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CLASSIFICATION OF ELEMENTARY PARTICLES AND QUARKS "FOR THE LAYMAN"

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A wide circle of physicists, and even some nonphysicists, are aware that extremely important events have occurred in the theory of elementary particles in the last two or three years. They know this from, say, the talk by I. E. Tamm at the general session of the USSR Academy of Sciences, which was reprinted in Izvestiya, from articles in popular magazines like "Scientific American," and especially from the flood of papers and communications* in special journals (Phys. Rev., Phys. Rev. Letters, JETP, and UFN).

These new achievements are compared with the discovery of the periodic system by Mendeleev. It is difficult to compare the importance of discoveries made during completely different scientific situations. In any case the seriousness of the new discoveries is clear from the fact that theorists have predicted the existence and all the properties of a new elementary particle, the omega minus hyperon, and experiments have brilliantly confirmed this prediction.

The specialists' papers make use of group theoretical techniques; they often have repulsive names, incomprehensible to the physical chemist, metallurgist or heat engineer. Can one explain the essence of the new discoveries, naturally minus many important details, at a more accessible level? In one paper such a presentation is said to be "for the layman."

The possibility of such an explanation follows from the work of one of the creators of the new theory, the American physicist Murray Gell-Mann; the same idea was put forth independently by Zweig (CERN). The idea is the following.

A classification of the elementary particles is obtained in a natural way from the assumption that all the particles are composed of three types of "truly fundamental particles," which are called quarks. Thus, each baryon consists of three quarks (the same or different), each meson consists of one quark and one antiquark.

The new classification applies only to the strongly interacting particles, which are now called "hadrons." Consequently these do not include the electron, muon, neutrino and photon. This wise self-restraint appears to be extremely important, and was precisely the reason for success. I should warn the reader who gets the idea of including light particles in the classification: the author definitely does not favor such attempts.*

The concept of the spin of a particle, the division of particles into fermions and bosons, and the concept of particle and antiparticle will be assumed to be familiar. We point out immediately that in introducing the new particles (quarks) we assume that there exist the corresponding antiparticles—antiquarks, which are also used as building blocks.

The concept of baryon charge, or baryon number, is also well known; this concept is related to the exact law of conservation of the number of baryons. We remind the reader that a baryon is any particle that decays finally into a proton and any number of electrons, neutrinos, and mesons.

The concept of strangeness has already existed for about ten years; the values of S for various particles are given below. The importance of S is that in strong interactions, i.e., for example, in collisions, only processes that conserve strangeness occur†, for example, $\pi^+ + p = \Sigma^+$ $(S = -1)$ $+ K^+$ $(S = +1)$, but not $\pi^- + n = \Lambda^0$ $(S = -1)$ $+ K^-$ $(S = -1)$. The law of conservation of strangeness is not absolute, like the law of conservation of baryons. There is a small probability (because of weak interactions) for processes in which the strangeness changes, for example the decay Λ^0 $(S = -1) = p + \pi^-$. But we shall here consider only strong interactions. The strange baryons are called "hyperons."‡

The concepts of strangeness and isotopic spin and the connection between them are considered in many popular articles and books.** The trends of the last

*For example, the UFN alone has recently published papers by Chew, Gell-Mann and Rosenfeld, UFN 83, 695 (1964); original, Scientific American 270, 74 (1964), Ya. A. Smorodinskiĭ UFN 84, 3 (1964); Soviet Phys. Uspekhi 7, 637 (1963), J. DeSwart, Revs. Modern Phys. 35, 916 (1963), and V. B. Berestetskiĭ, UFN 85, 393 (1965), Soviet Phys. Uspekhi 8, 147 (1965).

*This remark does not apply, however, to the hadrons in Tables III and IV (at the end of the paper), which are not treated here, but unquestionably belong in a classification within the framework of the general ideas presented here.

†Particles for which the strangeness is not indicated have $S = 0$.

‡Recently, instead of strangeness use has been made of the notion of hypercharge Y, which is equal to the sum of the baryon number and the strangeness. Thus, for N, P, or Δ, the hypercharge is $Y = 1$, for the Σ and Λ, $Y = 0$, for the Ξ, $Y = -1$, and for Ω, $Y = -2$. Strangeness and hypercharge are the same for mesons. The quarks have fractional hypercharge: for p and n, $Y = 1/3$, for λ, $Y = -2/3$.

**We refer, for example, to the paper of M. Gell-Mann and E. Rosenbaum UFN 64, 391 (1958), Ya. B. Zel'dovich, UFN 78, 549 (1962), Soviet Phys. Uspekhi 5, 931 (1963). We also mention two monographs: Yu. V. Novozhilov, Elementarnye chastitsy (Elementary Particles), Fizmatgiz, 1963, and K. I. Sochelkin, Fizika mikromira (Physics of the Microworld), Gosatomizdat, 1963.

3—4 years are not so well known.

The new point is the courageous step of including the so-called resonances among the elementary particles to be classified. In 1952, Fermi studied the scattering of pions by protons. He discovered a sharp maximum ("resonance") in the scattering cross section at a pion energy around 200 MeV. The resonance can be understood as the fusing of the pion and proton into a new particle (now called the "delta"—Δ), which then decays, emitting the pion in some other direction. The maximum of the cross section corresponds to the pion energy at which the sum of the energies (including mc^2) of the pion and proton is equal to the energy of the Δ. We then find the rest mass of the Δ to be 1236 MeV (where the mass of the proton in energy units is 938 MeV, that of the pion is 138 MeV). The width of the resonance is of order 100 MeV, which gives a lifetime of 10^{-23} sec.

The resonance observed in the scattering of π^+ by P corresponds to the formation and decay of a baryon with twice the electronic charge, i.e., the particle Δ^{++}. The resonance in the $\pi^+ + N$ system indicates the existence of a singly charged particle Δ^+; the resonance in the $\pi^- + P$ system corresponds to a neutral Δ^0 and, finally, the $\pi^- + N$ resonance indicates the existence of Δ^-.

The lifetimes and masses of all the Δ's are the same within the experimental accuracy, and the spins of the Δ's are all 3/2. Other resonances are found in processes in which several particles are created: for example, in $P + \overline{P}$ annihilation, when five π mesons are created, $2\pi^+ + 2\pi^- + \pi^0$, it appears that in the majority of cases the energy of two of the mesons in their center of mass system is 763 MeV. This means that in these cases the process occurs in two stages: $P + \overline{P} = \rho^+ + 2\pi^- + \pi^+$, $\rho^+ = \pi^+ + \pi^0$. The mass of the ρ is 763 MeV, and its lifetime 10^{-22} sec, corresponding to the energy spread.

We shall not here enumerate all particles (resonances), especially since one or two new particles are found each month. Instead we concentrate our attention on two groups of baryons and two groups of mesons and show how they are built up from quarks. We assume that the quarks (p, n, λ) have the following quantum numbers (charges) (Table I).

Please note that the quarks are designated by lower case letters p, n, λ, in contrast to P—the proton, N—the neutron, and Λ—the hyperon.

The group of eight baryons that includes the classical particles P and N and the relatively longlived (10^{-10} sec, except for the Σ^0) hyperons,* is shown at the left in scheme (1); on the right we indicate how each of the terms is made up out of quarks; the lightest particles are at the bottom, the heavier ones are above:

$$\left.\begin{array}{ccccccc} & \Xi^0 \;\; \Xi^- & & & p\lambda\lambda & & n\lambda\lambda \\ \Sigma^+ & \Sigma^0 & \Sigma^-, & p p\lambda & & p n\lambda & & n n\lambda. \\ & \Lambda^0 & & & & p n\lambda & \\ & P \;\; N & & & ppn & & pnn \end{array}\right\} \qquad (1)$$

The group of ten baryons is shown in scheme (2); It includes the Δ resonances, already discovered by Fermi, above them excited strange particles (the asterisk indicating excitation); finally at the top is the Ω^- particle, a product of the theorist's pen; again we give at the right the analysis of the particles into quarks:

$$\left.\begin{array}{cccccccc} & & \Omega^- & & & & \lambda\lambda\lambda & \\ & \Xi^{0*} & \Xi^{-*} & & & p\lambda\lambda & & n\lambda\lambda \\ \Sigma^{+*} & \Sigma^{0*} & \Sigma^{-*} & & pp\lambda & p n\lambda & n n\lambda & \\ \Delta^{++} \;\; \Delta^+ & \Delta^0 & \Delta^-, & ppp & ppn & pnn & nnn. & \end{array}\right\} \qquad (2)$$

Scheme (2) is particularly orderly and lucid. One can explain simply and clearly to any child that there are ten particles, because each particle consists of 3 building blocks; there are three kinds of blocks and it is easy to verify that there are ten, and only ten, different combinations, which are enumerated at the right. Further we assume that p and n have approximately the same mass, while λ is heavier by 146 MeV. We then naturally find that each line is heavier than the preceding one by 146 MeV. This is precisely the regularity that made possible the prediction of 1675 MeV for the Ω^- mass.

In the two schemes for the 8 and the 10 particles (the so-called octet and decuplet) the strangeness is zero in the bottom row, in the second row $S = -1$, in the third $S = -2$ and finally Ω^- is the only particle known at present with $S = -3$.

Now let us shift to scheme (1). A whole series of questions arise. Why are there no "corner" particles ppp, nnn, λλλ in this scheme? Why is the combination pnλ found twice in scheme (1) (Σ^0, Λ^0)? Finally, why is the simple scheme (2) (the decuplet) realized for particles of spin 3/2, while the first scheme (the octet) describes particles of spin 1/2?

The theory of quarks gives simple and logical answers to all these questions. It is necessary only to assume that the quarks themselves have spin 1/2 and are fermions (satisfy the Pauli principle). It is necessary to make one (and only one, even though there are two schemes and 18 particles) additional assumption about the wave function of the three quarks. We assume that the wave function is completely antisymmetric in the coordinates of the three quarks and has

Table I

	Electric charge	Strangeness	Baryon number	Spin
p	+2/3	0	1/3	1/2
n	−1/3	0	1/3	1/2
λ	−1/3	−1	1/3	1/2

*Cf. Table VI at the end of the paper.

no orbital angular momentum. We can give as an example the wave function of the three outer (valence) electrons of a nitrogen atom: these are $(2p)^3$ electrons with $L = 0$; the three electrons are in three different states with $l = 1$—those with $l_z = -1$, 0 and 1. The wave function is completely antisymmetric in the electron coordinates (since the electrons repel one another, this is energetically favorable).* Such a combination corresponds to a total angular momentum $L = 0$. Since the function is antisymmetric in the coordinates, it must be symmetric in the spins of all three electrons. Thus the spin of the nitrogen atom is 3/2.

We must still discuss the question of the orbital function for the quarks, but it is already clear from the preceding example that in our scheme one can take three identical particles (ppp or nnn or λλλ, by analogy with the triple of electrons) and spin 3/2, as is observed in the decuplet.

Now we consider what cases can have spin 1/2. We first take the state ppp, $s = 3/2$ and projection $s_z = +3/2$. We shall denote the projection of the spin on the z axis by an arrow:

$$\Delta^{++}, \quad s = \frac{3}{2}, \quad s_z = +\frac{3}{2} : p\uparrow p\uparrow p\uparrow.$$

We turn over one of the arrows. We then get $p\uparrow p\uparrow p\downarrow$. This is the only possible state in the present case, since the three p-quarks are identical, so it makes no difference which one has its spin turned down. But with $s = 3/2$, we should have, in addition to the state with $s_z = +3/2$, another state with $s = 3/2$ and $s_z = 1/2$. We have found it in the form $p\uparrow p\uparrow p\downarrow$. This trivially dull procedure serves as an introduction to a more interesting case.

We take ppn, $s = 3/2$ (i.e., the Δ^+). The state with $s_z = +3/2$ is unique: $p\uparrow p\uparrow n\uparrow$.

But there are two different states with $s_z = +1/2$: a) $p\uparrow p\downarrow n\uparrow$ and b) $p\uparrow p\uparrow n\downarrow$.

From these two states we can construct two combinations; one is the Δ^+ particle, rotated in space, i.e., with its spin turned away from the z axis ($s = 3/2$, $s_z = +1/2$). The second combination is something new. It is easy to see that it describes a state with $s = 1/2$, $s_z = +1/2$. It is one of the terms of the octet, namely p, the proton. We have obviously assumed that the orbital functions of the quarks are not changed; again $L = 0$.

If we take pnλ, there is only one state with $s_z = +3/2$: $p\uparrow n\uparrow \lambda\uparrow$.

But there are three different states with $s_z = +1/2$:

$$p\uparrow n\uparrow \lambda\downarrow, \quad p\uparrow n\downarrow \lambda\uparrow, \quad p\downarrow n\uparrow \lambda\uparrow.$$

Obviously, from these three states we can construct three linear combinations, of which only one corresponds to $s = 3/2$, $s_z = +1/2$, i.e., to a rotated Σ^{0*} of the decuplet. The other two correspond to $s = 1/2$, i.e., belong to the octet. Thus we have gotten the octet structure with all its properties (spin 1/2, absence of corner particles, doubling at the center).

These concepts can be developed further. The magnetic moment of each member of the decuplet is equal simply to the sum of the intrinsic moments of the three quarks. Even if the interaction distorts the magnetic moments (denoted by μ), this distortion is the same for all three quarks and leaves their moment proportional to the charge: $\mu_p = 2/3\, \mu_1$, $\mu_n = -1/3\, \mu_1$, $\mu_\lambda = -1/3\, \mu_1$, where μ_1 is an unknown value. Then

$$\mu_{\Delta^{++}} = 2\mu_1, \quad \mu_{\Delta^-} = -\mu_1, \quad \mu_{\Omega^-} = -\mu_1 \text{ etc.};$$

in the decuplet the magnetic moment is simply proportional to the charge of the particle.

We now go to the octet and recall how it was obtained. We again take Δ^+ with $s_z = +3/2$ $(p\uparrow p\uparrow n\uparrow)$ and turn it; the probability of then getting $p\uparrow p\downarrow n\uparrow$ is twice as great as the probability for getting $p\uparrow p\uparrow n\downarrow$, since there are two p-quarks and only one n-quark.

Thus Δ^+, $s = 3/2$, $s_z = +1/2$ is a state which represents $p\uparrow p\downarrow n\uparrow$ with probability 2/3 and $p\uparrow p\uparrow n\downarrow$ with probability 1/3:

$$\frac{2}{3} p\uparrow p\downarrow n\uparrow + \frac{1}{3} p\uparrow p\uparrow n\downarrow;$$

the corresponding wave function has the form

$$\sqrt{\frac{2}{3}}(p\uparrow p\downarrow n\uparrow) + \sqrt{\frac{1}{3}}(p\uparrow p\uparrow n\downarrow).$$

The octet wave function made up in the same way, i.e., consisting of ppn, is orthogonal to the decuplet wave function. It is equal to

$$-\sqrt{\frac{1}{3}}(p\uparrow p\downarrow n\uparrow) + \sqrt{\frac{2}{3}}(p\uparrow p\uparrow n\downarrow);$$

for the probability of finding a particular combination we get a result opposite to that for the decuplet; consequently P, $s = 1/2$, $s_z = +1/2$, is

$$\frac{1}{3}(p\uparrow p\downarrow n\uparrow) + \frac{2}{3}(p\uparrow p\uparrow n\downarrow),$$

i.e., a mixing of $p\uparrow p\downarrow n\uparrow$ with probability 1/3 and $p\uparrow p\uparrow n\downarrow$ with probability 2/3.

For the average value of the magnetic moment of the proton we get: *

$$\mu_P = \frac{1}{3}\left(+\frac{2}{3}\mu_1 - \frac{2}{3}\mu_1 - \frac{1}{3}\mu_1\right) + \frac{2}{3}\left(+\frac{2}{3}\mu_1 + \frac{2}{3}\mu_1 - \left(-\frac{1}{3}\mu_1\right)\right) = \mu_1.$$

*We note that the 1S and 2S levels of nitrogen are already filled by the first four electrons. Because of the Pauli principle the last three electrons occupy the 2p shell.

*We find the projection μ_P on the z axis for a proton whose spin is directed up along the axis: this is μ_P, not to be confused with the magnetic moment μ_p of the p-quark. There is obviously no orbital angular momentum, since $L = 0$.

Similarly we find for the neutron:

$N,\ s=\frac{1}{2},\ s_z=+\frac{1}{2}$ is $\frac{1}{3}(p\uparrow n\uparrow n\downarrow)$ and $\frac{2}{3}(p\downarrow n\uparrow n\uparrow)$,

$$\mu_N=\frac{1}{3}\left(+\frac{2}{3}\mu_1-\frac{1}{3}\mu_1+\frac{1}{3}\mu_1\right)$$
$$+\frac{2}{3}\left(-\frac{2}{3}\mu_1-\frac{1}{3}\mu_1-\frac{1}{3}\mu_1\right)=-\frac{2}{3}\mu_1.$$

Thus the theory predicts

$$\frac{\mu_N}{\mu_P}=\frac{-\frac{2}{3}\mu_1}{\mu_1}=-\frac{2}{3}=-0.667;$$

while experimentally

$$\frac{\mu_N}{\mu_P}=\frac{-1.9103\mu_B}{2.7896\mu_B}=-0.685,$$

where $\mu_B = eh/Mc$ is the nuclear Bohr magneton. The agreement is unexpectedly good, better than 2%! This agreement shows the correctness of the basic assumptions of the theory. It is extremely important to measure the magnetic moments of other members of the octuplet and decuplet.* But this is a much more complicated problem than the measurement of the magnetic moments of the proton and neutron.

Transformations of particles, for example, $P + \gamma = \Delta^+$, represent a rotation of the spin of one of the quarks under the influence of the electromagnetic field and are also predicted by the theory.

Let us briefly consider the mesons. From three quarks and three antiquarks we can form 9 pairs; the Pauli principle allows all possible combinations (the antiparticles are indicated by a dash). Again we write them in order of strangeness (bottom row: S = +1, middle: S = 0, top: S = −1), at the left are the known mesons; the quark diagrams are at the right:

$$\left.\begin{array}{ccccccc} & \bar{K}^0 & K^- & & \lambda\bar{n} & \lambda\bar{p} \\ \pi^+ & (\pi^0,\eta^0,X^0) & \pi^-, & p\bar{n} & (p\bar{p},\ n\bar{n},\ \lambda\bar{\lambda}) & n\bar{p} \\ K^+ & K^0 & & p\bar{\lambda} & n\bar{\lambda} & \end{array}\right\}. \quad (3)$$

If we had arranged the quark scheme more naturally:

$$\left.\begin{array}{ccc} p\bar{p} & n\bar{p} & \lambda\bar{p} \\ p\bar{n} & n\bar{n} & \lambda\bar{n} \\ p\bar{\lambda} & n\bar{\lambda} & \lambda\bar{\lambda} \end{array}\right\}, \quad (4)$$

the rows would not have constant strangeness, or the columns constant charge.

There is a complication in the center box of (3); we must establish a correspondence between the three mesons and three combinations of quarks. The interaction of a quark with an antiquark (and in general of a particle with its antiparticle) introduces a new feature.

The interaction of two different particles can always be pictured as the exchange of a quantum of some hypothetical field, as shown in Fig. 1, a for the interaction of p and n. The arrow indicates the direction of time, the wavy line indicates a quantum, and is deliberately not marked with an arrow: the quark p can first emit a quantum which is then absorbed by the quark n (Fig. 1, b), or conversely (Fig. 1, c); Fig. 1, a combines both cases. The same scheme applies to the interaction of a particle with some other antiparticle, for example, the interaction of p and $\bar{n}$ (Fig. 1, d). But for the interaction of a particle with its own antiparticle, for example p with $\bar{p}$, a new possibility arises: annihilation and creation of pairs (Fig. 2).

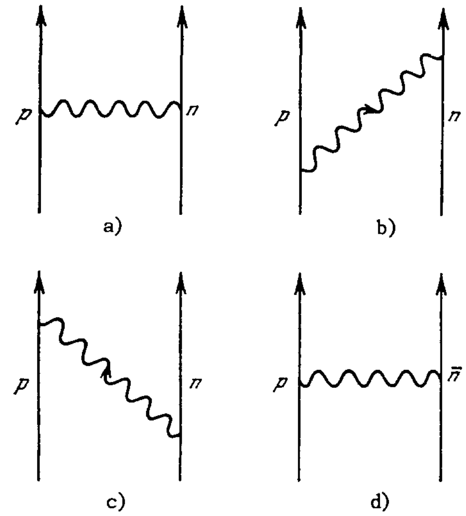

FIG. 1

Such a process has been studied experimentally in the case of positronium, which consists of e^+ and e^-; it leads to an observable change in the energy levels.

In the quark theory it is assumed that in the very crudest approximation all three quarks are identical in all properties of the strong interaction.* This is why we could unite the particles into the octet and decuplet. It then follows that the quanta of the neutral field obtained from annihilation of a pair, for example p and $\bar{p}$ (Fig. 2) can then materialize with equal probabilities as any pair: $p\bar{p}$, $n\bar{n}$ or $\lambda\bar{\lambda}$.

Thus the theory distinguishes the combination in which all three pairs are equally probable:

$$\frac{1}{3}(p\bar{p})+\frac{1}{3}(n\bar{n})+\frac{1}{3}(\lambda\bar{\lambda}),$$

or, in terms of the wave function,

$$\sqrt{\frac{1}{3}}(p\bar{p})+\sqrt{\frac{1}{3}}(n\bar{n})+\sqrt{\frac{1}{3}}(\lambda\bar{\lambda});$$

in annihilation and creation it is just this combination that is transformed into itself.† Thus, of the nine combinations there is one special one, written above, which is identified with the X meson, while the eight

*The magnetic moment of the Λ^0 is $\mu_{\Lambda^0} = (-0.80 \pm 0.15)\ \mu_B$ and also agrees with theory

*We must, of course, remember that the quarks differ in strangeness and charge, that only two identical quarks are subject to the Pauli principle, and that each quark can annihilate only with its own antiquark.

†This explanation is due to I. Yu. Kobzarev and L. B. Okun'.

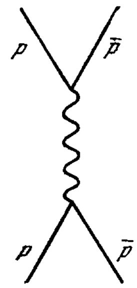

FIG. 2

others form the octet of mesons: $3\pi + 2K + 2\overline{K} + \eta$.

Then

$$\sqrt{\tfrac{1}{2}}(p\bar{p}) - \sqrt{\tfrac{1}{2}}(n\bar{n}) = \pi^0,$$

and the combination

$$\sqrt{\tfrac{2}{3}}(\lambda\bar{\lambda}) - \frac{1}{\sqrt{6}}(p\bar{p}) - \frac{1}{\sqrt{6}}(n\bar{n}) = \eta.$$

The last two combinations are selected so that they cannot transform into a neutral quantum: for example, in the case of π^0, the contributions of $p\bar{p}$ and $n\bar{n}$ cancel each other (there is a minus sign between them in the combination for the π^0) and the quantum is not formed; the same applies to the η.

Experiment shows that the mesons of scheme (3) have spin zero. This means that quark and antiquark are combined with opposite spins. It is also possible, however, to have a combination of quark and antiquark with parallel spins; we then get mesons with spin one. They are identified with the resonances (particles) discovered during the period 1962–1964:

$$\left.\begin{array}{cccc} K^{+*} & & K^{0*} & \\ \varrho^{+} & & \varrho^{0},\ \omega^{0},\ \varphi^{0} & \varrho^{-}. \\ & & \overline{K^{0*}} & K^{-*} \end{array}\right\} \qquad (5)$$

Here too we can split the 9 particles into eight and one special one, which can annihilate or be created. But for this special particle we need a different neutral field with spin 1, in contrast to the previous case of quanta with spin 0. We note that in the case of positronium the whole interaction occurs via the electromagnetic field, which is a vector (spin 1), so that $e^+ + e^-$ annihilate in precisely the state with spin 1.

The ideas of classifying baryons and mesons can be pushed further. The masses of the particles in the baryon decuplet (Δ, Ω) shown in scheme (2) differ little from the masses of the octet (P, N, Ξ) given in scheme (1).

Under what circumstance can we regard the difference between octet and decuplet as small, and combine them into one common group? This is possible when the interaction between quarks is approximately independent of the relative directions of their spins, i.e., of whether the spins of the three quarks were pointed parallel, giving $s = 3/2$ (decuplet) or superposed to give $s = 1/2$ (octet). The interaction can be expected to be independent of the spin orientations when the interaction is established through a neutral scalar field without spin. As L. B. Okun' has noted, to split the spin-zero mesons we need another field, since these mesons are pseudoscalar. Because of the different parities of particle and antiparticle, in the Dirac theory a "particle-antiparticle" pair has negative parity in an S state. In the case of positronium this has been verified by experiment.

Thus we assume that there is another neutral pseudoscalar field. This field splits the 9 spinless mesons into 8 mesons (π, K, η, in our schemes) and one special one,

$$X = \frac{1}{\sqrt{3}}(p\bar{p}) + \frac{1}{\sqrt{3}}(n\bar{n}) + \frac{1}{\sqrt{3}}(\lambda\bar{\lambda})$$

also spinless. But the 9 mesons with spin 1 [scheme (4)] do not split into subgroups 8 + 1, since they cannot annihilate when there is no neutral field with spin. We remind the reader that we deduce the absence of such a field from the closeness in mass of the octet and decuplet of baryons.

In this case we can introduce a new terminology. The quarks have spin 1/2; if the interaction is independent of spin, we may say that there are two equivalent states for each quark, with $s_z = +1/2$ and $s_z = -1/2$. Three quarks give six states: $p\uparrow$, $p\downarrow$, $n\uparrow$, $n\downarrow$, $\lambda\uparrow$, $\lambda\downarrow$.

Taken three at a time, they give the eight baryons with spin 1/2, i.e., two states with $s_z = +1/2$ and $s_z = -1/2$ for each baryon, a total of 16 states. In addition they give 10 baryons with spin 3/2, in four states with $s_z = 3/2$, $1/2$, $-1/2$ and $-3/2$; a total of 40 states. Altogether we get 40 + 16 = 56 baryon states, differing in composition and spin projection. In a certain approximation they are equivalent.

For the mesons we get 9 particles with spin 1, in three states ($s_z = 1, 0, -1$), and 9 spinless mesons; a total of 36 states, as expected for combinations of the six quark states with six antiquark states. Among the 36 meson states the only special one should be the neutral X^0 meson with spin 0, which can be created or annihilated, and 35 others that do not annihilate and are equivalent in this approximation.

Now it remains to say that the idea of equivalence of the three quarks for strong interactions is called "unitary symmetry" and is labelled SU(3). The idea of spin independence of the interaction, i.e., the equivalence of the six states enumerated above, is called SU(6).* As you see there is no mystery like simultaneous rotations in ordinary and isotopic space—rotations that can give anyone a headache.

We must still mention unsolved problems. Around what do the three quarks in the baryon rotate? Suppose that all quarks repel one another, while quark and

*We note that the numbers $\sqrt{2/3}$, $\sqrt{1/3}$, etc. are called "Clebsch-Gordan coefficients", or "Clebsches" for short; we have learned about them in passing.

Table II

	Electric charge	Strange-ness	Baryon number	Spin
R^-	-1	0	1	0
p	$+1$	0	0	1/2
n	0	0	0	1/2
λ	0	-1	0	1/2

antiquark attract. Then what binds the three quarks into a baryon? A possible idea is that there is a heavy neutral boson with baryon charge R^0 playing the role of the atomic nucleus; the three quarks rotate around it in a state with $l = 1$. But if we change our assumption and suppose that the heavy boson (protobaryon) is negatively charged, R^-, then the quarks can be assigned integral charges (Table II). But in this variant the theory no longer gives a definite simple recipe for calculating magnetic moments; the impressive agreement of the theory with the ratio of the neutron and proton magnetic moments is lost. The idea has been suggested that there are three sorts of particles like the quarks, but that the baryons consist of nine such particles (they were called "baryonettes," and assigned baryon number 1/9). The first six baryonettes are combined in an S state (like the 4 nucleons in the He nucleus) with oppositely paired spins ($p\uparrow p\downarrow n\uparrow n\downarrow \lambda\uparrow \lambda\downarrow$). Then one naturally finds that the next three baryonettes are assigned according to the Pauli principle to the p state, since the S levels are already occupied. The whole classification of the octet, decuplet and mesons is retained in all these versions of the theory.

Finally, last but not least, do the quarks (or baryonettes) exist? In the variants of the theory with fractional charges, at least one type of quark should be stable in the free state.

The first reaction of experimenters to the new ideas was to search for particles with fractional charges ($2/3\,e$, $-1/3\,e$) in accelerators and in cosmic rays.

It seems that one can assert that there are no such particles with a mass less than 6—8 GeV (i.e., 6—8 times heavier than the nucleon).* In any case, combining them into baryons or mesons is accompanied by an enormous evolution of energy, a reduction of mass of the composite particles by factors of ten compared to the masses of the building blocks from which the particles are made. It is an attractive possibility to search for stable quarks or nuclei combined with a single quark, i.e., to look for residual particles with fractional charge in ordinary matter—in the atmosphere and in the waters of the ocean.

But perhaps there are actually no quarks? Perhaps there is only the (now unquestionable) symmetry of the properties of particles, just as if the quarks really existed?* In August, 1964, at Dubna, Gell-Mann remarked: "Who knows?" I fear that one would need the pen of an author to conjure up all that he put into these two short words. One hears in them the enormous importance attributed to experiment, which in the last analysis decides and leads science forward; one senses the intellectual courage of Gell-Mann, and a feeling of newness and willingness to accept anything that nature offers and to produce from it a new theory and to do new experiments.

The dilemma facing physics can be formulated as follows: either we have explained only the classification and symmetry properties of the known particles or this symmetry is the consequence of the existence of quarks, i.e., of a completely new fundamental type of matter, an atomism of a new kind.

The physicists of our day are fully justified in repeating the lines of Tyutchev:

"How fortunate to be alive
During the world's exciting time,
To be invited to partake
As guest at such a sumptuous feast;
Its greatest sights were his to see,
Its councils welcomed him to speak;
Living, he has, like the Gods,
Drunk of the immortals' cup."

We may say on the basis of all of historical experience, that discoveries like those we have witnessed during the past 2—3 years basically change our picture of nature.

Let the reader draw his own conclusions from the prognosis that the author foresees in the following examples.

It was said of the kinetic theory of gases that maybe things happen as if there were molecules, but that actually molecules and atoms don't exist; molecules and atoms are simply concepts for describing chemical and thermodynamic laws.

The significance of the periodic system as the manifestation of a uniform building up of chemically different atoms out of nuclei and different numbers of electrons was only disclosed a half century after Mendeleev's discovery.

Formal genetics, the Mendelian laws, permitted the prediction of the existence of genes long before they were discovered and investigated directly.

The visualization of the internal causes of phenomena on the basis of their outward manifestations may well be the most important, valuable and attractive task in all of Science.

*According to data obtained with accelerators, the limit is around 4 GeV; according to the statements of the authors of the less reliable experiments on cosmic rays, the limit is 16 GeV.

*We note that the scheme with the R^- and unstable quarks (Table II) can survive even if free quarks are not found. In this scheme the quarks, after creation, immediately decay into leptons (μ, e or ν), whose detection in interactions at superhigh energies is extremely difficult.

APPENDIX*

Table III. Mesons

Symbol	Spin, parity	Mass, MeV	Isospin	Hypercharge (same as strangeness for mesons)
π	0^-	138	1	0
K	0^-	496	1/2	1
η	0^-	549	0	0
X	0^-	960	0	0
ρ	1^-	763	1	0
ω	1^-	783	0	0
K^*	1^-	891	1/2	1
φ	1^-	1019.5	0	0
K_c	1^+	1215	1/2	1
B	1^+, 2^-?	1215	1	0
f	2^+	1253	0	0
A_2	2^+	1310	1	0

Table IV. Baryons

Symbol	Spin, parity	Mass, MeV	Isospin	Hyper-charge	Strange-ness
N	$1/2^+$	939	1/2	1	0
Λ	$1/2^+$	1115.4	0	0	−1
Σ	$1/2^+$	1193.2	1	0	−1
Ξ	$1/2^+$	1317.6	1/2	−1	−2
$\Delta = N^*_{3/2}$	$3/2^+$	1236	3/2	1	0
$\Sigma^* = Y^*_1$	$3/2^+$	1382	1	0	−1
Ξ^*	$3/2^+$	1529	1/2	−1	−2
Ω^-	$3/2^+$	1675	0	−2	−3
Y^*_0	?	1405	0	0	−1
Y^{**}_0	$3/2^-$	1519	0	0	−1
$N^*_{1/2}$	$3/2^-$	1518	1/2	1	0
Y^{**}_1	$3/2^-$?	1660	1	0	−1
$N^{**}_{1/2}$	$5/2^+$	1688	1/2	1	0
Y^{***}_0	$5/2^+$?	1924	3/2	1	0
$N^{***}_{1/2}$	?	2190	1/2	1	0
$N^{***}_{3/2}$	?	2360	3/2	1	0

Table V

Symbol	Rest mass, MeV	Lifetime, sec
γ	0	Stable
ν_e	0	Stable
ν_μ	0	Stable
e^-	0.511006	Stable
μ^-	105.659	$2.2 \cdot 10^{-6}$
π^-, π^+	139.60	$2.55 \cdot 10^{-8}$
π^0	135.01	$1.8 \cdot 10^{-16}$
K^+, K^-	493.8	$1.23 \cdot 10^{-8}$
K_1^0	498.0	$0.9 \cdot 10^{-10}$
K_2^0	498.0	$5.6 \cdot 10^{-8}$
η^0	548.7	10^{-22}

Table VI

Symbol	Mass, MeV	Lifetime, sec
P	938.256	Stable
N	939.550	1000
Λ	1115.4	$2.6 \cdot 10^{-10}$
Σ^+	1189.41	$0.79 \cdot 10^{-10}$
Σ^0	1192.3	10^{-19}
Σ^-	1197.1	$1.58 \cdot 10^{-10}$
Ξ^0	1314.3	$3 \cdot 10^{-10}$
Ξ^-	1320.8	$1.7 \cdot 10^{-10}$
Ω^-	1675	$0.7 \cdot 10^{-10}$

*In Tables III-VI we give a survey of multiplets, average masses within the multiplet, masses and lifetimes of individual particles. More detailed information can be found in the article of Rosenfeld et al. (Revs. Modern Phys. 36, 97 (1964)).

Translated by M. Hamermesh