ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

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R-1631

СИЛЬНО ВЗАИМОДЕЙСТВУЮЩИЕ ЧАСТИЦЫ

(Scientific American февраль 1964 г.)

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STRONGLY INTERACTING PARTICLES

Presenting an account of recent developments in high-energy physics. These particles that respond to the strongest of the four natural forces no longer seem "elementary." They may be composites of one another

by Geoffrey F. Chew, Murray Gell-Mann and Arthur H. Rosenfeld

Only five years ago it was possible to draw up a tidy list of 30 subatomic particles that could be called, without too many misgivings, elementary. Since then another 60 or 70 subatomic objects have been discovered, and it has become obvious that the adjective "elementary" cannot be applied to all of them. For this reason the adjective has been carefully avoided in the title of this article. There is now a widespread belief among physicists that none of the particles with which this article is mainly concerned deserves to be singled out as elementary.

What is happening has happened before in physics: the old way of looking at things, which was adequate for perceiving order in a limited number of observations, finally proved cumbersome and inadequate when the accuracy and range of observation increased. This happened with the Ptolemaic scheme of epicycles for describing the motions of the planets. Much the same thing occurred early in this century when spectroscopists, studying the light emitted by excited atoms, found a profusion of discrete wavelengths that were at total variance with the wavelengths predicted by classical electrodynamics. The spectroscopists accumulated so much empirical information, including sets of "selection rules" governing the permissible states of excited atoms, that it finally became possible in 1926 for Werner Heisenberg, Erwin Schrödinger and others to formulate a new mechanics—quantum mechanics—capable of predicting most of the states of matter on the atomic and molecular scale.

A similar situation may exist today in particle physics. The great unifying invention analogous to quantum mechanics is still not clearly in sight, but the experimental data are beginning to fall into striking and partly predictable patterns. What can be said to summarize the vast amount of particle information now available?

First of all, there is a clear distinction between strongly interacting particles, such as the neutron and proton, and other particles. The neutron and proton are known to interact through the strong, short-range nuclear force, which is responsible for the binding of these particles in atomic nuclei. All particles discovered to date participate in this strong interaction except the photon (the particle of light and other electromagnetic radiation) and the four particles called leptons: the electron, the muon (or mu particle) and the two kinds of neutrino.

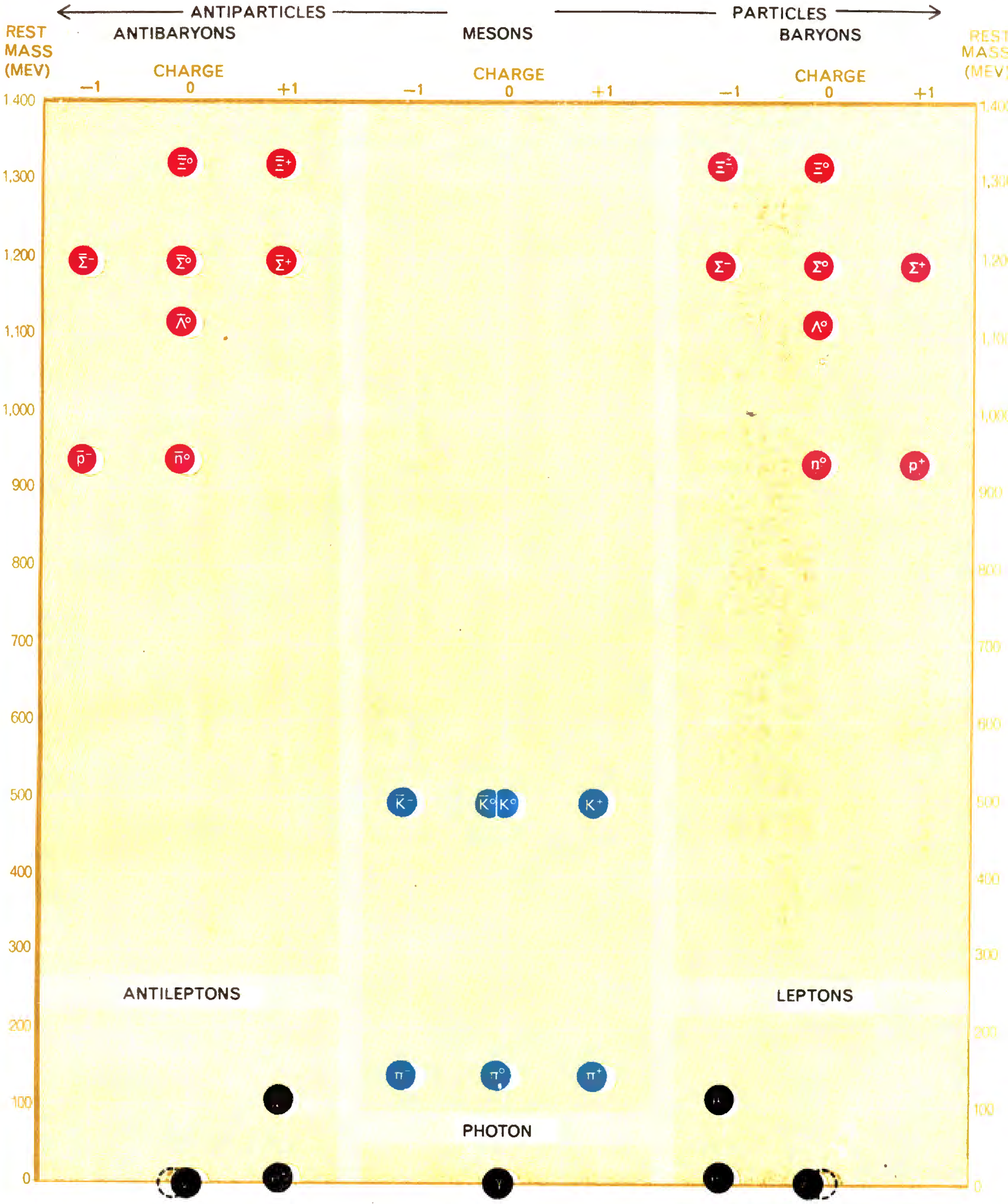
Another striking property of the strongly interacting particles is that none of them has a small rest mass. Rest mass is the mass that a particle would have if it were motionless; this is the minimum mass the particle can have. It is now common to express this mass as its equivalent in energy, rather than in units of the electron's mass, as was often done in the past. The lightest strongly interacting particle is the pion (or pi meson), which has a mass with an energy equivalent of some 137 million electron volts (Mev). In contrast, the mass of the electron is about .5 Mev and that of the photon and the neutrinos is believed to be zero.

A third general observation is that the recent proliferation of particles has so far occurred almost exclusively among the strongly interacting particles. Although this proliferation came as a surprise to physicists, a precedent for this state of affairs can be found in ordinary atomic nuclei. It is well known that all compound nuclei, from the nucleus of deuterium (heavy hydrogen) to those of the heaviest elements, can exist at a variety of energy levels, comprising a "ground" state and many excited states. These levels, which can be detected in several ways, indicate different degrees of binding energy among the component nucleons (neutrons and protons) in the nucleus. The binding energy, of course, is an expression of the strong nuclear force.

It is now clear that the nuclear force can similarly give rise to numerous states among those strongly interacting particles sometimes designated elementary. The lower states are "bound," or stable; the higher states are only partly bound, or unstable, decaying in a tiny fraction of a second. The result is that all strongly interacting particles exhibit a spectrum of energy levels with no sharp upper limit.

Since the leptons do not participate in strong interactions, it is not surprising that their spectrum of states, beginning with the massless neutrino and apparently terminating sharply at the muon, with a mass of 106 Mev, bears no resemblance to any known dynamical spectrum. In recent years physicists have learned much about the simplicity and regularity in the properties of leptons, but they have learned nothing of why these particles exist.

In the following discussion we shall begin by considering the place of the strong force in the hierarchy of four forces that seem to underlie all the operations of the physical universe. Next we shall describe a new nomenclature that assigns each of the strongly interacting particles to one of a small number of families, each characterized by a distinctive set of properties. One group of these families embraces the baryons, which in general are the heaviest particles; a second group consists of mesons, the first members of which to be discovered were lighter than the baryons. The new naming system will require a brief review of the seven quantum num-



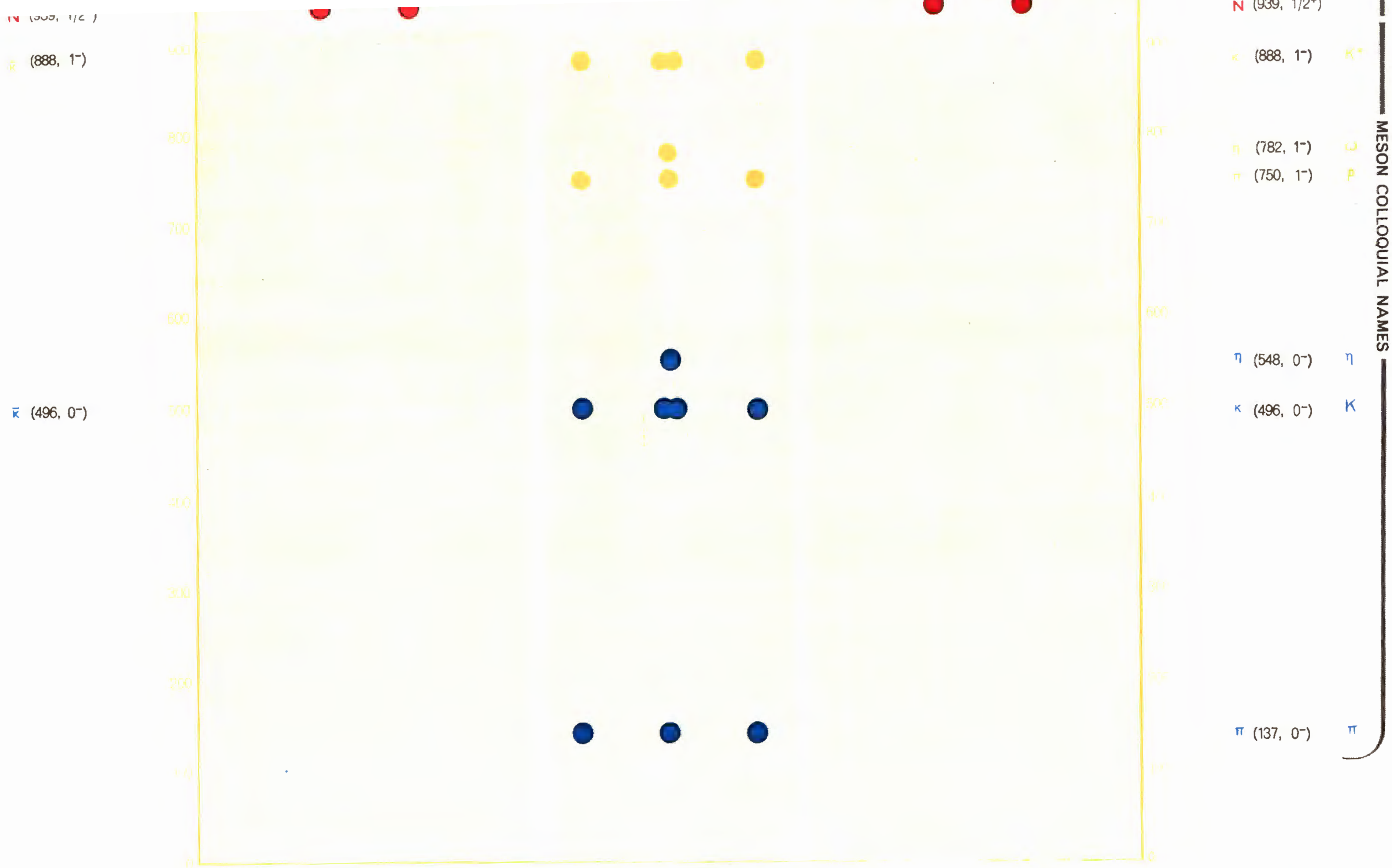
BARYONS
Ξ XI
Σ SIGMA
Λ LAMBDA
n NEUTRON
p PROTON

MESONS
K K MESON, OR KAON
π PI MESON, OR PION

LEPTONS
μ MU, OR MUON
e ELECTRON
ν NEUTRINO

THIRTY PARTICLES of 1957 consisted of 16 baryons and antibaryons, seven mesons, six leptons and antileptons and the photon. (Baryon, meson and lepton respectively signify heavy, medium and light particles.) The strongly interacting particles, which respond to the strong, or nuclear, force, are in color. Particles shown in black do not respond to this force. It is the former that have proliferated in the past half-dozen years, as shown on the next two pages. In the same period the number of leptons and antileptons has increased by only two. It is now known that there are two kinds of neutrino instead of one, each with its own antiparticle (indicated by broken lines next to the two particles known in 1957). One other neutral and massless particle is believed to exist but is not shown here: the graviton, the carrier of the gravitational force. The hypothetical carrier of the weak force, also not shown, should have a considerable mass and one unit of electric charge. Evidence for it is now being sought.


ANTIPARTICLES
PARTICLES
SYMBOL
REST MASS (MEV)
ANTIBARYONS (A = −1)
CHARGE
MESONS (A = 0)
CHARGE
BARYONS (A = +1)
CHARGE
REST MASS (MEV)
SYMBOL
Δ̄ (1,920, 7/2)
Λ̄ (1,815, 5/2)
N̄ (1,688, 5/2)
Ω̄ (1,676, 3/2+)
Σ̄ (1,660, 3/2)
Ξ̄ (1,530, 3/2+)
Λ̄ (1,520, 3/2−)
N̄ (1,512, 3/2)
Λ̄ (1,405,)
Σ̄ (1,385, 3/2+)
Ξ̄ (1,318, 1/2)
Δ̄ (1,238, 3/2+)
Σ̄ (1,193, 1/2+)
Λ̄ (1,115, 1/2+)
N̄ (939, 1/2+)
Δ (1,920, 7/2)
Λ (1,815, 5/2)
N (1,688, 5/2)
Ω (1,676, 3/2+)
Σ (1,660, 3/2)
Ξ (1,530, 3/2+)
Λ (1,520, 3/2−)
N (1,512, 3/2)
Λ (1,405,)
Σ (1,385, 3/2+)
Ξ (1,318, 1/2)
η (1,250, 2+)
Δ (1,238, 3/2+)
Σ (1,193, 1/2+)
Λ (1,115, 1/2+)
(1,020, 1−)
N (939, 1/2+)



BARYONS
Ξ XI
Σ SIGMA
Λ LAMBDA
N (NUCLEON)
Δ DELTA
Ω OMEGA

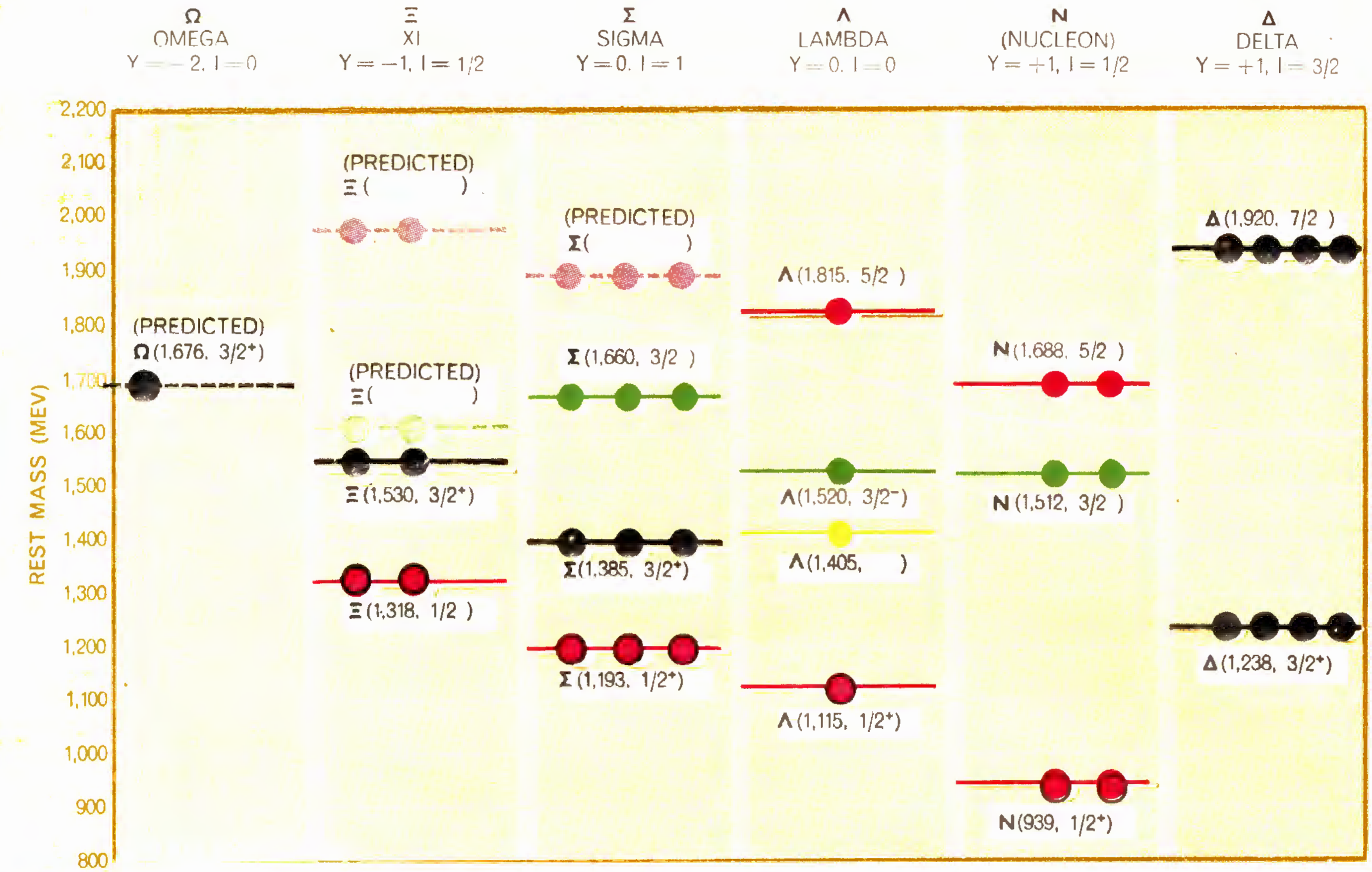
MESONS
η ETA
π PI
κ̄ ANTIKAPPA
κ KAPPA

COLLOQUIAL NAMES
φ PHI
ω OMEGA
ρ RHO

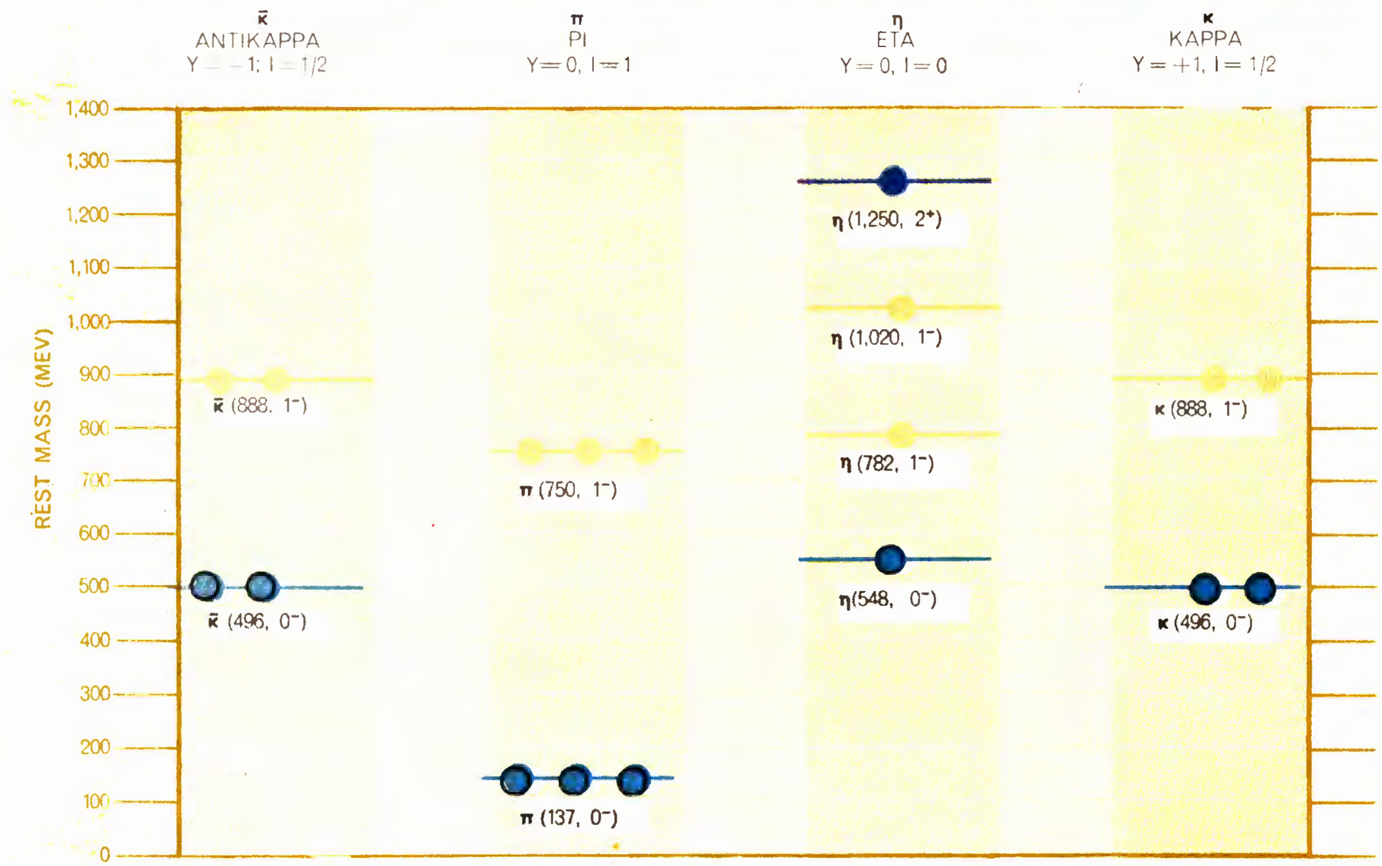
LETTER A = ATOMIC MASS, OR BARYON, NUMBER

PARENTHESES CONTAIN: (REST MASS IN MILLION ELECTRON VOLTS, SPIN ANGULAR MOMENTUM, PARITY)

STRONGLY INTERACTING PARTICLES are presented with a new naming system. The 82 particles and antiparticles in this chart include only those with a rest mass below 2,000 million electron volts (Mev) and with atomic mass number (*A*) of − 1, 0 or + 1. All the particles shown here are known to exist, with the exception of the negative omega baryon, Ω(1,676, 3/2⁺) and its antiparticle, Ω̄(1,676, 3/2⁺). Their existence has been predicted by the "eightfold way." The numbers in parentheses are explained at lower left. The mass assignments are averages for the members of a charge multiplet, or family of states differing only in their electric charge. Multiplets that have the same spin angular momentum (*J*) and parity (*P*) are assigned a common color. The same color is also assigned to "recurrences" of these particles. Recurrences are particles with 2, 4, 6 (and so on) more units of spin than their "ground" states of lowest mass. (Where parity values have not yet been established they have been left blank, but they have been guessed for purposes of color-coding.) Stable and metastable particles are circled in black; unstable particles (also called resonances) are uncircled.



BARYON MULTIPLETS that have the same values of hypercharge (Y) and isotopic spin (I) are arranged in columns. Only six combinations of Y and I are known at present, each identified by an upper-case Greek letter. The particle symbols and color code are those presented on the preceding two pages. Particles above the break in the tan background are recurrences of low-lying states.



MESON MULTIPLETS with like values of Y and I are arranged in columns. Four combinations of Y and I are identified by lower-case Greek letters. No meson recurrences have yet been identified. The first predicted recurrence is a pi triplet at about 1,700 Mev.

bers, or physical quantities, that are conserved in strong interactions.

We shall next describe how these quantities are conserved when particles decay into different "channels," representing different modes of decay. This will lead to a description of "resonances," or unstable particles, which account for most of the proliferation among strongly interacting particles.

We shall then be ready to discuss two classification systems, or rules for the formation of groups, that have brought to light deep-seated family relations among strongly interacting particles. These rules have made it possible to predict the existence of still undiscovered particles, their approximate masses and certain other properties. One system is based on the concept of the "Regge trajectory"; the other is the "eightfold way."

Next we shall explain why the term "elementary" has fallen into disrepute for describing strongly interacting particles. There is growing evidence that all such particles can be regarded as composite structures. Finally we shall describe the "bootstrap" hypothesis, which may make it possible to explain mathematically the existence and properties of the strongly interacting particles. According to this hypothesis all these particles are dynamical structures in the sense that they represent a delicate balance of forces; indeed, they owe their existence to the same forces through which they mutually interact. In this view the neutron and proton would not be in any sense fundamental, as was formerly thought, but would merely be two low-lying states of strongly interacting matter, enjoying a status no different from that of the more recently discovered baryons and mesons and the nuclei of atoms heavier than those of hydrogen.

Forces and Reaction Times

In present-day physics the concepts of force and interaction are used interchangeably. The strong, or nuclear, force is the most powerful of the four basic interactions that, together with cosmology, account for all known natural phenomena. (Cosmology provides the stage on which the forces play their roles.) The strong interaction is limited to a short range: about 10^{-13} centimeter, which is about the diameter of a strongly interacting particle.

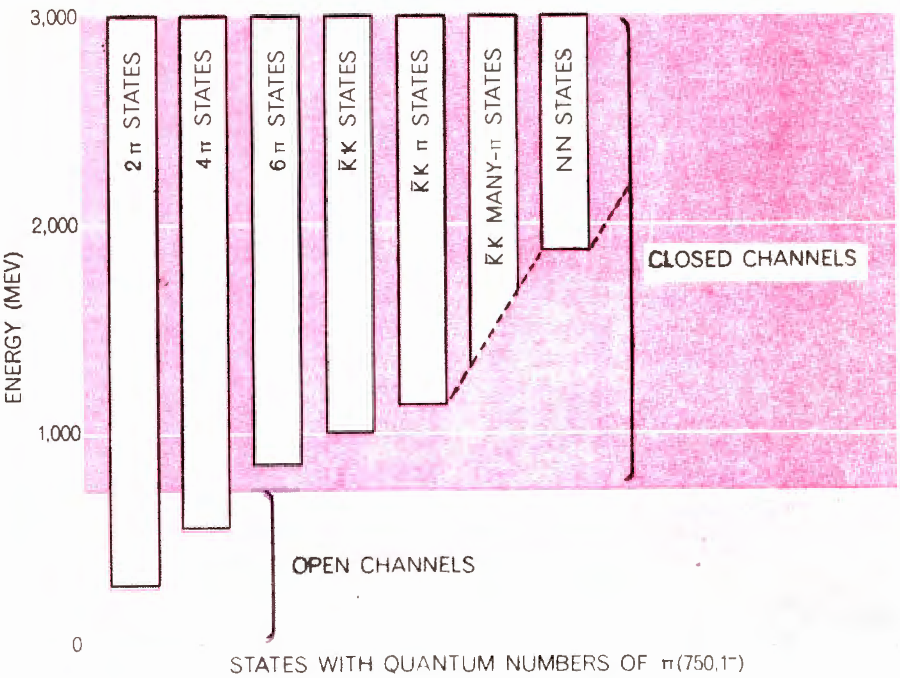
The next force, in order of strength, is the electromagnetic force, which is about 1 per cent as powerful as the strong force. Its strength decreases as the square of the distance between interacting particles, and its range is in principle unlimited. This force acts on all particles with an electric charge and involves the uncharged photon, which is the carrier of the electromagnetic-force field. The electromagnetic force binds electrons to the positively charged nucleus to form atoms, binds the atoms together to form molecules and thus in its manifold workings is responsible for all chemistry and biology.

Next in order, with only about a one-hundred-trillionth (10^{-14}) of the strength of the strong interaction, is the weak interaction. It also has a short range and cannot, as far as anyone knows, bind anything, but it governs the decay of many strongly interacting particles and is responsible for the decay of certain radioactive nuclei. It is most easily studied in the behavior of the four leptons, which do not respond to the strong force.

The fourth and weakest force is gravity, which has only about 10^{-39} of the strength of the strong interaction. It produces large-scale effects because it is always attractive and operates at long range. On the scale of atomic nuclei, however, its effects are undetectable.

Many particles are "coupled" to all four of these interactions. Take, for example, the proton. It is a strongly interacting particle, and since it is electrically charged it must also "feel" the electromagnetic force. It can be created by the beta decay of a neutron, a decay in which the neutron emits a negative electron and an antineutrino by a weak-interaction process; hence it must be involved in weak interactions. And like all other matter the proton is attracted by gravity. The least reactive particle is the neutrino, which is directly coupled only to the weak interaction and to gravitation. The neutrino shares with the other leptons a total immunity to the strong force.

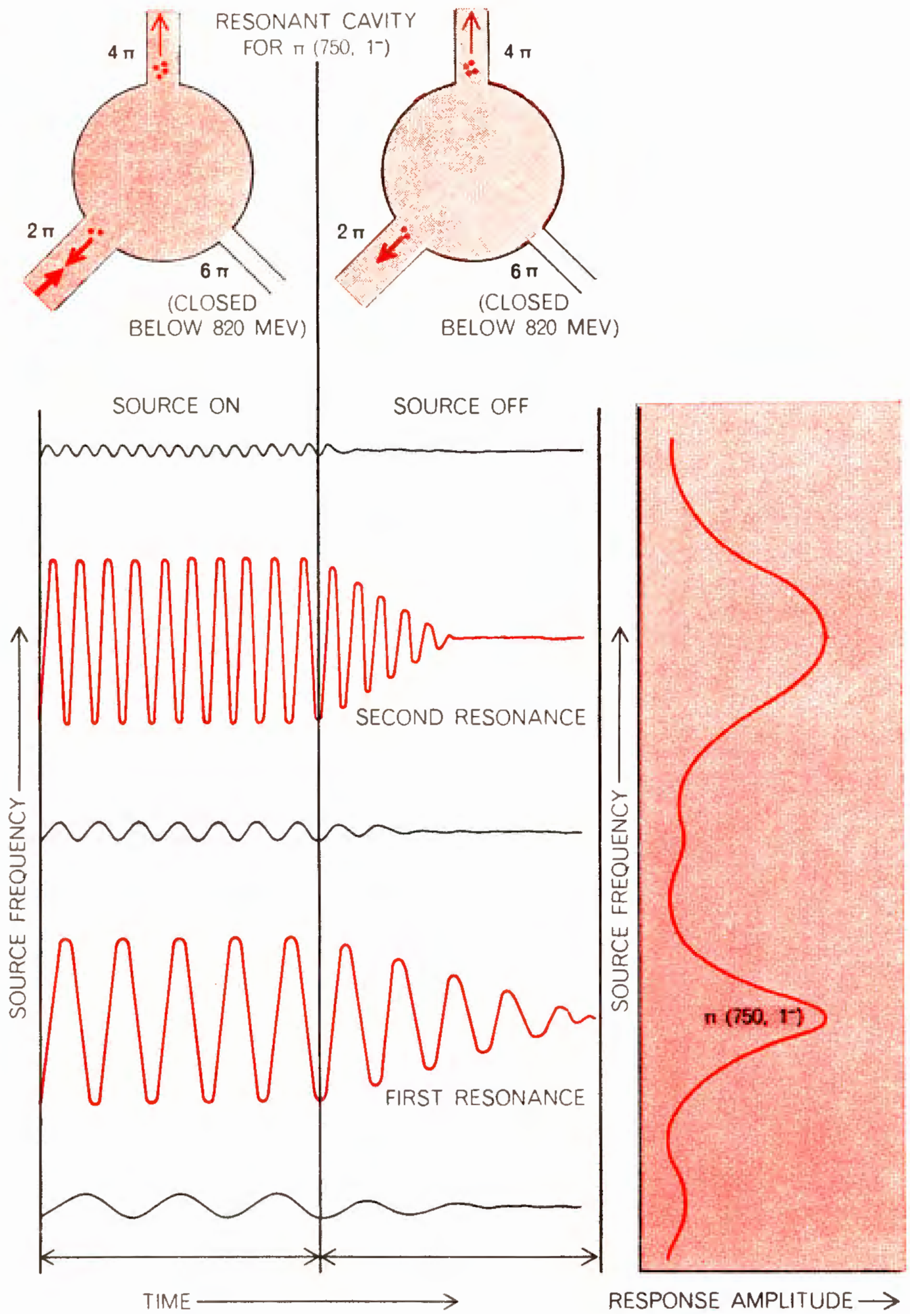
An important idea, not self-evident in the foregoing, is that the basic forces can do more than bind particles together. For instance, when two particles collide and go off in different directions (the phenomenon called scattering), an interaction is involved. If a particle is moving with enough energy before striking a particle at rest, a new particle can be created in the collision. The collision of a proton and a neutron can yield a proton, a neutron and a neutral pion, or it can yield two neutrons and a positive pion. The collision can also yield strongly interacting particles that are more massive than either of the colliding particles. This, in fact, is the process by which particle-accelerating machines have created the scores of new particles heavier than protons and neutrons. Thus the basic forces are



"COMMUNICATING CHANNELS" (*vertical bars*) **are nuclear states that possess all the same quantum numbers as a particular particle, in this case π(750, 1⁻). Channels into which it has sufficient energy to decay are "open" channels. Channels for which it lacks sufficient energy are "closed." The threshold energy for gaining access to a communicating channel is the sum of the rest masses (in Mev) of the various particles constituting the channel.**

interactions that can scatter, create, annihilate and transform particles.

The interactions of principal interest in high-energy physics take place when one of the particles in the interaction is traveling at nearly the speed of light, or more than 10^{10} centimeters per second. Since the size of a particle is typically about 10^{-13} centimeter, the minimum reaction time is less than 10^{-23} second for a particle moving at the speed of light. What we mean when we call the strong interaction "strong" is that even in that brief time the strong force is powerful enough to cause a reaction to take place. Electromagnetic reactions, being 100 times weaker than strong reactions, take around 100 times longer, or typically 10^{-21} second. Processes involving the weak interaction, which is 10^{-14} times weaker than the strong interaction, commonly take about 10^{-9} second.



RESONANT CAVITY analogy accounts for the appearance of unstable particles called resonances. The "cavity" for the $\pi(750, 1^-)$ meson is shown at top with an energy source present (*left*) and removed (*right*). Energy (*colored arrows*) can flow into the cavity through one channel and leave through one or more open channels. The 5π channel, however, is closed because access requires a higher frequency (that is, more energy) than $\pi(750, 1^-)$ possesses. The sinusoidal curves show that at certain frequencies the cavity resonates, and when the energy is turned off, the resonance can persist for several cycles. The first resonance corresponds to $\pi(750, 1^-)$ itself. A second resonance with the same quantum numbers could conceivably exist. The colored curve at right represents the amplitude of the resonant waves when the source amplitude is kept constant and the frequency is varied.

Conservation Laws

When one of the present authors (Gell-Mann) and E. P. Rosenbaum discussed particles in these pages not quite seven years ago [see "Elementary Particles," Scientific American, July, 1957], 30 well-established particles and antiparticles were singled out for attention. In this collection there were 16 baryons and antibaryons, seven mesons, six leptons and antileptons and the photon [*see illustration on page 75*]. At that time it was customary to classify as elementary not only the photon and the leptons but also all the baryons and mesons—the strongly interacting particles.

A distinction, which we now regard as unjustified, was drawn between these strongly interacting particles and the states of ordinary atomic nuclei containing two or more nucleons, which, of course, are also strongly interacting. These nuclei, such as the deuteron (the nucleus of heavy hydrogen) and the alpha particle (the nucleus of helium), had been classified as composite structures, made essentially of protons and neutrons, almost from the beginning of nuclear physics because of the small binding energies involved in them. This article will place little emphasis on such nuclei. We shall concentrate on the lighter particles, not because we believe them to be more elementary than their heavy brothers but because their status is still in doubt. If they are in fact composite dynamical structures, their binding energies are often enormous. Furthermore, if elementary particles do exist, they will certainly not include the obviously composite nuclei.

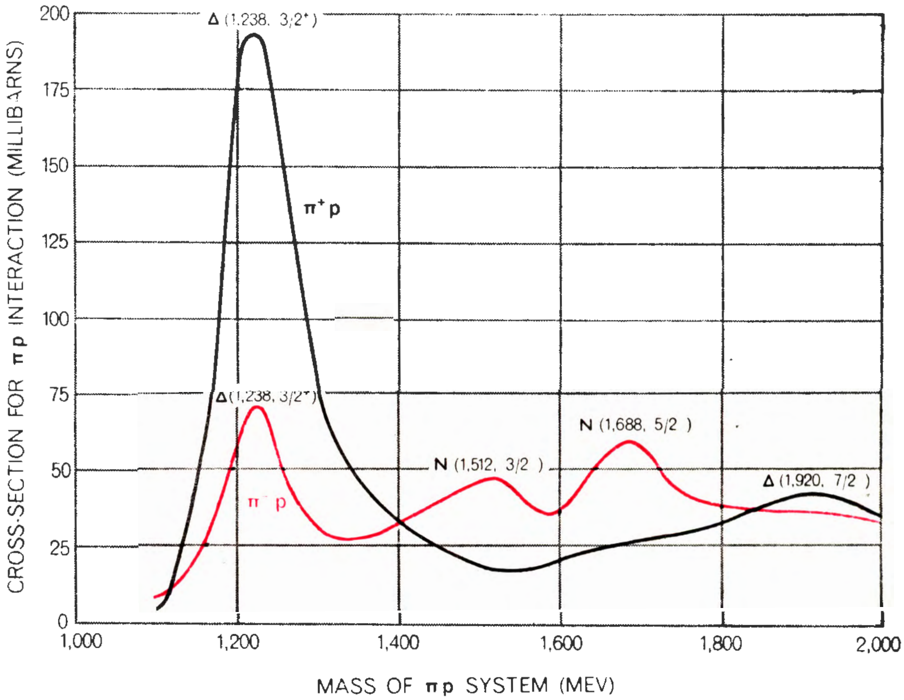
The chart on pages 76 and 77, which omits the photon and leptons, shows 82 particles and antiparticles, all of them strongly interacting, and the list has been arbitrarily limited to baryons and mesons with a rest mass less than 2,000 Mev. Most of the 82 particles belong to family groups that have acquired pet names comparable to, but usually less elegant than, the names given to those in the 1957 list. It would be unreasonable to expect the reader to master this specialized vocabulary, which reflects chiefly the confused state of high-energy physics a few years ago. We shall therefore introduce the reader to a new system of nomenclature that has developed quite recently and that provides a great deal of information about each particle. Although it may look forbidding at first sight, it is really no harder to master than the telephone company's all-digit dialing system.

The new classification scheme takes advantage of the fact that nature conserves many quantities (in addition to energy and momentum) and shows various symmetries (such as that between left and right). As a result groups of particles have similar properties, which, as we shall see, can be indicated by a common notation. There is a close relation between symmetries and conservation laws, and in a particular case one can refer either to a symmetry or to the associated conservation law, whichever is more convenient. The conserved quantity appears in quantum mechanics as a quantum number, which is often either an integer (such as 0, 1, 2, 3 and so on) or a half-integer (such as 1/2, 3/2, 5/2 and so on).

Some conservation laws appear to be universal: they are obeyed by all four basic interactions. This inviolable group includes the conservation of energy, of momentum, of angular momentum (the momentum associated with rotation) and of electric charge. Another exact conservation law is best described as a kind of mirror-image symmetry. It is the symmetry between particles and antiparticles, in which whatever is left-handed for one is right-handed for the other. For each particle there is an antiparticle with the same mass and lifetime but with some properties, such as electric charge, reversed. Some neutral particles, such as the photon and the neutral pion, are their own antiparticles.

In the new system for naming strongly interacting particles we shall make use of five quantities, each indicated by a letter symbol, that are conserved by the strong interactions but not necessarily by the electromagnetic or weak interactions. These five quantities are: atomic mass number (*A*), hypercharge (*Y*), isotopic spin (*I*), spin angular momentum (*J*) and parity (*P*). The chart on the next page should help the reader to keep these five quantum numbers in mind as we discuss them in more detail. Also included in the chart are two other quantities that are conserved by strong interactions but that are not essential to the naming system: electric charge (*Q*) and a quantity called G that has only two values, $+1$ and -1, and can be assigned only to mesons that have a hypercharge of 0.

The first three quantum numbers—*A*, *Y* and *I*—provide the basis of the naming system. What these three numbers do, in effect, is to describe the geometric pattern of the particles as they are arranged in the chart on pages 76 and 77. There it will be seen that mesons and baryons occur in "charge multiplets," or families of states differing only in their electric charge. The number of particles and their charges occur in different patterns: singlets, doublets, triplets and quadruplets. Only 10 different patterns are known or predicted at present, and each pattern represents a different set of values for *A*, *Y* and *I*. As we shall explain, each of the 10 patterns is identified by a different Greek letter.



FIRST RESONANCE, the unstable particle called Δ(1,238, 3/2+), was discovered by Enrico Fermi and his colleagues in 1952. The resonance appears when protons are bombarded with high-energy pions. When the interaction "cross section" is plotted against the effective mass of the pion-proton system, a peak is found at around 1,238 Mev. The peak is much larger for the π^+p interaction than for the π^-p interaction. Other resonances occur at 1,512, 1,688 and 1,920 Mev, each peak corresponding to an unstable particle.

Now we shall describe the physical significance of *A*, *Y*, *I*, *J* and *P*, but for convenience we shall discuss them in a slightly different order to emphasize certain relations among them. *A* is simply the long-familiar atomic mass number used to describe atomic nuclei. It is also known as baryon number. Like electric charge, *A* can be 0, ± 1, ± 2, ± 3 and so on. For uranium 235, *A* is 235, indicating that the nucleus of this isotope contains 235 neutrons and protons, for each of which *A* equals 1. Neutrons and protons are baryons and, by definition, so are all other particles with an *A* of 1. Particles with an *A* of -1 are antibaryons. Mesons have an *A* of 0 (as do the leptons and the photon). The law of baryon conservation states that the total value of *A*, like electric charge, can never change in a reaction. Baryons cannot be created or destroyed, except when a baryon-antibaryon pair annihilate each other or are created together.

The second conserved quantity is *J*, or spin angular momentum, which measures how fast a particle rotates about its axis. It is a fundamental feature of quantum theory that a particle can have a spin of only integral or half-integral multiples of Planck's constant. (This constant, $\hbar$, relates the energy of a quantum of radiation to its wavelength: energy equals 2π times frequency times $\hbar$.) For baryons *J* is always half-integral (that is, half an odd integer, such as 1/2, 3/2, 5/2 and so on) and for mesons *J* is always integral (that is, 0, 1, 2 and so on).

The third conserved quantity, closely associated with *J*, is *P*, or intrinsic parity. Parity is conserved when nature does not distinguish between left and right. Because such symmetry is observed in strong interactions, quantum mechanics tells us that an intrinsic parity value of $+1$ or -1 can be assigned to each strongly interacting particle. In the case of weak interactions, however, nature does distinguish between left and right, and the symmetry is violated.

The bookkeeping on parity is not quite so simple as that for electric charge and baryon number; the intrinsic parity values on each side of an equation are not necessarily the same. The reason is that the total parity is affected by spin angular momentum as well as by intrinsic parity. The close connection between parity and spin angular momentum makes it convenient to write the spin angular momentum quantum number J and the intrinsic parity P next to each other in describing each particle. For the proton, for example, J equals 1/2 and P equals + 1, which is shortened to J^P equals $1/2^+$. For the pion J equals 0 and P is − 1, so that one writes J^P equals 0^-. (The system of bookkeeping for J is actually quite complicated in quantum mechanics, but the details need not concern us here.)

The fourth quantity conserved in strong interactions is I, or isotopic spin. This quantum number has nothing to do with spin or angular momentum, except that its peculiar quantum-mechanical bookkeeping is similar to that for J. The concept of isotopic spin was originally introduced into quantum mechanics to accommodate the fact that the nucleon exists in two charge states: one positively charged (the proton) and the other neutral (the neutron). As far as strong interactions are concerned, these two states behave alike; they are related to each other by the symmetry of isotopic spin. Moreover, if the symmetry were observed by the electromagnetic interaction, the proton and the neutron would have the same mass. Precisely because isotopic-spin symmetry is violated by the electromagnetic interaction the neutron is 1.3 Mev (or .14 per cent) more massive than the proton.

A set of particles or particle states (we use the terms interchangeably) related to each other by isotopic-spin symmetry is a charge multiplet and is given a single name. Thus the nucleon doublet consists of the two charge states, positive and negative. The pion triplet consists of negative, neutral and positive charge states. The number of different charge states in a multiplet, or its "multiplicity" (M), is directly related to the isotopic-spin quantum number I by the equation $M = 2I + 1$. For the nucleon M equals 2 and I equals 1/2; for the pion M equals 3 and I equals 1.

The fifth conserved quantity goes by any of three names: average charge ($\bar{Q}$), hypercharge (Y) or strangeness (S), which are related to each other in a simple way. Average charge is just what its name implies: the average of the electric charges in a multiplet. Hence for the nucleon it is 1/2 (0 plus 1 divided by 2); for the pion it is 0. Hypercharge is defined as twice the average charge (Y equals $2\bar{Q}$) merely to make it an integral number. And strangeness is hypercharge minus the baryon number (S equals Y minus A). It is clear that the three quantities are in effect interchangeable.

The concept of strangeness and its conservation is only 11 years old. In the early 1950's certain particles such as the K, the sigma and the xi were being observed for the first time, and because of their unusual behavior they were referred to as "strange particles." Most of them have relatively long lifetimes, which indicates that they decay by the weak interaction rather than by the electromagnetic or strong interaction. On the other hand, they are readily produced in high-energy collisions of "ordinary" particles (pions and nucleons), which proves that the strange particles too are strongly interacting. When invariable behavior patterns of this sort are observed, the

CONSERVED QUANTITY	SYMBOL	OBSERVED VALUES	DESCRIPTION	EXAMPLES proton	EXAMPLES negative pion
ELECTRIC CHARGE	Q	0, ±1, ±2, ±3 . . .	Represents the number of electric-charge units carried by a particle, or atomic nucleus, in units of the positive charge on the proton. Charge multiplets, such as the neutron-proton doublet or the pion triplet, can be assigned an average charge, $\bar{Q}$.	Q = +1 $\bar{Q}$ = +1/2	Q = −1 $\bar{Q}$ = 0
ATOMIC MASS NUMBER OR BARYON NUMBER	A	0, ±1, ±2, ±3 . . .	Represents the familiar atomic mass number long used for nuclei. For uranium 235, A = 235. For baryons, A = +1; for antibaryons, A = −1; for mesons, A = 0.	A = +1	A = 0
HYPERCHARGE (Related to average charge, $\bar{Q}$, and to strangeness, S)	Y	−2, −1, 0, +1	Defined as twice the average charge, $\bar{Q}$, of a multiplet. Strangeness, S, is hypercharge minus the atomic mass number (S = Y − A).	Y = +1 S = 0	Y = 0 S = 0
ISOTOPIC SPIN (Related to multiplicity, M)	I	0, 1/2, 1, 3/2	Groups nuclear states into multiplets whose members differ only in electric charge. The number of charge states, or multiplicity, M, is related to I by the equation M = 2I+1.	I = 1/2 M = 2	I = 1 M = 3
SPIN ANGULAR MOMENTUM	J	1/2, 3/2, 5/2 . . . 0, 1, 2, 3 . . .	Indicates how fast a particle rotates about its axis, expressed in units of Planck's constant, ℏ.	J = 1/2	J = 0
PARITY	P	−1, +1	An intrinsic property related to left-right symmetry.	P = +1	P = −1
G	G	−1, +1	An intrinsic property found only in mesons with zero hypercharge.	not defined	G = −1

CHART OF QUANTUM NUMBERS shows seven quantities conserved by the strong interaction but not necessarily by the electromagnetic or weak interaction. The three quantities in color (*A, Y, I*) are easily established by experiment and provide the basis for assigning a family name to each particle. Only 10 combinations of *A, Y* and *I* are now known, each represented by a Greek letter.

physicist suspects that a conservation law (or symmetry) is at work. One of the authors of this article (Gell-Mann) and the Japanese physicist Kazuhiko Nishijima independently proposed that a previously unsuspected quantity (strangeness, or hypercharge) is conserved in strong and electromagnetic interactions but violated by weak interactions. The hypothesis made it possible to predict the existence and general properties of several strange particles before they were discovered.

The New Nomenclature

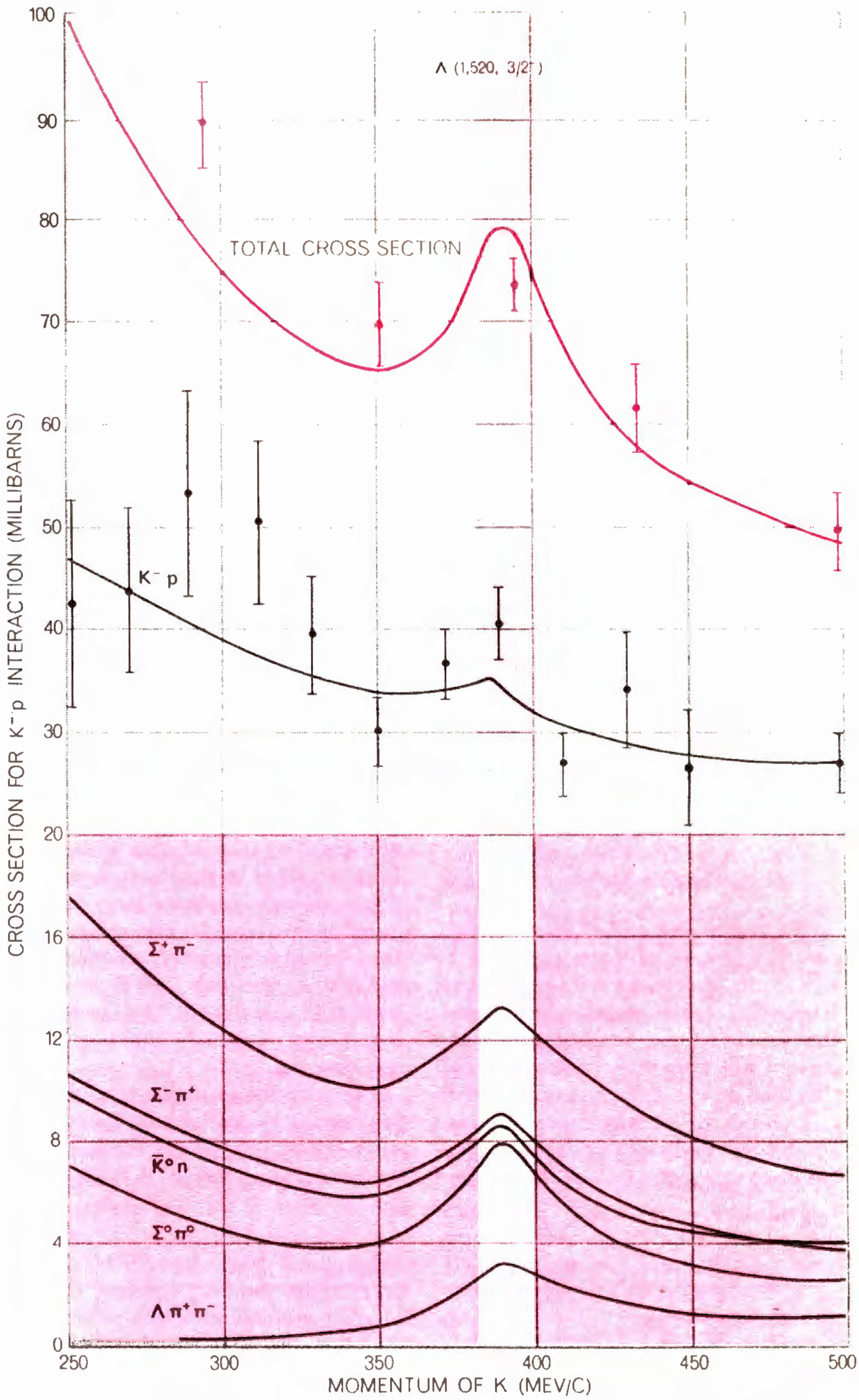
We are now ready to describe how the five quantum numbers can provide the basis for a new naming system. By appropriate selection of three of the five quantum numbers we can indicate immediately whether a strongly interacting particle is a baryon or a meson, how many members it has in its immediate family (that is, its multiplicity) and what its degree of strangeness is. The three quantum numbers that provide this information are the atomic mass, or baryon, number A, the hypercharge Y and the isotopic spin I. (It will be recalled that Y is directly related to strangeness and I to multiplicity.)

Now, partly as a mnemonic aid and partly out of respect for the old pet names, we shall employ a letter symbol to indicate various combinations of A, Y and I. To designate the known mesons, particles for which A is 0, it is sufficient to use four lower-case Greek letters: η (eta), π (pi), κ (kappa) and $\bar{\kappa}$ (antikappa, or kappa bar). The chart at the bottom of the next page shows the Y and I values for each symbol. Even though the multiplicity M can be found simply by doubling I and adding 1, it is shown separately for easy reference.

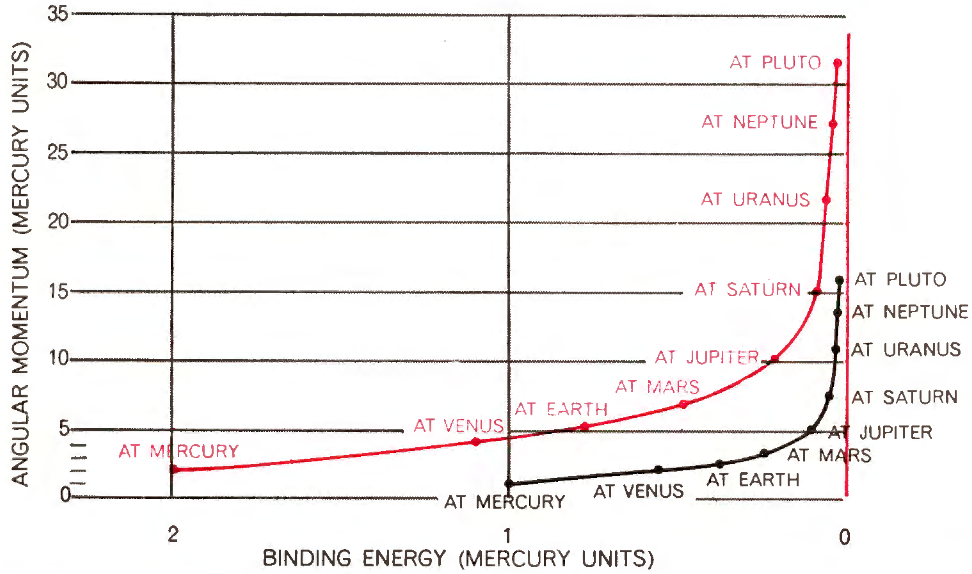
To designate baryons, for which A is 1, we will use the following upper-case Greek letters: Λ (lambda), Σ (sigma), N (which stands for the nucleon and is pronounced "en," not "nu"), Ξ (xi), Ω (omega) and Δ (delta). The values of Y, I and M for each symbol are also shown at the bottom of the next page.

These 10 symbols encompass all the kinds of meson and baryon states that are known at the present time. In other words, any of the 82 particles in the chart on pages 76 and 77 can be designated by one of these 10 symbols. The difference between the old naming system and the new one should now be apparent. In the old system, shown in the chart on page 75, the symbol π, for example, represented only a single family of three particles with a rest mass of 137 Mev. In the new system π represents both that group and a new group of three, with identical A, Y and I but with a rest mass of 750 Mev. Similarly, in the old system N stood only for the nucleon doublet with a mass of 939 Mev. In the new system N stands for the nucleon and for two higher energy states, also doublets, one with a mass of 1,512 Mev and one with a mass of 1,688 Mev. Thus the old particle names now stand for classes of particles with the same A, Y and I.

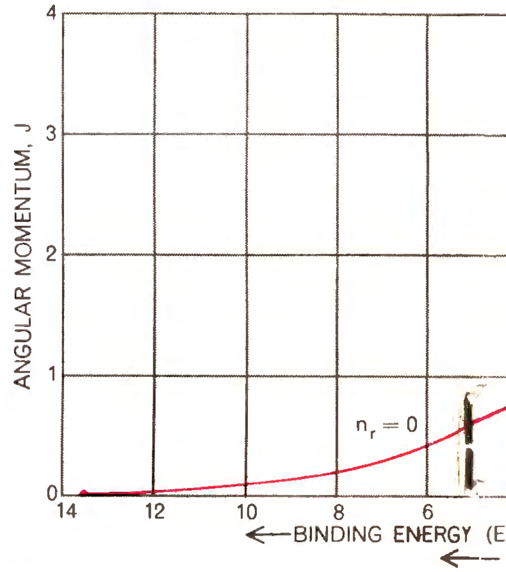
Various members of a class can be



MULTIPLE DECAY MODES of Λ(1,520, 3/2⁻) show that the baryon Λ is connected to six open channels. The Λ is created when K⁻ mesons [κ(496)] are scattered on protons. The total interaction cross section shows a peak corresponding to the formation of Λ(1,520, 3/2⁻), which speedily decays into one of the six channels indicated. Thus the curve labeled K⁻p represents the over-all reaction: K⁻p → Λ ↔ K⁻p. Thousands of bubble-chamber "events" *(see cover)* supplied data for the curves. Data points are given only for the top two.



"REGGE TRAJECTORIES," an important concept for predicting recurrences, can be explained with a spaceship analogy. If one-ton spaceships were placed in circular orbits around the sun at the distance of each of the nine planets, the ships would have the binding energies and angular momenta indicated. The black curve drawn through these values is a Regge trajectory. The colored curve is a Regge trajectory for a two-ton spaceship.



TRAJECTORIES FOR HYDROGEN resemble those for a spaceship. The hydrogen atom, made up of an electron "circling" a proton, can exist in various states of excitation. For each value of a certain quantum

distinguished by writing the mass value in parentheses after the name, for example $\pi(137)$ or $\pi(750)$; or by writing the angular momentum J and the parity P in parentheses, for example $\pi(0^-)$ or $\pi(1^-)$. Or, if desired, mass, J and P can all be shown: $\pi(137,\ 0^-)$ or $\pi(750,\ 1^-)$. In the following discussion an unadorned symbol will refer to the lowest mass state in the class. The new classification system is exhibited in the baryon and meson charts on page 78.

Particle Stability

We mentioned earlier that particles can decay in one of three ways: via the strong, the electromagnetic or the weak interaction. A few particles (the photon, the two neutrinos, the electron and the proton) are absolutely stable provided that they do not come into contact with their antiparticles, whereupon they are annihilated. Particles that decay through the electromagnetic or weak interaction are said to be metastable. Those that decay through the strong interaction are called unstable and have very short lifetimes, typically a few times 10^{-23} second. This is still a considerable length of time, however, compared with less than 10^{-23} second, which is the characteristic time required for a collision between high-speed particles.

Unstable particles are those with enough energy to decay into two or more strongly interacting particles without violating any of the conservation laws respected by the strong interaction. Some unstable particles have only one possible decay mode; others have more than one. As an example of the former, $\Xi(1{,}530)$ decays only into Ξ and π. On the other hand, $\Lambda(1{,}520)$ can decay into Σ and π, into N and $\bar{\kappa}$ or into Λ and two π's.

How can the existence of several decay modes be explained? This can be answered by introducing the concept of "communicating states." A nuclear state can be either a single particle or a combination of two or more particles. We have seen that each particle has definite values of the conserved quantum numbers A, Y, I, J, P and, where applicable, G. The strong interaction allows transitions, or communication, only among nuclear states with the same values for all the conserved quantum numbers.

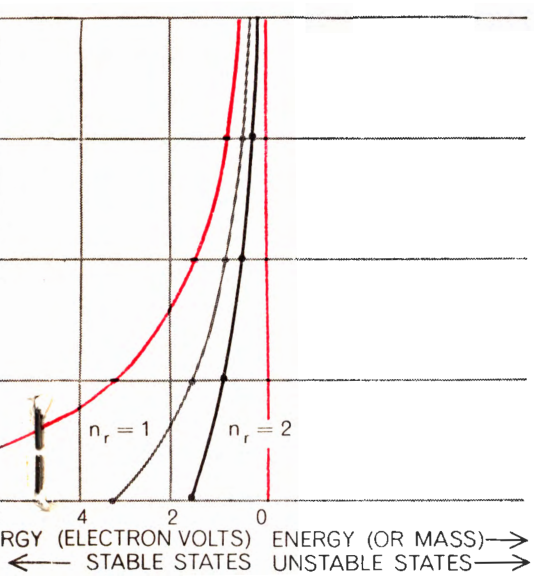
Now, one can write down many nuclear states, consisting of two or more particles, that have in the aggregate the same set of quantum numbers as any particular unstable particle. For decay to take place, however, the unstable particle must have a rest mass at least equal to the threshold energy (that is, the sum of the rest masses) of the particles into which it might conceivably decay. In other words, energy must be conserved. The various states into which an unstable particle has sufficient energy to decay are called open channels. Communicating states with threshold energies greater than that available to the unstable particle are called closed channels; decay into them is allowed by everything *but* conservation of energy. A schematic representation of some of the channels that communicate with $\pi(750,\ 1^-)$ is shown on page 79.

This leads us to the concept of "resonance," the term originally applied to unstable particles. The first of these was discovered in 1952 at the University of Chicago by Enrico Fermi and his colleagues. At the time no one suspected that a deluge was to follow.

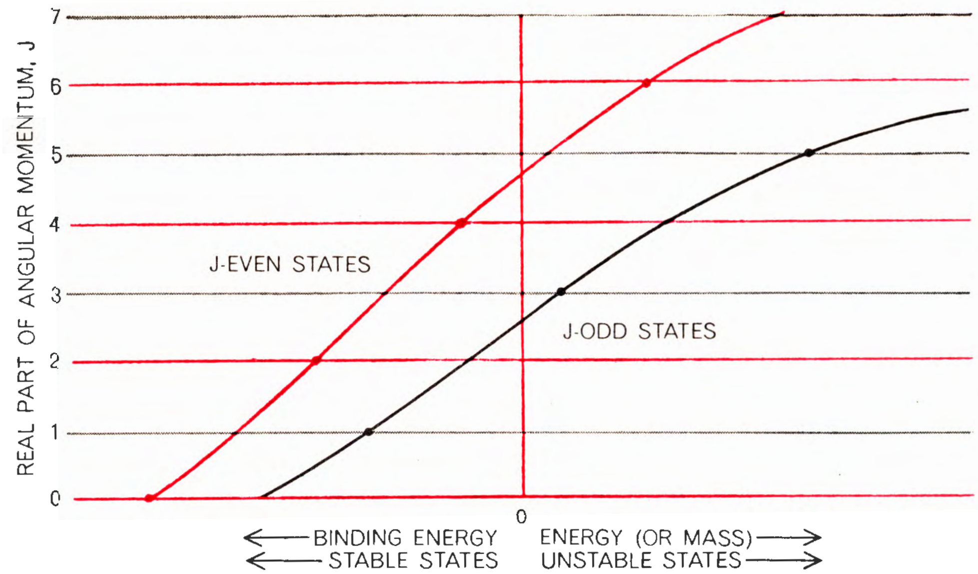
MESONS	Y	I	*M*
η	0	0	*1*
π	0	1	*3*
κ	+1	1/2	*2*
$\bar{\kappa}$	−1	1/2	*2*

BARYONS	Y	I	*M*
Λ	0	0	*1*
Σ	0	1	*3*
N	+1	1/2	*2*
Ξ	−1	1/2	*2*
Ω	−2	0	*1*
Δ	+1	3/2	*4*

SYMBOLS FOR MESONS AND BARYONS are Greek letters. For mesons atomic mass number *A* is 0; for baryons it is 1. The 10 letters identify the 10 known combinations of mass number (*A*), hypercharge (*Y*) and isotopic spin (*I*). Multiplicity (*M*) is related to *I*.



number (n_r) the binding energies of the hydrogen states decrease with increasing values of angular momentum (J). Smooth curves drawn through these states (each a different "particle") are Regge trajectories.



TRAJECTORIES FOR STRONGLY INTERACTING PARTICLES resemble those at left except that they include unstable states. An intersection with J in the stable region indicates the existence of a stable or metastable particle. Intersections in the unstable region indicate an unstable particle. Trajectories connect particle states separated by two full units of J. Lowest state is an "occurrence"; higher states are "Regge recurrences."

In the 1952 experiments pions from the University of Chicago cyclotron were directed at protons (in liquid hydrogen) and the scattering cross section was measured for different energies of the pion beam. Scattering refers to the change of direction when two particles collide; the scattering cross section is the probability that scattering will occur. When the probability is large, the two particles act as if they were big, with a large cross section.

For each setting of the pion beam the "effective" mass of the pion-proton system is calculated. The effective mass is the sum of the rest masses and the kinetic energies of all the particles in a system, as viewed from the system's center of mass. When the effective mass is plotted along one co-ordinate of a graph and the scattering cross section along the other, it is found that the cross section peaks sharply when the system has an effective mass of about 1,238 Mev. It is through this peak that the resonance was detected. We shall discuss below the connection between the peak and the resonance, or unstable particle, that is called Δ(1,238) in our new notation.

The University of Chicago cyclotron could not create pion-proton systems with an effective mass of much more than 1,300 Mev. Subsequently, with more powerful accelerators, it was found that pion-proton scattering produces a whole series of resonances. The illustration on page 81 shows two resonances created when positive pions are scattered by protons and, in a separate curve, four resonances created when negative pions are scattered by protons. The first two resonances are Δ(1,238, $3/2^+$) and Δ(1,920, 7/2). The same two should also show up in negative pion scattering, but in the actual experimental curve for the negative pion the upper one, Δ(1,920, 7/2), is hardly observable. We do see, however, two other resonances, N(1,512, 3/2) and N(1,688, 5/2), that cannot contribute to the scattering of positive pions by protons. (A space in the parentheses following the half-integer value of J indicates that the parity of the particle has not yet been established.)

Although Δ(1,238) decays mainly into one pion and a nucleon, the higher resonances can also decay into two or more pions and a nucleon. Most resonances can decay in more than one way; that is, they can communicate with several open channels [*see illustration on page* 83].

To explain how an unstable particle can communicate with several open channels we have found it helpful to draw an analogy between the behavior of unstable particles and the behavior of resonant cavities such as organ pipes and electromagnetic cavities. Cavities of the latter sort (such as the magnetron tube employed in radar) are used in electronics to create intense electromagnetic waves of a desired frequency, which is a resonant frequency of the cavity. Each cavity has a characteristic "lifetime": the time required for the electromagnetic radiation to leak out.

In quantum mechanics, particles and waves are complementary concepts, and the amount of energy associated with a particle, or nuclear state, can be expressed as an equivalent frequency. In other words, energy is proportional to frequency. The fact that the Δ particle appears when a pion is scattered by a proton at or near a certain energy—the resonance energy—is equivalent to saying that the particle appears at a certain frequency. Thus a resonance energy in particle physics can be compared to the resonance frequency of an acoustic or electromagnetic cavity. What is the "cavity" in particle physics? It is an imaginary structure: one cavity, each with its own special properties, for each set of values of the quantum numbers conserved in strong interactions.

The analogy between unstable particles and the resonant modes of electromagnetic cavities can be carried further. To the electromagnetic cavity one can attach the long pipes known as wave guides, which have the property of efficiently transmitting electromagnetic waves of high frequency but not those of low frequency. When the electromagnetic wavelength is slightly larger than the dimensions of the wave guide, the guide refuses to transmit. In this sense the wave guide acts like a particle channel that is open only above its characteristic threshold energy. If a cavity has attached to it several wave guides of different sizes, high-frequency radiation can flow into the cavity through one guide and flow out through the same or different guides.

By analogy energy can flow into a nuclear interaction through one channel and pass out through one or more open channels. As the energy (frequency) is increased from low values, the channels open up one by one and new nuclear reactions become possible, with energy going out through any of the open channels. Now, as the frequency is increased, suppose it passes through a resonance frequency of the nuclear cavity. At this point it becomes easier for the cavity to absorb and reradiate energy. The resonance appears as a peak in the scattering cross section of a nuclear reaction. In other words, a resonant mode of the cavity corresponds to an unstable particle, such as Δ or π(750).

Just as an electromagnetic cavity that is near resonance holds on to electromagnetic energy for a long time, so the unstable particle typically takes somewhat more than the characteristic time of less than 10^{-23} second to decay. If energy is fed into the cavity through one pipe, stays in the cavity for a while because of resonance and comes out again through the original pipe, that corresponds to a scattering collision between two π(137) particles that produce the unstable particle π(750), which finally decays again into the original particles. Alternatively, the energy can emerge through another pipe, which corresponds to the case in which π(750) decays into four π(137) particles. These, of course, are only two of many examples. The cavity and wave guide analogies are illustrated on page 80.

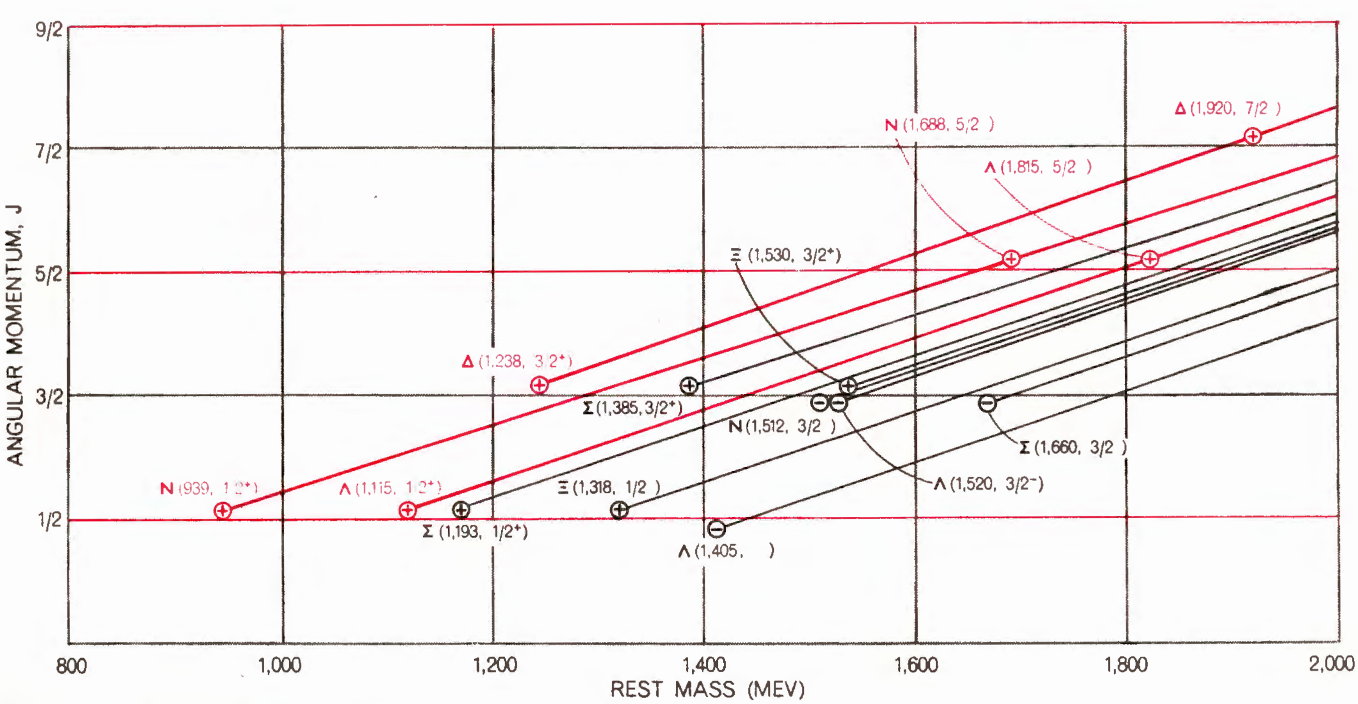
One can use the wave guide analogy to describe not only unstable particles but also stable ones. A stable particle is merely one that has such a low mass that all the communicating channels are closed. Therefore it is a "bound" state rather than a scattering resonance. For an electromagnetic cavity this condition would correspond to a resonant mode whose frequency is below the threshold frequency of all the wave guide outlets. If radiation could be put into the cavity in such a mode, it could not leak out. Of course, an actual cavity would eventually lose radiation by leakage into and through its walls. Such leakage corresponds to the decay of metastable particles via the weak and electromagnetic reactions. An absolutely stable particle really does live forever.

The reader who is unfamiliar with the phenomenon of resonance in electromagnetic cavities may be wondering if we have simplified his task by introducing the electromagnetic analogy. Would it not be just as easy to explain resonances in particle physics directly? Possibly so. But by drawing attention to similar behavior in two apparently different fields we hope we have illustrated a unity in physics that may make particle behavior seem less esoteric. The more basic value of the analogy, however, is that it has helped theorists to understand some deeper points in particle resonances than we have been able to talk about here.

Regge Trajectories

As the strongly interacting particles proliferated, physicists sought to find patterns that would show relations among them. In particular they tried to find classification systems that might predict new particles on the basis of those already known. The first concept to prove useful in this respect developed from an idea introduced into particle physics in 1959 by the Italian physicist Tullio Regge. The concept already had counterparts throughout quantum physics, notably in the study of atomic- and nuclear-energy levels.

It had been observed that as particles increase in mass they frequently (but not invariably) exhibit a higher value of spin angular momentum *J*. Regge pointed out the existence, in many important cases, of a mathematical relation between the value of *J* and particle mass. He showed that certain properties of particles can be regarded



REGGE TRAJECTORIES FOR BARYONS are shown for 14 well-established baryons with mass less than 2,000 Mev. Slanting colored lines connect three occurrences with their Regge recurrences. For baryons spin angular momentum (*J*) is half-integral (1/2, 3/2, 5/2 and so on). Recurrences must have 2, 4, 6 and so on more units of spin than their ground states (occurrences) of lowest mass. Spins for Λ(1,815, 5/2) and Δ(1,920, 7/2) are uncertain, but they probably satisfy this requirement. Slanting black lines show the probable Regge trajectories for other baryons. Circled symbols indicate parity; where not yet established, it has been guessed.

as "smooth" mathematical functions of J, that is, functions that vary continuously as J varies. But since in quantum mechanics J can have only integral and half-integral values, the functions have direct physical meaning only for those permitted values. The smooth mathematical curve that gives the physical mass for different values of J is called a "Regge trajectory."

A spaceship analogy may help to clarify the concept of the Regge trajectory. Suppose in the nearly circular orbit occupied by each of the sun's nine planets one were to place a one-ton spacecraft. These craft circle the sun as if they were miniature planets. The nearer a craft is to the sun, the more strongly it "feels" the sun's gravitational force and the more strongly it is bound. This binding energy, therefore, is highest for the craft in Mercury's orbit and least for that in Pluto's orbit. (The binding energy is just that amount needed to release the craft from the sun's attractive force.)

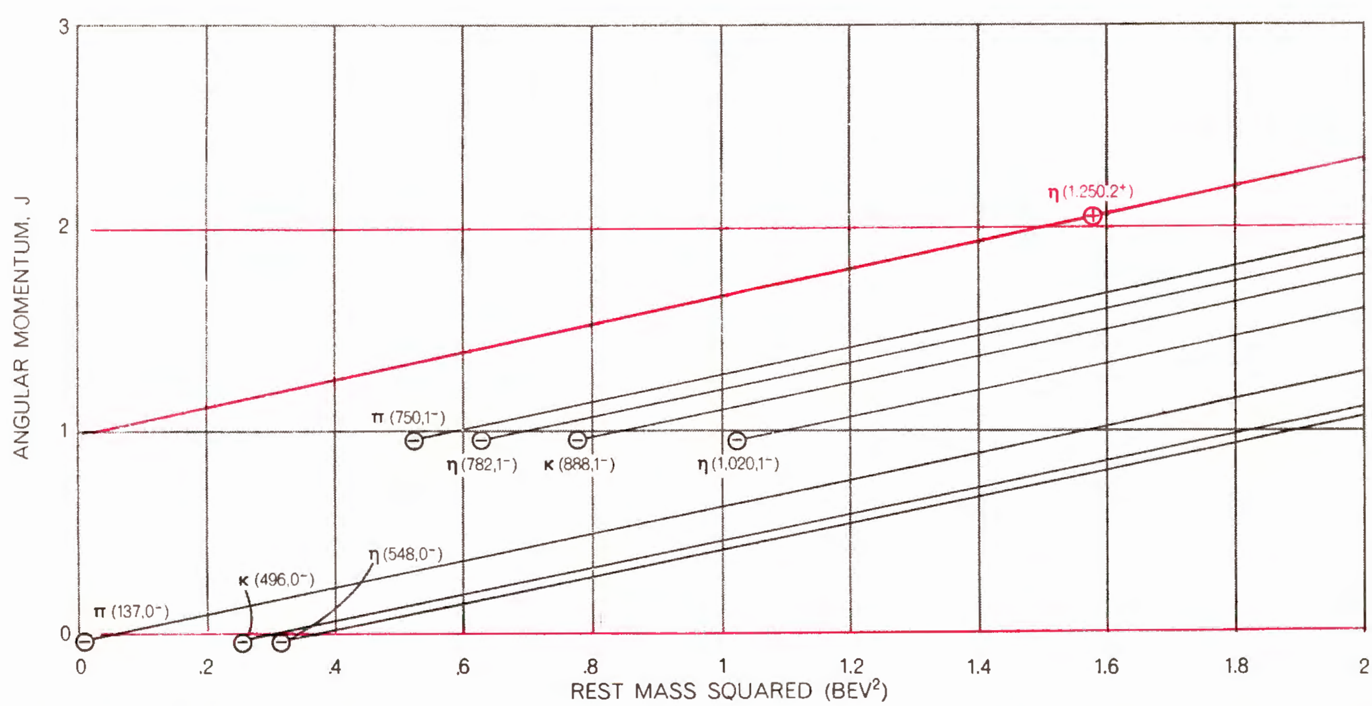
Each craft can be assigned another quantity that also varies with its distance from the sun: angular momentum. It frequently happens in physics that, other things being equal, the greater the binding energy, the smaller the angular momentum. In our example this means that angular momentum increases with the distance from the sun. One can now draw a graph for the nine spacecraft in which angular momentum is plotted on the vertical axis and binding energy on the horizontal axis [*see illustration at top left on page 84*]. The curve drawn through the plotted points is analogous to a Regge trajectory.

Now, suppose quantum mechanics were to have a controlling effect on the macroscopic scale of spacecraft and solar orbits. Suppose, that is, the angular momentum of the spacecraft in Mercury's orbit represented an elementary quantum of spin. If such were the case, a one-ton craft would be allowed to occupy only those orbits in which the angular momenta (expressed in Mercury units) assumed integral values. This is equivalent to saying that a one-ton craft in a circular orbit could exist only at certain energy levels. The Regge trajectory for the spaceship would then be physical only at these points. Another Regge trajectory could be drawn for a two-ton spacecraft. In any given circular orbit its binding energy and angular momentum would be twice that of a one-ton spacecraft.

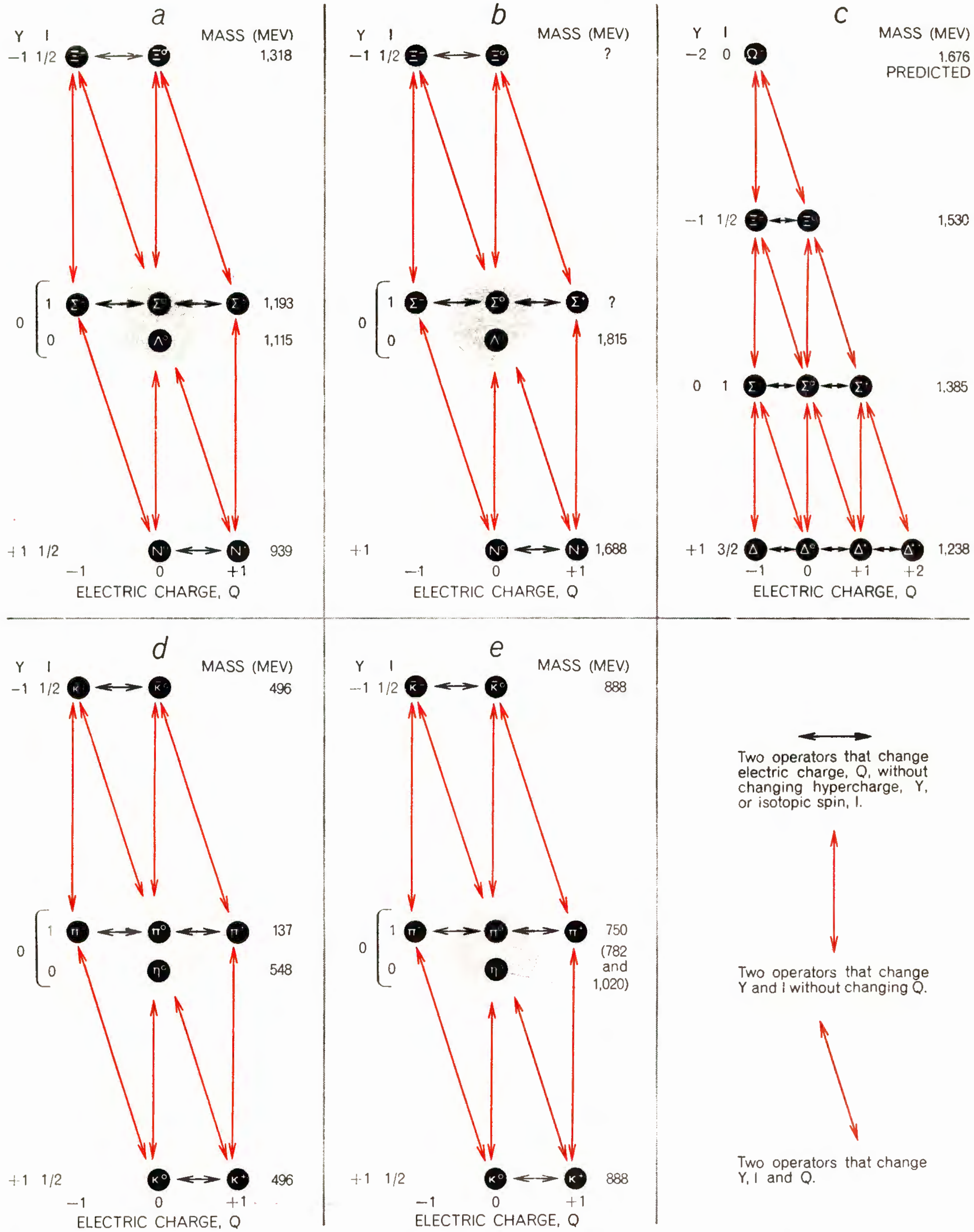
Although it was not used by physicists until recently, the notion of a Regge trajectory applies to problems long familiar in atomic physics. It is well known, for example, that the electron-proton system constituting the hydrogen atom can exist in various states of excitation. The electron can occupy various orbits around the proton, just as the spaceship could occupy many orbits around the sun. In the case of the electron, of course, the quantization of the orbits is very conspicuous. When the value of a certain quantum number, n_r (a number characterizing the energy of motion in a radial direction), is held fixed, the binding energies of the various hydrogen states decrease with increasing values of the angular momentum J. If a smooth curve is drawn through the permitted values of J, one obtains a Regge trajectory similar to that connecting the spacecraft in different orbits [*see middle illustration at top of pages 84 and 85*]. For each value of n_r in the hydrogen atom there is a different trajectory, just as there is for each spacecraft of different mass.

In the case of the hydrogen atom the intersection of a Regge trajectory with a permitted value of J (0, 1, 2 and so on) corresponds to the occurrence of a bound state. From an experimental standpoint each of these occurrences is a different "particle" with a different mass. The series of occurrences is brought to an end when the excitation energy becomes so great that the electron is dissociated from the proton. This energy limit divides stable states from unstable states.

Just as Regge trajectories can be



REGGE TRAJECTORIES FOR MESONS are shown for eight well-established particles. They are all in the ground state; no recurrences have yet been identified. It can be shown that the highest η trajectory (that is, a trajectory with a Y and I of 0) should have an unreal intersection at J of 1 and mass 0. A colored line drawn through that point and $\eta(1{,}250, 2^+)$ indicates the probable slope of Regge trajectories for mesons. The parallel black lines for other trajectories are hypothetical. Their intersections with a J of 2 or 3 predict where Regge recurrences are likely to be found. The lowest-lying recurrence should be a $\pi(2^-)$ of about 1,700 Mev.



"EIGHTFOLD WAY" invokes a new system of symmetries to group multiplets of particles into "supermultiplets." The term "eightfold" refers to a special algebra showing relations among eight things, in this case eight conserved quantities. The new system of symmetries (*colored arrows*) connects different values of hypercharge (*Y*) and isotopic spin (*I*) in the same way that isotopic-spin symmetry (*black arrows*) connects different values of electric charge. Four of the diagrams (*a*, *b*, *d*, *e*) show supermultiplets with eight members; another group (*c*) contains 10 members. Several new particles are predicted by the eightfold way, notably Ω(1,676, 3/2+), which appears in *c*. Note that the η meson in *e* is given two mass values, which leads to the "identity crisis" described in the text.

drawn for the gravitational force (spaceship example) and the electromagnetic force (hydrogen-atom example), trajectories can be drawn for the strong force governing strongly interacting particles. In this case the trajectories do not terminate at the boundary between stable and unstable states but continue across, cutting further integer values of J [*see illustration at top right on page 85*]. An intersection in the stable region indicates the existence of a bound state, meaning a particle that is either stable or metastable. Intersections in the unstable region indicate the existence of resonances, or unstable particles. It can be shown that for strongly interacting particles a particular trajectory joins up real states for either odd or even values of J but not for both. This means that an interval of two units of J must intervene between states on the same trajectory. The lowest state is called an occurrence; higher states can be referred to as Regge recurrences, or as a series of excited rotational states.

How can the existence of a trajectory be demonstrated? In analogy with the spaceship or hydrogen-atom example, one plots the angular momentum J against mass (in Mev) for all the particles that share all the same quantum numbers except J. One can then quickly see whether or not they fall into groups that lie on rising curves. If they do, one has an indication of Regge trajectories. Such trajectories for baryons are illustrated on page 86.

The rule says that only states separated by two full integers can lie on the same trajectory. So far three pairs of states appear to meet this requirement: the two N states, N(939, $1/2^+$) and N(1,688, 5/2); the two Λ states, Λ(1,115, $1/2^+$) and Λ(1,815, 5/2), and the two Δ states, Δ(1,238, $3/2^+$) and Δ(1,920, 7/2). (The spins of the higher Λ and Δ states are not certain; they may be greater than 5/2 and 7/2 respectively.)

In the illustration on page 86 these three pairs of states are connected by slanting colored lines. The black lines represent assumed trajectories on which only one occurrence has so far been definitely discovered. These conjectured trajectories are useful in telling experimenters where to search for baryons of higher angular momentum.

The adjacent illustration on page 87 shows Regge trajectories plotted for mesons. For mesons quantum mechanics tells us to take mass squared rather than mass for the horizontal scale. It will be seen that no Regge recurrences have been discovered as yet, perhaps because meson states of high mass have not yet been studied carefully.

The best evidence for the existence of a Regge trajectory among mesons is based on certain arguments showing that a particular Regge trajectory for a meson state with a Y of 0 and an I of 0 should have an unphysical, or unreal, intersection with a J of 1 and a rest mass of 0. The next lower intersection, at a J of 0, could be physical except that the state would have negative mass squared, which has no meaning. Thus the lowest real intersection should occur at two units of J above 0, that is, at a J of 2. In fact, a meson with a J of 2, designated η(1,250, 2^+), has apparently been discovered within the past year and a half. Its quantum numbers are still uncertain, however. If a Regge trajectory is drawn between η(1,250, 2^+) and its unphysical intersection at a J of 1 and a rest mass of 0, one obtains a crude indication of the slope for the other meson trajectories, shown by the black lines in the illustration. Vigorous experimental efforts are under way to find second members of these meson families, with a J of 2 or 3.

The Eightfold Way

Now we shall turn to another classification scheme that has proved valuable in predicting the existence of previously undiscovered particles. We have seen how the notion of Regge trajectories makes it possible to perceive family connections between particles with different values of J but the same values of all other quantum numbers. Now we shall describe a relation that seems to exist among particles with the same values of J and of parity P but different values of mass, hypercharge Y and isotopic spin I.

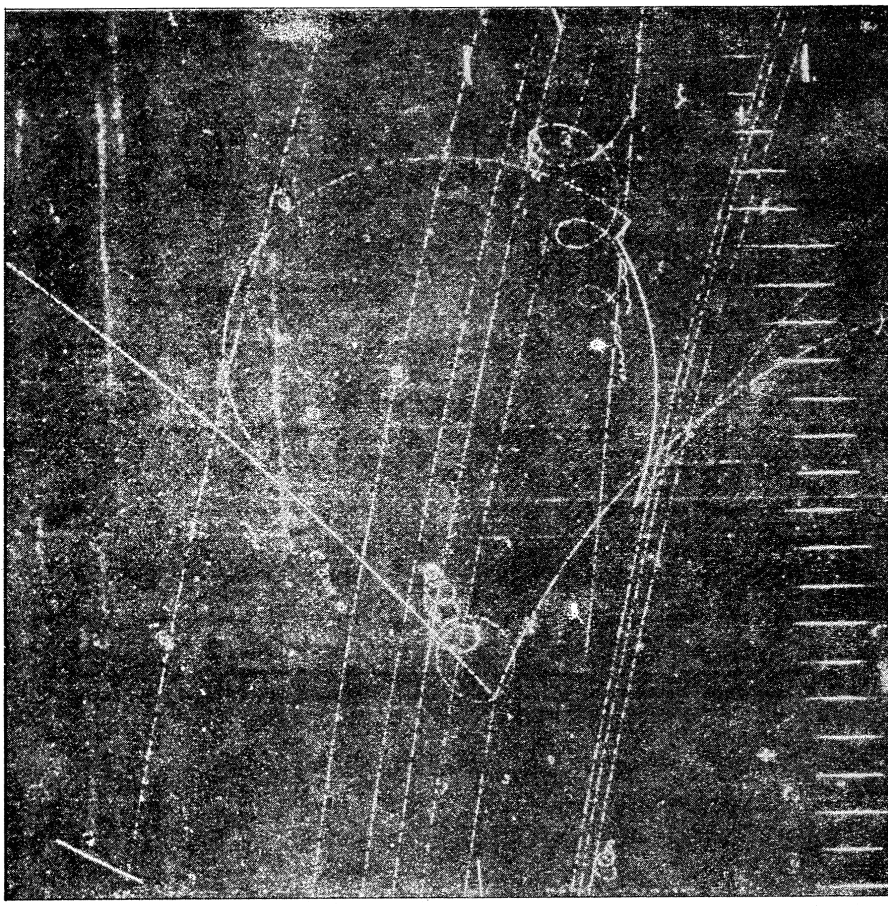
We mentioned earlier that the difference in mass between charge multiplets such as the nucleon doublet (neutron and proton) can be regarded as a "splitting" caused by the fact that isotopic spin is not conserved by the electromagnetic interaction, which underlies the electric charge. This violation produces a maximum mass difference of about 12 Mev in the case of the Σ triplet.

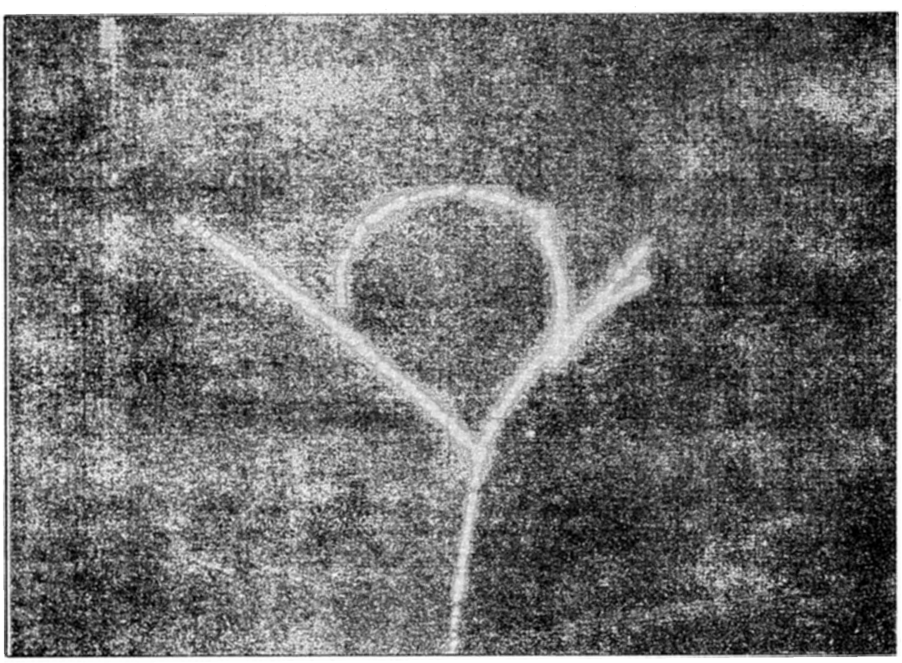
Now, it is a remarkable fact that the four best-known members of the baryon family, N, Λ, Σ and Ξ, are separated by average mass differences only about a factor of 10 greater than that separating members within each multiplet. The gaps in average mass separating the four baryon states are only 77, 75 and 130 Mev respectively. Moreover, these four baryons all seem to have the same J^P; it is $1/2^+$. (Actually the J of Ξ is not firmly established and its parity is still unmeasured.)

If the difference in mass within a multiplet is caused by a violation of the isotopic spin I, is it conceivable that the somewhat greater difference in mass between neighboring multiplets is caused by the violation of the conservation of some other quantum numbers? The kind of solution needed is one in which Y and I are exactly conserved by the strong interaction but certain other conservation laws are broken by some aspect, or some part, of this same interaction. If such a partial violation of new symmetry principles were permitted, one might be able to group baryon multiplets into "supermultiplets" with various values of Y and I but the same J and P. This new system of symmetries would connect different Y and I values in the same way that isotopic spin connects different values of electric charge. The aspect of the strong interaction that violates the new symmetries—represented by new quantum numbers—would split each supermultiplet into charge multiplets of different mass, much as the electromagnetic interaction causes splitting of mass among the members of a charge multiplet by violating isotopic-spin symmetry. The scale of the mass splitting within the supermultiplet, however, would be much greater than that observed within a multiplet, since it is an appreciable fraction of the strong force that is at work rather than the electromagnetic force, which is much weaker.

Early in 1961 an Israeli army colonel and engineer-turned-physicist, Y. Ne'eman, and one of the authors (Gell-Mann), working independently, suggested a particular unified system of symmetries and a particular pattern of violations that made plausible the existence of supermultiplets. The new system of symmetries has been referred to as the "eightfold way" because it involves the operation of eight quantum numbers and also because it recalls an aphorism attributed to Buddha: "Now this, O monks, is noble truth that leads to the cessation of pain: this is the noble *Eightfold Way:* namely, right views, right intention, right speech, right action, right living, right effort, right mindfulness, right concentration."

The mathematical basis of the eightfold way is to be found in what are called Lie groups and Lie algebras, which are algebraic systems developed in the 19th century by the Norwegian mathematician Sophus Lie. The simplest Lie algebra involves the relation of three





BUBBLE-CHAMBER EVENT (*top*) is typical of more than 300,000 measured annually at the Lawrence Radiation Laboratory of the University of California at Berkeley. Many events are measured with the help of a Scanning and Measuring Projector. This device, which is linked to a computer, gives step-by-step instructions to the measurer and redisplays what he has measured on a cathode-ray screen (*bottom*). The photograph shows a K^- meson entering from the bottom and striking a proton in the 72-inch bubble chamber. The reaction creates a K^0, a proton and a π^-. The proton curves to the left, the π^- to the right in the chamber's magnetic field. The K^0 leaves no track, but after going about 10 centimeters it decays into a π^+ and π^-. The π^+ curves counterclockwise and comes to rest. After 10^{-8} second it decays into a μ^+, which goes only about one centimeter and comes to rest. After 10^{-6} second the μ^+ decays into an e^+, a neutrino and an antineutrino. The large curve at the top of the photograph and the oscilloscope redisplay is the path of the e^+.

components, each of which is a symmetry operation of the kind used in quantum mechanics. Isotopic spin consists of three such components (I_+, I_- and I_z) related by the rules of this simplest algebra. The algebra is that of the Lie group called SU(2), which stands for special unitary group for arrays of size 2×2; there is one condition in the 2×2 arrays that reduces the number of independent components from four to three (hence the term "special").

The component operations of the eightfold way satisfy the mathematical relations of the next higher Lie algebra, which has eight independent components. Here the Lie group is called SU(3), which stands for special unitary group for arrays of size 3×3; again a special condition reduces the number of components from nine to eight. The eight conserved quantities of the eightfold way consist of the three components of isotopic spin, the hypercharge Y and four new symmetries not yet formally named. Two of the new symmetries change Y up or down by one unit without changing electric charge; the other two symmetries change both Y and electric charge by one unit [*see illustration on page 88*]. The violation of all four new symmetries by part of the strong interaction changes the masses of the multiplets forming a supermultiplet. An example of a supermultiplet (an octet) is provided by N, Λ, Σ and Ξ, if indeed they all have an angular momentum J of 1/2 and positive parity, that is, a J^P of $1/2^+$.

The kind of violation suggested by the eightfold way leads to a rule connecting the masses of a supermultiplet, provided that the violation is not too severe. The rule for N, Λ, Σ and Ξ is that 1/2 mass N plus 1/2 mass Ξ equals 3/4 mass Λ plus 1/4 mass Σ. Substituting the actual masses of the four particle states gives 1,129 Mev for the left side of the equation and 1,135 Mev for the right side. The agreement with the approximate mass rule is surprisingly good.

This apparent success suggested a search for other octets. At the beginning of 1961 the only meson multiplets certainly known were π, κ and $\bar{\kappa}$, all with a J^P of 0^-. They just fit the octet pattern if one adds a neutral singlet meson with a predicted mass of 563 Mev. (The masses are predicted as they are for baryons except that for mesons the masses in the equation must be squared.) Late in 1961 the η meson was found, with a mass of 548 Mev. Later its J^P was determined to be 0^-, as required.

Meanwhile, mesons with a J^P of 1^- were turning up: the $\pi(750, 1^-)$ triplet and the $\kappa(888, 1^-)$ and $\bar{\kappa}(888, 1^-)$ doublets. Once more the octet pattern was appearing, and the existence of a neutral singlet with a mass of about 925 Mev was expected. Very soon experiments revealed the $\eta(1^-)$ meson, but its mass was only 782 Mev. The mass rule, so successful before, had mysteriously failed.

The mystery may since have been cleared up somewhat. The octet is only one of several supermultiplets allowed by the eightfold way. Another possibility is a lone neutral singlet with a Y of 0 and an I of 0. Suppose there were such a meson with a J^P of 1^-, which we call $\eta'(1^-)$. If its mass value were near that of $\eta(1^-)$, only the broken symmetries of the eightfold way would distinguish the two particles. Under these conditions quantum mechanics predicts that a kind of "identity crisis" would set in, making each of the mesons assume to some extent the properties of the other one. Moreover, the masses would be affected by this sharing of properties, and one meson would have a higher mass, the other a lower mass, compared with the simple case in which the rule for the octet holds. The predicted mass squared for $\eta(1^-)$, or $(925)^2$, should then lie roughly halfway between the actual values of mass squared for $\eta(1^-)$ and $\eta'(1^-)$. Since the actual mass of $\eta(1^-)$ is 782 Mev, one might expect to find another meson, $\eta'(1^-)$, with a mass of around 1,045 Mev. Indeed, in 1962 such a meson with the right values of Y and I (both 0), and with a mass of 1,020 Mev, was discovered independently by two groups of physicists. There is actually no clear way to decide which of the two η mesons, $\eta(782)$ or $\eta(1{,}020)$, belongs to an octet and which is the singlet. We assume that nature is as perplexed as we are.

The $\eta(1{,}250, 2^+)$ meson, the most recently found of the mesons shown in the chart on pages 76 and 77, seems to be a singlet. Thus the 18 mesons listed can be accounted for as two octets and two singlets. Not all the experimental facts are certain, however, and the picture, particularly the identity crisis of $\eta(1^-)$ and $\eta'(1^-)$, must still be considered tentative.

Returning to the baryons, what other supermultiplets have been found beyond the original one containing N, Λ, Σ and Ξ? $\Lambda(1{,}405)$ seems to be a singlet; its J^P has not been definitely established. $N(1{,}688, 5/2^+)$, the first Regge recurrence of the nucleon, should, like the nucleon, belong to an octet containing other Regge recurrences of Λ, Σ and Ξ. The Λ member of this excited octet may well be $\Lambda(1{,}815)$, if indeed it has a J^P of $5/2^+$. The Σ and Ξ members are now being sought; if one of the two particles can be found, the mass of the other can be predicted approximately by the octet mass rule.

$N(1{,}512, 3/2^-)$ may also belong to an octet. Another probable member has already been found: $\Lambda(1{,}520, 3/2^-)$. It is possible that $\Sigma(1{,}660)$ has a J^P of $3/2^-$. If this assignment is correct, the octet mass rule predicts a Ξ multiplet with a mass around 1,600 Mev. Here, however, the experimental situation is very uncertain.

That brings us to $\Delta(1{,}238)$, the unstable baryon discovered in 1952. Since it is a quartet, it cannot belong to either the octet or the singlet pattern. The simplest supermultiplet permitted by the eightfold way into which it can fit is a 10-member group, or decuplet, consisting of a Δ quartet, a Σ triplet, a Ξ doublet and an Ω singlet [*see "c" in illustration on page 88*]. For decuplets the mass rule predicts approximately equal mass spacing between members of the supermultiplet. Since $\Sigma(1{,}385)$ is thought to have a J^P of $3/2^+$, it could very well belong to a decuplet with $\Delta(1{,}238)$. The equal-spacing rule predicts a Ξ particle at about 1,532 Mev. The discovery of $\Xi(1{,}530)$, with a J^P probably of $3/2^+$, appears to be a striking confirmation of the prediction. The mass rule further predicts an Ω particle at about 1,676 Mev, which would be the only particle state consisting of a negative charge singlet. Such a particle would actually be stable under strong and electromagnetic interactions, since it would lack the energy to decay into any of the channels with which it communicates. Thus it should live about 10^{-10} second and decay by weak interactions. It is now being sought eagerly. If it is found, the correctness of the eightfold way will be strikingly established.

We close this section with the remark that the symmetry game may not yet be finished for strongly interacting particles. For example, there might exist some undiscovered quantum number that is conserved by the strong interactions and that has the value 0 for all known particles. Before strange particles were discovered, the strangeness quantum number (equivalent to Y) was of this kind. Experiments at very high energies with the next generation of accelerators might produce a similar situation with respect to an entirely new quantum number.

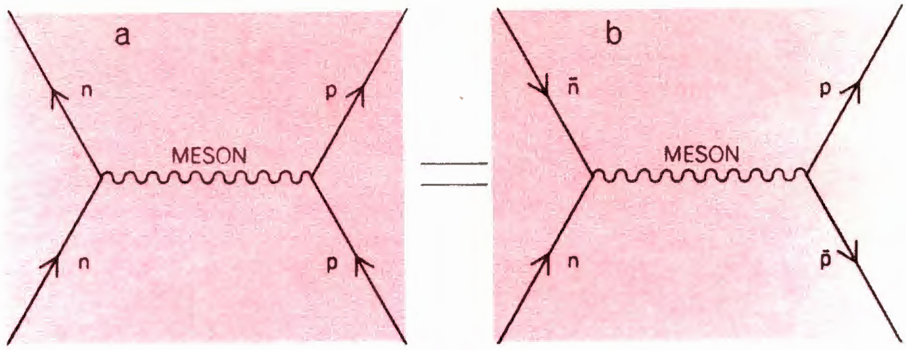
Composite Particles

The meaning of the term "elementary particle" has varied enormously as man's view of the physical universe has become more detailed. In the past few years it has become increasingly awkward to consider several scores of particles as elementary. Evidently a reappraisal of the entire elementary-particle concept is in order.

Let us begin by asking why we feel sure that certain particles such as the hydrogen atom are *not* elementary. The answer is that even though these particles have properties qualitatively similar to those of neutrons, protons and electrons, it has been possible theoretically to explain their properties by assuming that they are composites of other particles.

The hydrogen atom itself provides an outstanding example of what is meant by composite, because its properties have been theoretically predicted with enormous accuracy. It is important to realize that the hydrogen atom is not exactly composed of one proton and one electron. It is more accurate to say that it is so composed *most* of the time. The ground state of the hydrogen atom is a stable "particle" that communicates (via strong, electromagnetic and weak interactions) with a great variety of closed channels, of which electron plus proton is the most important. According to quantum mechanics any state consists part of the time of each of the channels that communicate with it. As an example, for a certain small fraction of the time the ground state of the hydrogen atom consists of the expected electron and proton plus an electron-positron pair. The effect of this channel on the energy of the atom is tiny, but it has been calculated and measured; the agreement is excellent. There are infinitely many other closed channels that contribute to the structure of the hydrogen atom, but fortunately their effect is negligibly small.

In strongly interacting systems complicated channels are more important. For example, the properties of the deuteron (A equals 2) have been predicted, assuming that this particle is a composite of neutron and proton, but here the accuracy of the predictions is much poorer than it is for the hydrogen atom because the effect of additional channels (involving pions, say) is substantial. Nevertheless, there is a general belief that, since the simplest channel accounts for the bulk of the observed properties of the deuteron, it should eventually be possible to improve the predictions systematically by inclusion of more channels. The same kind of statement can be made for all nuclei heavier than the deuteron, and there is no disposition to re-



"CROSSED REACTIONS" illustrate the close correspondence between the concept of a force and the concept of a particle. Reaction *a*, which is read upward, represents a scattering collision between a neutron and a proton. The meson "exchanged" represents the strong force acting between two baryons. Reaction *b*, which is read from left to right, is a crossed reaction of *a*. It shows a meson acting as an intermediate particle in a reaction that converts a neutron and antineutron into a proton and antiproton. The two reactions are equivalent.

gard any of these compound nuclei as "elementary."

Confusion about the distinction between composite and elementary particles has arisen for particles with an *A* of 0 and 1 (mesons and baryons) because here one rarely has a single dominant channel nearby in energy. Consider one of the worst cases: the pion. The communicating channel with the lowest threshold is a 3π configuration; some channels with still higher thresholds are 5π, κ plus $\bar{\kappa}$ plus π, N plus $\bar{\text{N}}$, and Ξ plus $\bar{\Xi}$. Hence part of the time the pion exists as 3π, part of the time as κ plus $\bar{\kappa}$ plus π, and so forth.

All the relevant thresholds are much higher than the pion mass, and many rather complicated closed channels contribute substantially to the pion state. The result is that even a rough calculation of pion properties has not yet been achieved. A more favorable case is that of $\pi(750)$, where the 2π channel is believed to dominate; but even here a glance at the illustration on page 79 shows that there are many nearby channels to be reckoned with.

We may nevertheless employ the operational definition: a particle is nonelementary if all its properties can be calculated *in principle* by treating it as a composite. Such a calculation must yield various probabilities for the various closed channels; the binding forces in these channels must yield the right mass for the particle.

The problem of including all the significant channels is in most cases still too difficult, but suppose the calculation could be carried out. Would we then get a correct description of each particle? Would the quantum numbers and the mass come out right? Until recently there was an almost universal belief that a few strongly interacting particles, including the nucleon, could not be calculated on such a basis. In the present theory of electrons and photons, which gives such an excellent description of electromagnetic phenomena, the properties of the electron and photon cannot be dynamically predicted. The reason is that the known forces are not powerful enough to form bound states with masses as small as those of the electron and the photon.

Reasoning by analogy, theorists tended to give the nucleon a special status parallel to that of the electron. Thus they were inhibited from trying to treat the nucleon as a composite particle. Gradually, however, this select status seemed increasingly dubious. And when an attempt was finally made to calculate the properties of the nucleon from an analysis of its communicating channels, the same qualitative success was achieved as with the deuteron and the $\Delta(1{,}238)$ particle, which had for years been called composite just because it had first been observed in a pion-proton scattering experiment.

It seems, furthermore, on the basis of recent developments in which the concept of the Regge trajectory plays an important role, that in all such dynamical calculations no distinction need be made on the basis of the angular momentum or other quantum numbers of the particle involved. If there is no need for an aristocracy among strongly interacting particles, may there not be democracy?

"Bootstrap" Dynamics

Composite particles owe their existence to the forces acting in channels with which the particles communicate. How do these forces arise and how can they be calculated?

The key concept behind the calculation is "crossing." Consider the following reaction involving four particles:

$$a + b \longleftrightarrow c + d$$

This says that the channel *a,b* is coupled to the channel *c,d*. The probability that this reaction will take place (in either direction) is expressed mathematically as the absolute value squared of the "reaction amplitude," which depends on the energies of the four particles involved. The principle of crossing states that the same reaction amplitude also applies to the two "crossed" reactions in which *ingoing* particles are replaced by *outgoing* antiparticles (indicated by a bar over a letter) thus:

$$a + \bar{c} \longleftrightarrow \bar{b} + d$$
$$a + \bar{d} \longleftrightarrow \bar{b} + c$$

These different reactions are distinguished by the signs of the energy variables, which are positive or negative according to whether ingoing or outgoing particles are involved, but if the reaction amplitude is known for any one of the three reactions, it can be obtained for the other two by inserting the proper signs for energy.

An example of crossing is the following pair of reactions involving neutrons and protons:

$$\text{(a)} \quad n + p \longleftrightarrow n + p$$
$$\text{(b)} \quad n + \bar{n} \longleftrightarrow p + \bar{p}$$

Both reactions are described by the same reaction amplitude, an important aspect of which can be depicted diagrammatically, as shown in the illustration on this page. The first way of drawing the arrows in this diagram is appropriate to reaction *a* and the second to reaction *b*. The two figures differ, of course, only in the direction one reads them, either from bottom to top or left to right, as indicated by the arrowheads.

One interprets the first figure by saying that in a scattering collision between a neutron and a proton a meson is "exchanged," and it can be shown that this exchange is a way of representing the force acting between those two baryons. The interpretation of reaction *b* is that a meson that communicates with both the *n*,$\bar{n}$ and *p*,$\bar{p}$ channels provides a means for connecting the two channels of the reaction. Thus a single diagram corresponds both to a force in one reaction and to an intermediate particle in the crossed reaction. It follows that forces in a given channel may be said to arise, in general, from the exchange of intermediate particles that communicate with crossed channels.

With this as background we return to the idea mentioned in the introduction to this article, that the strongly interacting particles are all dynamical structures that owe their existence to the same forces through which they mutually interact. In short, the strongly interacting particles are the creatures of the strong interaction. We refer to this as the "bootstrap" hypothesis. It was formulated by one of the authors (Chew) and S. C. Frautschi at the University of California at Berkeley.

According to the bootstrap hypothesis each strongly interacting particle is assumed to be a bound state of those channels with which it communicates, owing its existence entirely to forces associated with the exchange of strongly interacting particles that communicate with crossed channels. Each of these latter particles in turn owes its existence to a set of forces to which the first particle makes a contribution. In other words, each particle helps to generate other particles, which in turn generate it. In this circular and violently nonlinear situation it is possible to imagine that no free, or arbitrary, variables appear (except for something to establish the energy scale) and that the only self-consistent set of particles is the one found in nature.

We remind the reader that in electromagnetic theory a few special particles (leptons and photon) are *not* treated as bound (or composite) states, the masses and coupling characteristics of each particle being freely adjustable. Conventional electrodynamics, as far as anyone knows, is not a bootstrap regime.

It is too soon to be sure that free variables are absent for strong interactions, but we shall close in an optimistic spirit by mentioning a fascinating possibility that would represent the ultimate contribution of the bootstrap hypothesis. If the system of strongly interacting particles is in fact self-determining through a dynamical mechanism, perhaps the special strong-interaction symmetries are not arbitrarily imposed from the outside, so to speak, but will emerge as necessary components of self-consistency. It is remarkable, and puzzling, that isotopic-spin symmetry, strangeness and now the broader eightfold-way symmetry have never been related to other physical symmetries. Perhaps their origin is destined to be understood at the same moment we understand the pattern of masses and spins for strongly interacting particles. Both this pattern and the puzzling symmetries may emerge together from the bootstrap dynamics.