8h. Elementary Particles and Interactions[1]

ARTHUR H. ROSENFELD

University of California, Berkeley

GEORGE A. SNOW

University of Maryland

Matter as we know it is built up of a large number of particles (called "elementary" partly on account of our ignorance about them), which interact with one another via four kinds of forces. No theory has been completely successful in predicting or explaining the number of different particles that exist or many of their intrinsic properties, although a substantial amount of order has emerged in recent years.

In Sec. 8h-1 the four basic interactions between particles are described.

Section 8h-2 contains a general description of the different kinds of particles: some of which are called "stable," others unstable "resonances."

Section 8h-3 describes the conservation laws obeyed by the forces in nature which then lead to quantum numbers used to classify elementary particles.

Section 8h-4 contains a table of "elementary" particles and their intrinsic properties.

Section 8h-5 briefly describes the SU_3 classification of particles, called the eightfold way.

Section 8h-6 suggests some further reading.

8h-1. The Four Basic Interactions. All the physical phenomena and all the states of matter observed in the universe are apparently manifestations of one or more of four basic interactions between particles. These four kinds of forces differ enormously in strength and in range. In order of increasing strength, they are: gravitation, the "weak" interaction, electromagnetism, and the "strong" interaction. The basic properties of these four forces are summarized in Table 8h-1.

TABLE 8h-1. THE FOUR BASIC FORCES AND THEIR CHARACTERISTICS

Force	Acts on:	Strength	Range	Examples
Gravity	Mass or energy	$\sim 10^{-38}$	$\infty\ (\sim 1/r^2)$	Solar system
Weak	Leptons, hadrons	$\sim 10^{-14}$	$< 10^{-14}$ cm	Radioactivity
Electromagnetic	Charged particles	$\frac{1}{137}$	$\infty\ (\sim 1/r^2)$	Atoms, molecules, . . .
Strong	Hadrons	~ 1	$\simeq 10^{-13}$ cm	Nuclei

The *force of gravity* acts between all objects that have mass or energy. With large aggregates of matter, the force of gravity even at large distances can be dominating—for example, the force between earth and sun or between moon and earth. However, at the scale of atomic or subatomic particles it is by far the weakest of the four forces

[1] Supported in part by the U.S. Atomic Energy Commission.

If one introduces a dimensionless constant to characterize the strength of each interaction and assigns a strength of 1 to the strongest interaction (not surprisingly called the *strong interaction*), then for gravity that constant is about 10^{-38}. The range of the gravitational force extends essentially to infinity decreasing inversely as the square of the distance between the masses ($\sim 1/r^2$).

The *weak interaction* is indeed weak relative to the electromagnetic or strong interactions since its characteristic dimensionless strength constant is $\sim 10^{-14}$. The weak interaction is responsible for natural and artificial radioactivity and for reactions amongst the lightest elementary particles, called *leptons* (i.e., neutrinos, electrons, and muons). It also gives rise to interactions between leptons and all other more massive elementary particles. The characteristic range of the weak interaction is known to be very small, less than 10^{-14} cm, but its actual size has not yet been measured. (Higher-energy accelerators are needed to examine these interactions at such small distances.) The fact that the range of the weak interaction is so small means that, unlike gravity, its influence over macroscopic distances is completely negligible.

The *electromagnetic interaction* is the force between electrically charged particles. Just as for gravity, the range of this force extends to infinity ($\sim 1/r^2$). Despite the fact that the intrinsic strength of electromagnetism is much larger than that of gravitation ($e^2/\hbar c = \frac{1}{137}$, where e is the basic unit of charge, $\hbar$ is Planck's constant divided by 2π, and c is the velocity of light), massive aggregates of matter (e.g., raindrops, or the earth) tend to have zero electric charge (one can neutralize charge but not mass!) so that the electric forces cancel. The electromagnetic force is the one that keeps electrons and positively charged nuclei bound to each other in atoms, molecules, and crystals, so that all of chemistry and biology is governed by the laws of electromagnetism.

The *strong interaction* manifests itself as the force that binds neutrons and protons together in nuclei, but it has many other forms as well. All particles that experience the strong interaction are called *hadrons*. These include *baryons* like the proton and the neutron, as well as *mesons*, described in the next section. Hadrons and leptons are mutually exclusive in that only the former participate in the strong interaction, whereas both sets of particles participate in the three other interactions—electromagnetic, weak, and gravitational. The range of the strong interaction is $\sim 10^{-13}$ cm, so that they dominate all other forces only at very small subatomic distances, despite their great strength.

8h-2. Types of Particles. *Gravitons.* When the gravitational field that is generated by any particle is quantized, the theory predicts the existence of gravitons. They have zero rest mass and intrinsic spin $2\hbar$, and interact with other particles through the gravitational interaction only. This interaction is extremely weak. The first report of the experimental detection of gravitational waves was made by J. Weber in 1969 [1].

Photons (γ). These are the quanta of the electromagnetic field. They have zero rest mass and intrinsic spin $1\hbar$, and are emitted and absorbed exclusively by the charge or current of other particles via the electromagnetic interaction.

Leptons. These are relatively light particles (rest mass either zero or small) of spin $\frac{1}{2}\hbar$, whose interactions with each other and with all other known particles (other than photons and gravitons) are "weak." They include two kinds of neutrinos ν_e and ν_μ with zero electric charge, the electron e^-, the negative muon μ^-, and the antiparticles[1] of these four particles denoted as antineutrinos $\bar{\nu}_e$ and $\bar{\nu}_\mu$, the positron e^+, and the positive muon μ^+. Whenever leptons are produced, transformed into each other, or annihilated by the weak interaction, the number of leptons minus the number of antileptons is preserved, e.g. $n \rightarrow pe^-\bar{\nu}_e$ in ordinary neutron radioactivity. This property of the weak interaction gives rise to a conservation law for leptons that will be discussed further in Sec 8h-3.

[1] Except for a few special particles (e.g., γ, π^0, η) every particle has a distinct antiparticle counterpart.

Hadrons. These are particles that interact with each other via the strong interaction. They also experience electromagnetic, weak, and gravitational interactions. The strongest interaction that a particle experiences determines its classification. Hadrons are divided into two classes: mesons and baryons.

MESONS. The lightest mesons are particles with *zero spin*, intermediate in mass between leptons and protons, that interact strongly with each other and with all the baryons. These spin-0 mesons are designated as pi mesons (π^-, π^0, π^+) [the superscript denotes electric charge], η mesons (0 charge), and K mesons (K^0, K^+) and their antiparticles ($\bar{K}^0$, K^-). Unlike the leptons and the baryons, the antiparticle of a meson can be itself as is the case of the π^0 and η mesons. The π^- meson is the antiparticle of the π^+ meson. These eight mesons are "stable with respect to disintegration via the strong interactions," but they are unstable with respect to disintegrations into leptons, photons, or lighter mesons via the weak and electromagnetic interactions. Table 8h-3 in Sec. 8h-4 lists these decays in detail.

There are many heavier mesons, all with *integral spin* in units of $\hbar$, including a family of eight mesons of spin 1 called "vector" mesons. These heavier mesons play an important role in all phenomena involving the strong interaction, but the number and variety of them keeps us from discussing them in detail here. They differ in one important way from the lighter-spin zero mesons: namely, they are unstable with respect to disintegration into the lighter mesons via the strong interactions. As a result, the mean lives of vector mesons and other still heavier mesons are very short, $\sim 10^{-22}$ sec, as compared to mean lives $\sim 10^{-8}$ to 10^{-10} sec for spin-0 mesons that decay only via the weak interaction. The heavier mesons are sometimes called *resonant* states, that is states of the constituent particles into which they disintegrate. For example, the ρ^+ meson, a vector meson that decays via the reaction $\rho^+ \rightarrow \pi^+ + \pi^0$, can be considered to be a resonant state of the $\pi^+\pi^0$ system with total angular momentum equal to one. Particles and resonant states are two different names for the same thing. In fact, there is no profound difference between particles that are stable with respect to the strong interactions and particles or resonant states such as the vector mesons that are not stable; rather instability or stability simply depends upon whether or not there exist appropriate hadronic states of smaller mass into which the particle can decay without violating the laws of physics.

BARYONS. These are strongly interacting particles of half-integral spin ($\frac{1}{2}\hbar$, $\frac{3}{2}\hbar$, . . .) of mass greater than or equal to the mass of the proton. The lightest spin-$\frac{1}{2}$ group consists of the *nucleons* N (proton p and neutron n) and the *hyperons* Y called a lambda Λ (0 charge), three sigmas Σ^+, Σ^0, Σ^- and two xis Ξ^-, Ξ^0. These hyperons are heavier than nucleons, and stable with respect to strong interactions, but unstable via the weak interaction. Corresponding to each baryon there exists an *antibaryon* which has identical mass and spin as the baryon but opposite charge and magnetic moment. These antibaryons are called antinucleons $\bar{N}(\bar{p},\bar{n})$ and antihyperons $\bar{Y}(\bar{\Lambda}, \bar{\Sigma}^+, \bar{\Sigma}^0, \bar{\Sigma}^-, \bar{\Xi}^0, \bar{\Xi}^-)$. All these antibaryons have been produced and observed at high-energy accelerators. In the processes of production or annihilation of antibaryons in high-energy collisions, an antibaryon is always produced in a pair together with a baryon. The kinetic energy of motion of the incoming beam particle is transformed into rest-mass energy of a baryon-antibaryon pair. Just as the weak interaction preserves the number of leptons minus antileptons in any reaction, the strong interactions preserve the number of baryons minus antibaryons. In fact, this property of conserving the number of baryons minus antibaryons holds not just for the strong interaction but for all interactions, and is responsible for the stability of the proton[1] and all stable nuclei, and hence for the stability of matter as we know it.

The forces that hold nucleons together to form nuclei are due to exchanges of mesons

[1] If it were not for this conservation law, protons would decay by reactions like $p \rightarrow e^+\gamma$, $e^+\pi^0$, . . . see Sec. 8h-3.

between pairs of nucleons. The short range r_0 of the nuclear force is related to the mass M of the exchanged mesons via the Heisenberg uncertainty principle, $r_0 \sim \hbar/Mc \sim 10^{-13}$ cm. Beside the spin-$\frac{1}{2}$ baryons mentioned above, there are a host of higher-mass baryon resonant states or particles with spins $\frac{3}{2}\hbar$, $\frac{5}{2}\hbar$, and higher. None of these states is stable with respect to disintegration via the strong interaction except for the Ω^- hyperon, of spin $\frac{3}{2}\hbar$, which decays via the weak interaction, and to which we shall return later. Again we shall not discuss in detail the properties of such higher-mass unstable baryonic states.

8h-3. Conservation Laws and Quantum Numbers. Our understanding of the interactions in the physical world rests heavily upon the discovery of the existence of conservation laws in physics. Some of these conservation laws are found to have universal validity for all interactions, whereas others are only approximate, holding for one kind of interaction but not for another. In either case, the elementary particles are labeled by quantum numbers and continuous parameters, such as mass, that denote how much of each kind of conserved quantity the particular particle has. In addition to such additive quantum numbers, there exist multiplicative quantum numbers, such as parity that are related to discrete symmetries of particle interactions, which are conserved for some of the known interactions but not for others.

In order to decipher the quantum numbers assigned to the elementary particles listed in Table 8h-3 of Sec. 8h-4, the conservation laws and their associated quantum numbers are listed and briefly discussed below in order of decreasing generality.

Conservation of Energy and Momentum (Four-momentum) and the Concept of Rest Mass. The total energy E and the total linear momentum $\mathbf{p}$ are conserved in any reaction. Within the framework of Einstein's special theory of relativity these two conservation laws can be combined into the law of conservation of four-momentum $(E, c\mathbf{p})$. The fact that the quantity $E^2 - (c\mathbf{p})^2 \equiv (mc^2)^2$ is an invariant with respect to Lorentz transformations (transformations to different constant-velocity reference frames) makes it convenient to assign a rest mass m to each elementary particle. The name *rest mass* is used because its mass is just m in a Lorentz frame in which the particle is at rest. In such a frame, the total energy of the particle is given by $E = mc^2$, so that it is common to measure the mass in units of energy such as MeV (million electron volts, where 1 MeV = 1.6×10^{-6} ergs). Conservation of energy and momentum implies that if particle A of rest mass m_A is at rest and spontaneously disintegrates into two other particles B and C of rest masses m_B and m_C, then $m_Ac^2 = E_B + E_C$, and $0 = \mathbf{p}_B + \mathbf{p}_C$, so that the invariant mass of particles $B + C$ defined as $c^{-2}[(E_B + E_C)^2 - (\mathbf{p}_B + \mathbf{p}_C)^2c^2]^{\frac{1}{2}}$ equals m_A.

Conservation of Angular Momentum, the Spin-quantum Number, and Statistics. The fact that total angular momentum is conserved in *all* reactions is profoundly related to the local isotropy, or nondirectionality, of space. Total angular momentum $\mathbf{J}$ is found to be quantized so that $\mathbf{J}^2 = J(J + 1)\hbar^2$, where J, the total angular-momentum quantum number, can take on only half-integral or integral values. For a given particle $\mathbf{J}$ is the sum of $\mathbf{l} + \mathbf{S}$ where $\mathbf{l}$ is the orbital angular momentum of the particle about some axis, and $\mathbf{S}$ is the intrinsic-spin angular momentum of the particle. If the particle is at rest, $\mathbf{l} = 0$ and $\mathbf{J} = \mathbf{S}$, so that the intrinsic spin of the particle is identical to the total angular momentum of that particle in its rest system. Table 8h-3 of Sec. 8h-4 denotes the intrinsic spin of each particle by the symbol J. As mentioned earlier, all baryons and leptons have half-integral spin, while all mesons have integral spin. When one considers a system containing more than one indistinguishable particle, further restrictions occur in the "statistics" of these identical particles, that is, in the ways of combining these into quantum-mechanical states. Identical half-integral spin particles (e.g., e^-e^- or $\mu^-\mu^-$) obey Fermi-Dirac statistics, which means that the allowed states must be antisymmetric with respect to the interchange of any two such particles. (The Pauli principle for electrons in atoms is a famous example of this relationship.) On the other hand, integral-spin particles obey Bose-Einstein statistics, which imply that the allowed states must be symmetric with respect to the interchange of identical particles. (Planck's law for black-body radiation is a famous illustration of this relationship.) As a result of this connection between spin and statistics, half-integral spin particles are often called *fermions;* and integral spin particles, *bosons.*

Conservation of Electric Charge. One of the oldest and best-established conservation laws is that for electric charge. (This was first clearly stated and demonstrated by Benjamin Franklin.) The total amount of charge Q is found to be conserved in all reactions. In addition, charge is quantized in units of $+e$ or $-e$, where e is the magnitude of charge on the electron. The total charge in any state is obtained by simply adding algebraically the charges on each of the particles in that state. All the particles listed in Table 8h-3 of Sec. 8h-4 have charges 0 or $\pm e$. On the other hand, there do exist higher-energy excited states of nucleons that are doubly charged such as N^{++} which decays to $p + \pi^+$.

Conservation of Baryon Number. If one assigns an additive quantum number $B = +1$ to each baryon, $B = -1$ to each antibaryon, and $B = 0$ to all other particles (leptons, mesons); then all reactions conserve the total baryon number. For ordinary nuclei the total baryon quantum number is identical with the atomic mass number. This conservation law implies that the mode of production of antibaryons must be in the form of baryon-antibaryon pairs, e.g., $p + p \rightarrow p + p + \bar{p} + p$. Even more significant for the stability of the universe is the fact that baryon conservation forbids baryons from decaying into leptons, via reactions such as $p \rightarrow e^+ + \gamma$, which otherwise would be allowed by the laws of conservation of energy, momentum, angular momentum, and charge. When antimatter such as an antiproton $\bar{p}$, which has charge $-e$, interacts with a proton or a neutron, the final products are mesons: e.g., $\bar{p} + n \rightarrow \pi^+ + \pi^- + \pi^- + \pi^0$. This is an example of "annihilation" of matter by antimatter.

In Table 8h-3 of Sec. 8h-4 the antibaryons are not listed separately from the baryons, since all their properties can be deduced directly from the properties of the baryons. The relationships are same mass, same intrinsic spin, opposite charge, opposite magnetic moment, same lifetime, and same proportion of decay modes, where the emitted particles in each decay mode are also converted from particles to antiparticles. This symmetry between particle and antiparticle is related to a symmetry of the relativistic quantum theory of strong, electromagnetic, and weak interactions under the operation of *TCP*. *T*, *C*, and *P* stand for time reversal, particle-antiparticle interchange, and spatial reflection, respectively. As far as we know at present, all interactions are invariant under the simultaneous action of the *TCP* operator, but as we shall discuss below, this is not true for each of these operators separately.

Conservation of Lepton Number and Muon Number. If one assigns an additive quantum number $l = +1$ to each lepton (e^-, μ^-, ν_e, ν_μ), $l = -1$ to each antilepton (e^+, μ^+, $\bar{\nu}_e$, $\bar{\nu}_\mu$), and $l = 0$ to all other particles, then all observed reactions conserve the total lepton number. For example, energetic neutrinos produced by π^+ decays, $\underset{l=0}{\pi^+} \rightarrow \underset{-1}{\mu^+} + \underset{+1}{\nu_\mu}$, are observed to interact with nucleons via the reaction $\underset{l=+1}{\nu_\mu} + \underset{0}{n} \rightarrow \underset{0}{p} + \underset{+1}{\mu^-}$ but *not* via the reaction $\underset{l=+1}{\nu_\mu} + \underset{0}{p} \rightarrow \underset{0}{n} + \underset{-1}{\mu^+}$. The muon number can be introduced to distinguish muons from electrons by assigning a muon number $+1$ to μ^-, ν_μ, -1 to μ^+, $\bar{\nu}_\mu$, and 0 to all other particles, including $e^\pm$, ν_e, $\bar{\nu}_e$. Conservation of muon number can be invoked to "explain" the observed absence of decays such as $\mu^+ \rightarrow e^+ + \gamma$ or $\mu^\pm \rightarrow e^\pm + e^+ + e^-$. The usual mode of disintegration of a muon is $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ or $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. These decays conserve total lepton number and total muon number.

The five conservation laws described so far in this section are absolute in the sense that no violations of any of them have been observed at our present level of sensitivity of experiment. The conservation laws discussed in the remainder of this section are valid only for subsets of the four kinds of interactions but not for all of them.

Invariance under Spatial Inversion P and Particle-Antiparticle Conjugation C. Parity, denoted by the symbol P, refers to the symmetry of a wave function describing a given state under the operation of spatial inversion, $(x \rightarrow -x,\ y \rightarrow -y,\ z \rightarrow -z)$. P can be either plus or minus one. Experimentally, parity is conserved in all strong and electromagnetic interactions but not in the weak interaction. The parity of a given state is determined by multiplying the intrinsic parities of its constituent particles with the parity due to any orbital angular momentum between these particles. For example, the parity of a wave function describing two identical particles with relative orbital angular momentum l is $(-1)^l$.

Particle-antiparticle conjugation C, often called *charge conjugation*, refers to the operation of transforming a particle into its antiparticle. Again the strong and electromagnetic interactions are invariant under such a transformation, but the weak interaction is not. This means that all the properties of strong reactions such as $p + p \rightarrow p + p$, or electromagnetic decays of excited atoms, $(\text{atom})^* \rightarrow (\text{atom}) + \gamma$, are exactly the same as the corresponding antiparticle reactions $\bar{p} + \bar{p} \rightarrow \bar{p} + \bar{p}$ or $(\overline{\text{atom}})^* \rightarrow (\overline{\text{atom}}) + \gamma$. However, the weak decay of a Λ hyperon, $\Lambda \rightarrow p + \pi^-$, is not identical in all respects to the decay $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$. Note that under the operation C, baryons go to antibaryons, and leptons go to antileptons, but mesons and photons go to mesons and photons. Antimesons belong to the same species as mesons, so that an anti-π^- meson is just a π^+ meson. Even more remarkable, an anti-π^0 meson is itself, a π^0 meson. An antiphoton is "minus" itself. Neutral mesons have the possibility of being their own antiparticles, whereas neutral baryons or neutral leptons do not because of the reversal of baryon number and lepton number, respectively. When a neutral particle is its own antiparticle, it is assigned a C quantum number, listed in Table 8h-3 of Sec. 8h-4, which may be either $+1$ or -1. However, not all neutral mesons are their own antiparticles.

Until a few years ago it was thought that the weak interaction was invariant to the combined operation of particle-antiparticle conjugation and spatial inversion, i.e., CP. However, at the level of $\sim 10^{-3}$ of the usual weak amplitude, the weak decay $K_L{}^0 \rightarrow \pi^+ + \pi^-$ has been observed. This process violated CP invariance. Hence the only discrete symmetry invariance of the weak interaction that appears to be exact is TCP invariance, not P or C or CP separately.

We turn now to the conservation laws for the quantities I spin and hypercharge. The former is conserved for the strong interactions only, the latter for both strong and electromagnetic interactions.

The two concepts, I spin and hypercharge, are closely tied to each other and have played an essential part in the current classification scheme of all the hadrons.

Conservation of I spin and Hypercharge, and the Gell-Mann–Nishijima Classification Scheme. The concept of I spin, or "isotopic spin," is introduced in order to describe the charge multiplet structure of hadrons. The particles in a given multiplet have identical spin and parity, and almost identical mass, but different charges. Examples of such multiplets are the (n,p) doublet and the (π^-,π^0,π^+) triplet. One defines an I-spin vector operator $\mathbf{I}$ with three components analogous to the angular-momentum operator $\mathbf{J}$. $\mathbf{I}$ operates in a new *internal* coordinate space of the hadrons, distinct from ordinary space. In exact analogy to J in real space, the eigenvalues of the operator $\mathbf{I}^2$ are $I(I + 1)$, where I is called the total I-spin quantum number. The number of different charge states in a multiplet I is $2I + 1$. For nucleons and π mesons, the charge state is related to the third component I_3 of the I-spin vector by the relation

$$Q = I_3 + \frac{B}{2} \qquad \text{(8h-1)}$$

where Q is the charge in units of $+e$, and B is the baryon number [+1 for (n,p), 0 for π mesons]. The formula implies that $I_3 = +\frac{1}{2}$ and $-\frac{1}{2}$ for proton and neutron; $I_3 = +1, 0, -1$ for π^+, π^0, π^- mesons, respectively. The neutron and proton are seen to form an $I = \frac{1}{2}$ multiplet in isotopic spin space, while the π^+, π^0, π^- mesons form an $I = 1$ multiplet. The I-spin formalism was found to be useful because the strong interactions conserve total I spin ($I_{\text{final}} = I_{\text{initial}}$, or $\Delta I = 0$). This property of the strong interaction is called *charge independence*. The total I spin for a system of more than one particle is built up out of the component I spins of each particle by rules of addition that are identical to the rules of addition for total angular momentum. For example, with the help of Table 8h-2 it can be seen that a (p,p) system is in a pure $I = 1$ state, whereas an (n,p) system is in a 50:50 mixture of $I = 0$ and $I = 1$ states.

Charge independence means that the strong interaction for the (p,p) system is identical to the strong interaction for that *part* of the (n,p) system that is in the $I = 1$ state. By using the I-spin formalism, one can extend the concept of identical particles from protons alone or neutrons alone to both together, that is, to nucleons. Just as a proton can have its spin angular-momentum quantum number S_Z equal to $+\frac{1}{2}$ or $-\frac{1}{2}$ (in units of $\hbar$), a "nucleon" can have the third component of its I spin, I_3, equal to $+\frac{1}{2}$ or $-\frac{1}{2}$, corresponding to a proton or a neutron, respectively. Neither the electromagnetic nor the weak interaction conserves I or I_3, but instead each changes the hadronic I and I_3 quantum numbers in a definite way.

When the K mesons and hyperons were first discovered, they too were found to cluster in charge multiplets, as listed in Sec. 8h-2. However, these K mesons and hyperons presented a puzzle in that they were produced copiously via the strong interactions in collisions between pions and nucleons; yet they had a very low transition probability, characteristic of the weak interactions, for decay back to pions and nucleons. As a result, they were called "strange" particles. Gell-Mann and Nishijima independently showed how to classify the K mesons and hyperons and their interactions by introducing a new quantum number S for "strangeness." The "ordinary" particles like the π mesons and nucleons were assigned $S = 0$, whereas the new strange particles were assigned nonzero integral values of S. Actually it is more common now to use the hypercharge quantum number Y which is simply related to strangeness S by the equation $Y = B + S$, where B = baryon number. The new idea was to generalize the relation between charge Q and I_3, given for pions and nucleons by Eq. (8h-1), to

$$Q = I_3 + \frac{Y}{2} \tag{8h-2}$$

They also added the hypothesis that all strong and electromagnetic reactions conserved hypercharge while the weak interactions, which were responsible for the *decays* of the strange particles, did not conserve hypercharge. Table 8h-2 lists the values of I, I_3, and Y for the eight pseudoscalar mesons ($J^P = 0^-$) and for the eight spin-$\frac{1}{2}$ baryons.

The hypercharge quantum numbers for antiparticles are obtained from those for particles by letting $Y \to -Y$. Furthermore, since $Q \to -Q$, Eq. (8h-2) implies that $I_3 \to -I_3$ when particle $\to$ antiparticle. The total I spin is the same for a particle and its antiparticle since the multiplicity of charge states does not change. So the hypercharge Y is a simple additive quantum number just as ordinary charge or baryon number.

The Gell-Mann–Nishijima classification scheme for all reactions involving only mesons and baryons can be simply codified by the following selection rules:

1. Strong interactions: $\Delta Q = \Delta B = \Delta Y = \Delta I = 0$
2. Electromagnetic interactions: $\Delta Q = \Delta B = \Delta Y = 0$
3. Weak interactions: $\Delta Q = \Delta B = 0$, $\Delta Y = \pm 1$

TABLE 8h-2. *I*-SPIN AND HYPERCHARGE QUANTUM NUMBERS FOR STABLE MESONS AND BARYONS

Mesons	π^+	π^0	π^-	K^+	K^0	$\bar{K}^0$	K^-	η
I	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0
I_3	+1	0	−1	$+\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$-\frac{1}{2}$	0
$Y(B = 0)^a$	0	0	0	+1	+1	−1	−1	0
Baryons	p	n	Λ	Σ^+	Σ^0	Σ^-	Ξ^0	Ξ^-
I	$\frac{1}{2}$	$\frac{1}{2}$	0	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$
I_3	$+\frac{1}{2}$	$-\frac{1}{2}$	0	+1	0	−1	$+\frac{1}{2}$	$-\frac{1}{2}$
$Y(B = +1)^a$	+1	+1	0	0	0	0	−1	−1

[a] $Q = I_3 + Y/2$.

[The symbol ΔQ means ($Q_{\text{initial}} - Q_{\text{final}}$) for any reaction.] The leptons are not included in the Gell-Mann–Nishijima scheme. The quantum number of I spin and hypercharge Y are not assigned to them since they do not participate in the strong interactions. A photon has $Y = 0$ but no definite I spin. As a consequence of these rules, the strong interactions allow reactions of the type

$$\pi^- + p \rightarrow \Lambda + K^0 \qquad (8h\text{-}3)$$
$$K^- + p \rightarrow \Xi^- + K^+ \qquad (8h\text{-}4)$$
$$p + p \rightarrow \Lambda + \bar{\Lambda} \qquad (8h\text{-}5)$$

but forbid reactions of the type

$$\pi^- + p \rightarrow \Sigma^+ + K^- \quad \text{(violates } Y) \qquad (8h\text{-}6)$$
$$n + p \rightarrow \Lambda + p \quad \text{(violated } Y \text{ and } I) \qquad (8h\text{-}7)$$
$$\Lambda \rightarrow p + \pi^- \quad \text{(violates } Y \text{ and } I) \qquad (8h\text{-}8)$$

The weak interaction is responsible for the decays of most hyperons and K mesons. The final products may be nonleptonic, e.g., $\Lambda \rightarrow p\pi^-$ or $K^+ \rightarrow \pi^+\pi^0$, or leptonic, e.g., $\Lambda \rightarrow pe^-\bar{\nu}_e$ or $K^+ \rightarrow \mu^+\nu_\mu$. For three neutral particles, π^0, η, and Σ^0, the predominant modes of decay are electromagnetic, not weak, e.g., $\Sigma^0 \rightarrow \Lambda + \gamma$ or $\pi^0 \rightarrow \gamma + \gamma$. The weak decays of strange particles seem to obey other selection rules. For example, in leptonic decays of hadrons the selection rule $\delta S = \delta Q$ holds, where δS and δQ denote the change in strangeness and in charge of strongly interacting particles: e.g., $\Sigma^- \rightarrow n + l^- + \bar{\nu}$ is allowed ($\delta S = \delta Q = +1$), but $\Sigma^+ \rightarrow n + l^+ + \bar{\nu}$ is forbidden ($\delta S = +1$, $\delta Q = -1$).

The neutral K mesons provide a unique and fascinating application of the ideas described above when coupled with ordinary quantum mechanics. The K^0 meson is a particle with $Y = S = +1$, its antiparticle denoted by $\bar{K}^0$ has opposite hypercharge $Y = S = -1$. Once either particle is produced in a strong reaction, it is observed to decay with two lifetimes, not one. One calls the short-lived particle a K_S^0 and the longer-lived particle a K_L^0. Each of these particles has different linear combinations of K^0 and $\bar{K}^0$ mesons, approximately 50:50 mixtures in either case. By the general TCP theorem, the K^0 and $\bar{K}^0$ particles have identical mass, but the K_S^0 and K_L^0 differ slightly in mass, in fact, by the incredibly small amount of 2 parts in 10^{14}. The remarkable $K^0 - \bar{K}^0$ system is also the only one to date in which the weak interaction has been found not to conserve the value of the operator CP, in particular in both the leptonic and nonleptonic decays of K_L^0.

8h-4. Properties of Elementary Particles. A detailed list of the intrinsic properties of the stable elementary particles is given in Table 8h-3. By "stable" we mean stable with respect to the strong interactions, but not with respect to the weak or electromagnetic interactions. This table is reproduced essentially verbatim from the latest edition of the annual Review of Particle Properties, that is printed each January by *Reviews of Modern Physics* [2]. This article contains all the references to the experimental measurements that have gone into the data in Table 8h-3. Since the journal *Reviews of Modern Physics* is readily available, we have chosen not to reproduce the hundreds of references here. That article also contains a detailed listing of the properties of the known unstable particles as well.

In Table 8h-3 the first column lists the symbol for each particle. The second lists four quantum numbers: the I-spin, I, angular momentum, and parity (where appropriate) in the symbol J^P, and the C quantum number if applicable. The third column lists the mass in MeV, the mass² in GeV², and the mass difference where it has been measured directly for members of the same charge multiplet. The next column has the mean life in seconds along with the mean distance for decay $c\tau$ in centimeters. The remaining columns contain a list of the partial decay modes for each unstable particle, the fraction of the total decay probability for each decay mode, and the unique momentum (two body decay) or maximum momentum (three or more bodies) of a secondary particle in the rest system of the decaying particle. These detailed properties are given for each particle, but not for its antiparticle, since the TCP theorem implies that the properties of the antiparticle are identical to those of each particle except for the appropriate quantum-number transformations (see page 8-283).

8h-5. SU$_3$ Classification of Hadrons—The Eightfold Way. *Supermultiplets.* We have already shortened our table of hadrons by grouping them into I-spin multiplets. Thus, it was pointed out in Sec. 8h-3 that the neutron n and proton p both belonged to the I-spin doublet called the nucleon N, and the π mesons, which can appear with three electric charges Q, form an I-spin triplet (π^-,π^0,π^+). But we have so far treated the different multiplets as independent and "elementary."

Now we proceed to point out that particle physicists further group these multiplets into "supermultiplets," of 1, 8, or 10 particles; so that, in fact, all the mesons in Table 8h-3 are said to belong to the $J^P = 0^-$ octet, and all the baryons except the Ω^- belong to the $J^P = \frac{1}{2}^+$ octet.

Typical supermultiplets are illustrated in Fig. 8h-1. Each dot represents a particle, plotted in a space where electric charge Q increases to the right and hypercharge Y increases upward. (More precisely, $x = Q - Q_{av} = I_3$, $y = Y$, with I_3 and Y defined in Sec. 8h-3.) The eight baryons with $J^P = \frac{1}{2}^+$ are arranged at the upper left. Here the nucleon doublet N, (with $Y = +1$) contributes two dots (n and p), the Σ triplet ($Y = 0$) adds three $(\Sigma^-,\Sigma^0,\Sigma^+)$, the Λ singlet one, and the $\Xi(Y = -1)$ adds the other two. We shall comment below on the symmetry of the hexagon thus created, but first we continue empirically.

The next array also turns out to form a hexagon. This hexagon consists of the eight $J^P = 0^-$ mesons which happen all to be stable (against strong decay, Sec. 8h-2), and hence are listed in Table 8h-3 along with the eight stable baryons.

The next array (also hexagonal!) is made of $J^P = 1^-$ mesons which happen all to be unstable, and so they are called "resonances" and are omitted from Table 8h-3. (A table of ~50 resonant multiplets can be found in ref. 2.) Several other meson octets are now known.

Finally, Fig. 8h-1 shows a triangular "decuplet" of the 10 baryons with $J^P = \frac{3}{2}^+$. Nine of these are resonances; one is the stable Ω^- baryon.

Quarks. The SU$_3$ explanation of the hexagons and triangles is also sketched in Fig. 8h-1. In 1961 Gell-Mann and Ne'eman independently pointed out that these supermultiplets of 10, 8, 1 would be built up out of a single supermultiplet of 3 "primitive"

Table 8h-3. Intrinsic Properties of Stable Elementary Particles: January, 1970

Particle	$I^G(J^P)C$	Mass, MeV Mass², GeV²	Mean life, sec $c\tau$, cm	Decays: Partial mode	Decays: Fraction[a]	P or P_{max},[b] MeV/c
γ	$0, 1(1^-)^-$	$0(<2 \times 10^{-21})$	Stable	Stable		
ν	$\nu_e\ J = \frac{1}{2}$ ν_μ	$0(<60$ eV$)$ $0(<1.6)$	Stable	Stable		
e	$J = \frac{1}{2}$	0.511006 ± 0.000002	Stable $(>2 \times 10^{21}\ y)$	Stable		
μ	$J = \frac{1}{2}$	105.659 ± 0.002 $m^2 = 0.0112$ $m_\mu - m_{\pi^\pm} = -33.920 \pm 0.013$	$(2.1983 \pm 0.0008) \times 10^{-6}$ $c\tau = 6.592 \times 10^4$	$e\nu\bar{\nu}$	100	53
				$e\gamma\gamma$	$(<1.6\ )10^{-5}$	53
				$3e$	$(<1.3\ )10^{-7}$	53
				$e\gamma$	$(<2\ )10^{-8}$	53
$\pi^\pm$	$1^-(0^-)$	139.578 ± 0.013 $m^2 = 0.0195$	$(2.603 \pm 0.006) \times 10^{-8}$, $S = 2.0$* $c\tau = 781$ $(\tau^+ - \tau^-)/\bar{\tau} = (0.05 \pm 0.07)\%$ (test of CPT)	$\mu\nu$	100 %	30
				$e\nu$	$(\ 1.24 \pm 0.03\ )10^{-4}$	70
				$\mu\nu\gamma$	[c]$(\ 1.24 \pm 0.25\ )10^{-4}$	30
				$\pi^0 e\nu$	$(\ 1.02 \pm 0.07\ )10^{-8}$	5
				$e\nu\gamma$	[c]$(\ 3.0 \pm 0.5\ )10^{-8}$	70
π^0	$1^-(0^-)^+$	134.975 $m^2 = 0.0177$ $m_{\pi^\pm} - m_{\pi^0} = 4.6041 \pm 0.0037$	$(0.89 \pm 0.18) \times 10^{-16}$, $S = 1.6$* $c\tau = 2.67 \times 10^{-6}$	$\gamma\gamma$	$(\ 98.83 \pm 0.04\ )\%$	67
				γe^+e^-	$(\ 1.17 \pm 0.04\ )\%$	67
				$\gamma\gamma\gamma$	$(<5\ )10^{-6}$	67
				$e^+e^-e^+e^-$	[d]$(\ 3.47\ )10^{-5}$	67
$K^\pm$	$\frac{1}{2}(0^-)$	493.82 ± 0.11 $m^2 = 0.244$	$(1.235 \pm 0.004) \times 10^{-8}$, $S = 1.8$* $c\tau = 370$ $(\tau^+ - \tau^-)/\bar{\tau} = (0.09 \pm 0.12)\%$	$\mu\nu$	$(\ 63.77 \pm 0.29\ )\%\ S = 1.1$*	236
				$\pi\pi^0$	$(\ 20.93 \pm 0.30\ )\%\ S = 1.2$*	205
				$\pi\pi^-\pi^+$	$(\ 5.57 \pm 0.04\ )\%\ S = 1.2$*	126
				$\pi\pi^0\pi^0$	$(\ 1.70 \pm 0.05\ )\%$	133

		$m_{K^\pm} - m_{K^0} = -3.94 \pm 0.13$	(test of CPT)	$\mu\pi^0\nu$	(3.18 ± 0.11)% $S = 2.0^*$	215
			$S = 1.3^*$	$e\pi^0\nu$	(4.85 ± 0.07)% $S = 1.2^*$	228
				$\pi\pi^\mp e^\pm\nu$	(3.3 ± 0.3)10^{-5}	203
				$\pi\pi^\pm e^\mp\nu$	(<7)10^{-7}	203
				$\pi\pi^\mp\mu^\pm\nu$	(0.9 ± 0.4)10^{-5}	151
				$\pi\pi^\pm\mu^\mp\nu$	(<3)10^{-6}	151
				$e\nu$	(1.2 ± 0.3)10^{-5}	247
				$\pi\pi^0\gamma$	[c](<1.9)10^{-4}	205
				$\pi\pi^+\pi^-\gamma$	[c](10 ± 4)10^{-5}	126
				$\pi e\nu\gamma$	[c](6 ± 4)10^{-4}	227
				πe^+e^-	(<0.4)10^{-6}	227
				$\pi\mu^+\mu^-$	(<2.4)10^{-6}	172
				$\pi\gamma\gamma$	(<1.1)10^{-4}	227
K^0	$\frac{1}{2}(0^-)$	497.76 ± 0.16	50% K_{short}, 50% K_{long}			
K_S^0	$\frac{1}{2}(0^-)$	$S = 1.5^*$	$(0.862 \pm 0.006) \times 10^{-10}$,	$\pi^+\pi^-$	(68.7 ± 0.6)% $S = 1.6^*$	206
			$S = 1.2^*$	$\pi^0\pi^0$	(31.3)%	209
		$m^2 = 0.248$	$c\tau = 2.59$	$\mu^+\mu^-$	(<3.1)10^{-7}	225
				e^+e^-	(<2.2)10^{-7}	249
				$\pi^+\pi^-\gamma$	[c](3.3 ± 1.2)10^{-3}	206
K_L^0	$\frac{1}{2}(0^-)$		$(5.38 \pm 0.19) \times 10^{-8}$	$\pi^0\pi^0\pi^0$	(21.5 ± 0.7)% $S = 1.2^*$	139
				$\pi^+\pi^-\pi^0$	(12.6 ± 0.3)%	133
			$c\tau = 1614$	$\pi\mu\nu$	(26.8 ± 0.7)% $S = 1.2^*$	216
			$S = 1.6^*$	$\pi e\nu$	(38.8 ± 0.8)% $S = 1.2^*$	229
		$m_{K_S} - m_{K_L} =$		$\pi^+\pi^-$	(0.157 ± 0.005)%	206
		$-(0.469 \pm 0.015) \times \frac{1}{\tau_S}$		$\pi^0\pi^0$	(0.121 ± 0.029)% $S = 1.5^*$	209
				$\pi^+\pi^-\gamma$	[c](<0.4)10^{-3}	206
			$\frac{\Gamma(K_S \to \pi^+\pi^-\pi^0)}{\Gamma(K_L \to \pi^+\pi^-\pi^0)} < 0.45$	$\gamma\gamma$	(5.2 ± 0.5)10^{-4} $S = 1.6^*$	249
				$e\mu$	(<0.6)10^{-5}	238
			(test of CP)	$\mu^+\mu^-$	(<1.5)10^{-6}	225
				e^+e^-	(<1.7)10^{-5}	249
η	$0^+(0^-)^+$	548.8 ± 0.6	$\Gamma = (2.63 \pm 0.64)$ keV	$\gamma\gamma$	(38.2 ± 2.1)% $S = 1.4^*$	274
			Neutral decays 71.5%	$\pi^0\gamma\gamma$	(2.0 ± 2.8)%	258
		$m^2 = 0.301$		$3\pi^0$	[c](31.4 ± 2.7)%	179

TABLE 8h-3. INTRINSIC PROPERTIES OF STABLE ELEMENTARY PARTICLES: JANUARY, 1970 (*Continued*)

Particle	$I^G(J^P)C$	Mass, MeV Mass², GeV²	Mean life, sec $c\tau$, cm	Decays: Partial mode	Decays: Fraction[a]	P or P_{max},[b] MeV/c
η			Charged decays 28.5%	$\pi^+\pi^-\pi^0$	(23.0 ± 1.1)% $S = 1.2^*$	174
				$\pi^+\pi^-\gamma$	(5.4 ± 0.5)%	236
				$\pi^0 e^+e^-$	(<0.01)%	258
				$\pi^+\pi^- e^+e^-$	(0.1 ± 0.1)%	236
p	$\frac{1}{2}(\frac{1}{2}^+)$	938.256 ± 0.005 $m^2 = 0.880$	stable (>2 × 10²⁸ y)			
n	$\frac{1}{2}(\frac{1}{2}^+)$	939.550 ± 0.005 $m^2 = 0.882$ $m_p - m_n = -1.2933 \pm 0.0001$	[e](0.932 ± 0.014) × 10³ $c\tau = 2.80 \times 10^{13}$	$pe^-\nu$	100 %	1
Λ	$0(\frac{1}{2}^+)$	1115.60 ± 0.08 $S = 1.3^*$ $m^2 = 1.245$	(2.51 ± 0.03) × 10⁻¹⁰, $S = 1.3^*$ $c\tau = 7.54$	$p\pi^-$	(65.3 ± 1.3)%	100
				$n\pi^0$	(34.7)%	104
				$pe\nu$	(0.85 ± 0.07)10⁻³ $S = 1.3^*$	163
				$p\mu\nu$	(1.35 ± 0.60)10⁻⁴	131
Σ^+	$1(\frac{1}{2}^+)$	1189.40 ± 0.19 $S = 1.7^*$ $m^2 = 1.412$ $m_{\Sigma^+} - m_{\Sigma^-} = -7.92 \pm 0.13$	(0.802 ± 0.007) × 10⁻¹⁰ $c\tau = 2.41$	$p\pi^0$	(51.7 ± 0.8)%	189
				$n\pi^+$	(48.3)%	185
				$p\gamma$	(*1.16* ± *0.17*)10⁻³ $S = 1.4^*$	225
				$n\pi^+\gamma$	(*1.3* ± *0.3*)10⁻⁴	185
				$\Lambda e^+\nu$	(2.02 ± 0.47)10⁻⁵	72
			$\frac{\Gamma(\Sigma^+ \to l^+ n\nu)}{\Gamma(\Sigma^- \to l^- n\nu)} = <0.03$	← $n\mu^+\nu$	(<1.1)10⁻⁵	202
				← $ne^+\nu$	(<0.7)10⁻⁵	224
Σ^0	$1(\frac{1}{2}^+)$	1192.46 ± 0.12 $S = 1.2^*$ $m^2 = 1.422$	<1.0 × 10⁻¹⁴ $c\tau < 3 \times 10^{-4}$	$\Lambda\gamma$	100 %	75
				Λe^+e^-	[d](5.45 ±)10⁻³	

Σ^-	$1(\frac{1}{2}^+)$	1197.32 ± 0.11 $S = 1.3$* $m^2 = 1.434$ $m_{\Sigma^0} - m_{\Sigma^-} = 4.86 \pm 0.07$	[e]$(1.49 \pm 0.03) \times 10^{-10}$, $S = 2.1$* $c\tau = 4.47$	$n\pi^-$	100 %	193
				$ne^-\nu$	$(1.06 \pm 0.05)10^{-3}$	230
				$n\mu^-\nu$	$(0.45 \pm 0.04)10^{-3}$	210
				$\Lambda e^-\nu$	$(0.60 \pm 0.06)10^{-4}$	79
				$n\pi^-\gamma$	[c]$(1.0 \pm 0.2)10^{-4}$	193
Ξ^0	$\frac{1}{2}(\frac{1}{2}^+)$[f]	1314.7 ± 0.7 $m^2 = 1.728$ $m_{\Xi^0} - m_{\Xi^-}$ [illegible] ± 0.7	$(3.03 \pm 0.18) \times 10^{-10}$ $c\tau = 9.10$	$\Lambda\pi^0$	100 %	135
				$p\pi^-$	$(<0.9)10^{-3}$	299
				$pe^-\nu$	$(<1.3)10^{-3}$	323
				$\Sigma^+e^-\nu$	$(<1.5)10^{-3}$	119
				$\Sigma^-e^+\nu$	$(<1.5)10^{-3}$	112
				$\Sigma^+\mu^-\nu$	$(<1.5)10^{-3}$	64
				$\Sigma^-\mu^+\nu$	$(<1.5)10^{-3}$	49
				$p\mu^-\nu$	$(<1.3)10^{-3}$	309
Ξ^-	$\frac{1}{2}(\frac{1}{2}^+)$[f]	1321.25 ± 0.18 $m^2 = 1.746$	$(1.66 \pm 0.04) \times 10^{-10}$, $S = 1.1$* $c\tau = 4.98$	$\Lambda\pi^-$	100 %	139
				$\Lambda e^-\nu$	[g]$(0.67 \pm 0.23)10^{-3}$	190
				$\Sigma^0e^-\nu$	$(<0.5)10^{-3}$	122
				$\Lambda\mu^-\nu$	$(<1.3)10^{-3}$	163
				$\Sigma^0\mu^-\nu$	(<0.5)%	70
				$n\pi^-$	$(<1.1)10^{-3}$	303
				$ne^-\nu$	(<1.0)%	327
Ω^-	$0(\frac{3}{2}^+)$[f]	1672.5 ± 0.5 $m^2 = 2.797$	$1.3^{+0.4}_{-0.3} \times 10^{-10}$ $c\tau = 3.9$	$\Xi^0\pi^-$	Total of 28 events seen	293
				$\Xi^-\pi^0$		289
				ΛK^-		210

From Review of Particle Properties, UCRL-8030. N. Barash-Schmidt, A. Barbaro-Galtieri, C. Bricman, S. E. Derenzo, L. R. Price, A. Rittenberg, Matts Roos, A. H. Rosenfeld, Paul Söding, and C. G. Wohl. (Closing date for data: Nov. 1, 1969.)

Quantities in italics have changed by more than one (old) standard deviation since January, 1969.

* S = Scale factor = $\sqrt{\chi^2/(N-1)}$, where $N \approx$ number of experiments. S should be ≈ 1. If $S > 1$, we have enlarged the error of the mean, δx, i.e., $\delta x \to S\,\delta x$. This convention is still inadequate, since if $S \gg 1$, the experiments are probably inconsistent, and therefore the real uncertainty is probably even greater than $S\,\delta x$. See text and ideogram in data card listings, UCRL-8030.

[a] Quoted upper limits correspond to a 90% confidence level.

[b] In decays with more than two bodies, P_{max} is the maximum momentum that any particle can have.

[c] See data card listings, (UCRL-8030) for energy limits used in measuring this branching ratio.

[d] Theoretical value; see also data card listings, UCRL-8030.

[e] See note in data card listings, UCRL-8030.

[f] Predicted from SU_3.

[g] Assumes rate for $\Xi^- \to \Sigma^0 e^-\nu$ small compared with $\Xi^- \to \Lambda e^-\nu$.

particles called quarks and an antimultiplet (antiquarks). (It is not known whether quarks exist in nature or only as a mathematical explanation.) The quarks "exist" as an I-spin doublet (such as n and p), and a singlet (such as Λ). In their simplest form they would have surprising *fractional* quantum numbers, $B = \frac{1}{3}$, $Q = -\frac{1}{3}$ or $+\frac{2}{3}$, etc. Mesons are then tightly bound states of quark + antiquark ($q\bar{q}$); baryons "contain" three quarks (qqq) held together by the strong interaction.

The mathematics of how three primitive objects can be combined into larger groups is called *group theory*, and the particular combination that correctly explains nature is called, in group theory, SU_3; hence the title for this section: "SU_3 Classification."

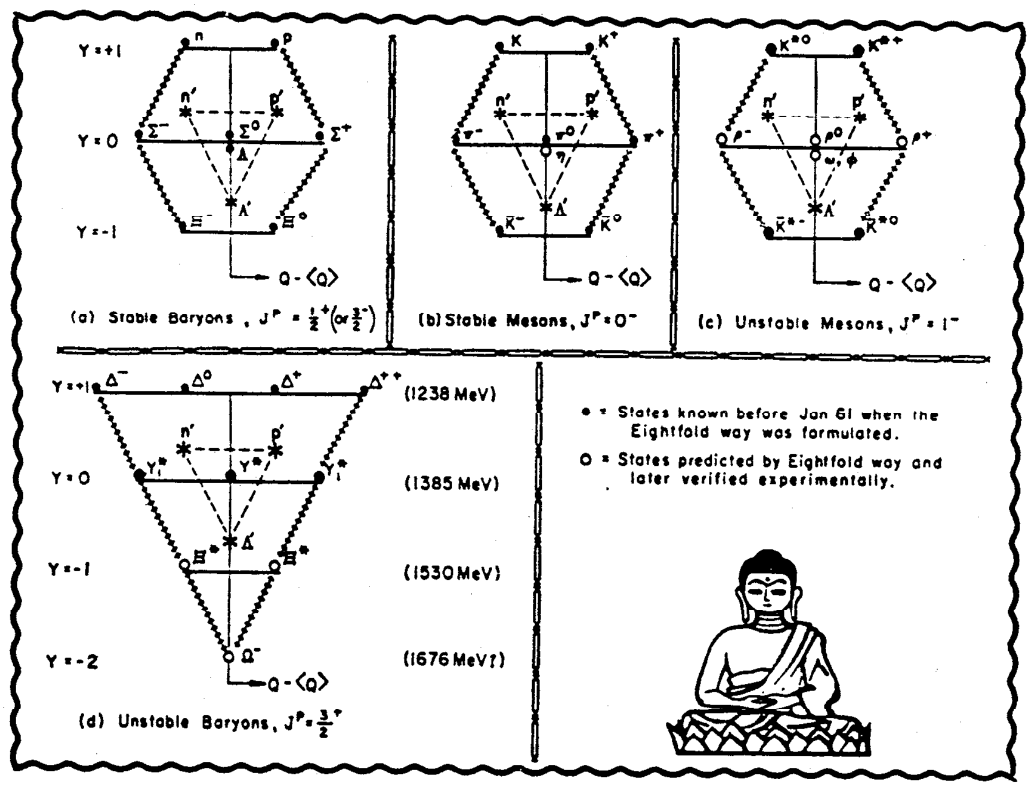

FIG. 8h-1. The asterisks labeled n', p', and Λ' are a possible set of primitive particles called "quarks," from which the mesons and baryons can be formed.

The algebraic rules of SU_3 explain much more than the size of multiplets—they also explain quite well the masses and decay modes of particles and resonances (see any textbook on particle physics [3]).

8h-6. Further Reading. There are many textbooks on particle physics. A sample of them are listed in ref. 3. Two fairly recent and complete books are those by Gasiorowicz [3] and by Frazer [3]. Many excellent semipopular articles can be found in the *Scientific American* [4], and more technical review articles in the *Annual Review of Nuclear Science* [5]. A mild apology to the reader—this text is rather compact and not too easy to read; two articles which cover much of the same material but in a more leisurely fashion have been written by Ne'eman [6] and Rosenfeld [7]. A more extended but nonmathematical discussion of the subject can be found in a readable book by Ford [8].

Acknowledgement. We wish to thank Dr. LeRoy Price of the Berkeley Particle Data Group for his help and criticism.

References

1. Weber, J.: *Phys. Rev. Letters* **22,** 1320 (1969).
2. Particle Data Group: *Rev. Mod. Phys.* **41,** 109 (1969).
3. (i) Gasiorowicz, S.: "Elementary Particle Physics," John Wiley & Sons, Inc., New York, 1966.
   (ii) Frazer, W.: "Elementary Particles," Prentice-Hall, Inc., Englewood Cliffs, N.J., 1966.
   (iii) Bernstein, J.: "Elementary Particles and Their Currents," W. H. Freeman and Company, San Francisco, 1968.
   (iv) Gell-Mann, M., and Y. Ne'eman: "The Eightfold Way," W. A. Benjamin, Inc., New York, 1964.
   (v) Källen, G.: "Elementary Particle Physics," Addison-Wesley Press, Inc., Cambridge, Mass., 1964.
   (vi) Sakurai, J. J.: "Invariance Principles and Elementary Particles," Princeton University Press, Princeton, N.J., 1964.
   (vii) Adair, R. K., and E. C. Fowler: "Strange Particles," Interscience Publishers, a division of John Wiley & Sons, Inc., New York, N.Y., 1963.
   (viii) Levi-Setti, R.: "Elementary Particles." University of Chicago, 1963.
   (ix) Yang, C. N.: "Elementary Particles," Princeton University Press, Princeton, N.J., 1962.
   (x) Williams, W. S. C.: "An Introduction to Elementary Particles," Academic Press, Inc., New York, 1961.
4. *Scientific American* Articles:
   (i) The Overthrow of Parity, P. Morrison, April, 1957.
   (ii) Pions, R. Marshak, January, 1957.
   (iii) Elementary Particles, Gell-Mann and Rosenfeld, July, 1957.
   (iv) The Weak Interactions, S. B. Treiman, March, 1959.
   (v) Two Neutrino Experiment, L. Lederman, January, 1962.
   (vi) Strongly Interacting Particles, Chew, Gell-Mann, and Rosenfeld, February, 1964.
   (vii) The Omega-Minus Experiment, W. B. Fowler and N. P. Samios, October, 1964.
   (viii) Violations of Symmetry in Physics, E. P. Wigner, December, 1965.
5. (i) Lee, T. D., and C. S. Wu: *Ann. Rev. Nucl. Sci.* **15,** 381(1965); **16,** 471(1966).
   (ii) Tripp, R. D.: *ibid.* **15,** 325 (1965).
   (iii) Feinberg, G., and L. M. Lederman: *ibid.* **13,** 431 (1963).
6. Ne'eman, Y.: "Science Year (the World Book Science Annual), 1968.
7. Rosenfeld, A. H.: Elementary Guide, UCRL-11 100 (unpublished).
8. Ford, K. W.: "The World of Elementary Particles," Blaisdell Publishing Company, a division of Ginn and Company, Waltham, Mass., 1963.