. 394.