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AN ELEMENTARY (?) GUIDE TO THE
ELEMENTARY (?) PARTICLES

Berkeley, California

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AN ELEMENTARY (?) GUIDE
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An Elementary (?) Guide to the Elementary (?) Particles

Part I: The Four Basic Forces of Nature

LRL physicist Arthur Rosenfeld (l.), author of the series which begins here, has had a hand in many of the "elementary" particle discoveries of the past few years. Within recent memory, he has appeared in these columns as a member of the team which discovered the omega meson (MAGNET, September '61) and as one of several physicists who helped work out the important theoretical implications of the Y^* , (1660) discovery (MAGNET, January '63). A graduate of Virginia Polytechnic Institute and the University of Chicago (Ph.D., 1954), Rosenfeld has been a member of the UC physics faculty and the LRL research staff since 1955.

Within the past few years, a quiet revolution has been taking place in the field of high energy physics—a revolution that may mark the beginning of one of those intensely productive and exhilarating eras in which a decade's accumulation of loose ends are tied together, and science makes a "quantum leap" forward to new concepts and new ways of regarding the old.

The most dramatic manifestation of this revolution so far is the well-known "population explosion" in subatomic particles—an explosion which has, within the space of eight years, tripled the number of known "elementary" particles, and (even more important) caused scientists to ask themselves whether it makes sense to call any particles "elementary."

In this series of articles, I shall trace the recent history of this revolution and attempt to show just what kind of sense present-day physicists are making of the experimental evidence accumulated so far. Because these events are so closely tied to discoveries made at LRL's Bevatron, it seems appropriate that this discussion and review should appear now, just as the Bevatron—in remodeled and

improved form—begins an important new era of research.

I have said above that scientists have, of late, been questioning the old concept of "elementary" particles. Instead, they are beginning to refer to these newly observed "particles" and "resonances" as various "states of the strong interaction." What is this strong interaction? And how can a particle be a "state" of it? These questions, confusing, at first, to the layman, I hope to make clear before the end of this series. Let us begin, then, by reviewing briefly the four forces of nature that are known to science.

The Four Basic Forces

Science has discovered that there are only four basic ways in which matter can interact; four fundamental forces (to put it another way) which account for all the various states and forms of matter found in the universe. Two of them are already very familiar to you; the other two are still mysterious even to scientists. These four forces are: gravity, electromagnetism, the "strong interaction," and the "weak interaction."

It should be noted in passing that even gravity and electromagnetism are "familiar" only in a very relative way. These forces have been observed and studied for so long that we have more or less "learned to live with them," but this should not imply that they are any "simpler" or more readily explained than are the strong and weak interactions. Let us examine each of these forces in turn.

Gravity is the force which causes all objects to attract one another with a force proportional to their mass. As you learned in school, gravitational force is

exerted by *all* matter, although its effects are generally not observable to us except in the case of large aggregates of matter. Thus, we know gravity mainly as the force which holds the earth together, binds the sun and the planets into the solar system, etc. It is the weakest of the four forces.

Electromagnetism is the force which causes electrically charged particles to attract or repel one another. Thus it keeps electrons swirling around nuclei to form atoms and binds atoms together into molecules and crystals. Electromagnetic attraction could, therefore, in this context be referred to as the "atomic force." It is much stronger than gravity, and its effects are more readily apparent to us—but it is still a hundred-fold weaker than the strong interaction. All of chemistry and biology is governed by the laws of electromagnetic attraction, the "atomic" force.

The *strong interaction* is the force which glues nuclear particles together, thus binding neutrons and protons to form the nuclei of all elements. It is by far the strongest force known in nature. (As you know, because it is so strong, we need modern atom smashers or reactors to break nuclear bonds and bring about artificially induced nuclear reactions.) The "particles" of nuclear matter figuring in strong interactions are called mesons and baryons, and clusters of baryons are called nuclei. We can relate these three particles with examples. The most familiar baryons are the proton and the neutron. Nuclei consist of several protons and neutrons, i.e., several baryons. Mesons are in general lighter than the proton. This distinction may be made more precise in terms of the "atomic mass number," symbolized by the letter "A." This number, you may remember from your high school science courses, defines the

FORCE:	GRAVITY	ELECTROMAGNETIC	WEAK	STRONG
ACTS ON:	All particles with mass	Particles with electric charge, and photons	Leptons, mesons, baryons	Mesons, baryons
EXAMPLES OF STABLE "SYSTEMS" OR "STATES":	Solar system	Atoms, molecules, crystals	None	nuclei ($A=2$), baryons ($A=1$), mesons ($A=0$), antibaryons ($A=-1$), etc.
EXAMPLES OF REACTIONS INDUCED BY THE FORCE:	Object falling, hot air rising, meteorite pulled to earth	All chemical reactions	Decay of uranium into lead	Scattering of pion off protons, and other nuclear reactions

Fig. 1.

number of basic nuclear "mass units," or "building blocks," contained in the particle. (The atomic mass number is usually printed in the right superscript position: e.g., C^{12} stands for a carbon nucleus containing twelve nuclear "building

blocks.") For the purposes of our discussion, we shall define mesons as particles with an "A" value of zero, baryons as particles with an "A" value of one, and nuclei as particles with an "A" value greater than one. This atomic mass number is always "conserved"; that is, in any type of reaction, whether electromagnetic, strong, or weak, the quantity expressed by "A" cannot change or be lost, but must be accounted for in the final products of the reaction. A final point to bear in mind is that for every meson and baryon there exists a corresponding *antiparticle*, whose atomic mass number is the identical quantity preceded by a minus sign. We shall return to these questions in greater detail in subsequent articles.

The *weak interaction* is the force that causes the light "elementary" particles called "leptons" (electrons, neutrinos, and muons) to interact with each other and with mesons and baryons. It is the weak interaction that is responsible for the "beta decay" of radioactive nuclei, as in the gradual natural transmutation of certain uranium isotopes into lead over millions of years. A very significant characteristic of the weak interaction is that it operates only over very short ranges. In this it differs from gravity, which, though comparably weak, can extend its effects over vast distances. Thus the weak interaction cannot form stable states of matter in the sense that the gravitational force can "form" a solar system, the electromagnetic force can "form" an atom, or the strong attraction can "form" a nucleus. The table on page one may give you a clearer idea of the differences and similarities between the four

basic forces of nature.

Many systems, it should be remembered, are governed by more than one force. Thus both gravity and electromagnetic forces act on galaxies, both electromagnetic and "strong" forces act on heavy nuclei, etc. If two forces are acting in opposition to each other, the effect of the weaker one will be masked, sometimes beyond detection, but it continues to contribute its effect to the total behavior of the system.

From the discussion above, we have seen the following analogy emerge: Gravity can act on some basic *objects* (sun and planets) to form an entity—the solar system. It is also partly responsible for the existence of the basic objects (earth and sun). Electrical forces can act on other objects (nuclei and electrons) to form an entity—an atom or a molecule. The strong interaction acts on baryons and mesons to form nuclei and is probably responsible for the very existence of mesons and baryons. Are there even more basic objects out of which it forms mesons and baryons? We'll return to this subject later in this series.

Part II: Atomic States and Nuclear States

Last month, you may remember, I opened this series of articles by reviewing the four basic forces of nature and showing how each of these forces (except the one called the weak interaction) acts on the stuff of the universe to form various stable systems. We saw that gravity acts on certain basic *objects* (the sun and the planets) to form an entity (the solar system) and is also partly responsible for the existence of the basic objects themselves. Similarly, the strong interaction acts on baryons and mesons to form nuclei and is probably also responsible for the very existence of baryons and mesons. This month, we shall turn our attention to a closely related subject: the place of experimental evidence in the development of our understanding of nuclear forces.

If you have been following our argument closely, you may be asking yourself, at this point, "Is it really necessary to identify each and every one of the probably countless number of these 'nuclear states'?" To what end, you might ask, do the Bevatron and similar accelerators operate around the clock to churn out this seemingly endless array of "particles" and "resonances"? Obviously, there must be more to such experimentation than the mere identification of sub-nuclear states. To understand what we are trying to do in our high energy research program, let us return to our historical precedent, the atom. Our theme is as follows: experiments on atoms led to the discovery of many atomic states; the pattern of these states led to the theoretical formulation of quantum mechanics and hence to a rather complete understanding of atomic physics, most of chemistry, etc. Experiments on nuclear matter are now leading to the discovery of a pattern of nuclear states called mesons and baryons. Perhaps a rather complete understanding of nuclear physics will not lag far behind.

Now, to embellish our theme, let us go back in time to the early years of this century, to the period immediately preceding the formulation of quantum mechanics. For many years prior to 1926, the physicist's "model," or schematic representation, of the atom resembled a tiny solar system, with an electron or electrons circling around a nucleus in a stable orbit, held there by electrical attraction. If one bombarded the atom

with other particles (photons, electrons, or other atoms) one could raise the orbiting electron temporarily into higher-energy, larger semi-stable orbits. The electron would circle the nucleus for many revolutions in its "excited" orbit, then release its energy in the form of light and "decay" into a lower energy level, eventually reaching the lowest-energy or "ground" state, which is, of course, stable.

So far, all this seemed reasonable. But in studying the light emitted during decay, spectroscopists discovered that nature had apparently concocted a set of absurd rules. Excited states could exist only at certain discrete energies. Empirically, the spectroscopists found not only a set of rules for these allowed energies, but also a group of equally baffling "selection rules"—i.e., an electron could jump from a given level only to some (but not all) of the other levels.

This is not the place to go into the long and fascinating series of events that led to the discovery of quantum mechanics. Let us just say that, by 1926, enough empirical information had been collected on atomic energy levels and selection rules. Only then did it become possible for Heisenberg and Schrödinger and others to guess the explanation and to reformulate the laws of mechanics of tiny particles moving under the influence of electromagnetic forces according to a new mechanics—an insight which convulsed, and finally revolutionized, the whole world of physics. Suddenly, every empirical rule of spectroscopy was explained; it became possible to understand and predict most of the states of matter—not only the states of atoms, but also of molecules, crystals, metals, etc. At last atomic physicists understood why some of their approximate models of the atom had worked, and

the extent to which they were only approximations.

A similar situation exists today in nuclear physics. The great unifying concept, analogous to the invention of quantum mechanics, is still not clearly in sight, but the experimental data are beginning to fall into striking, and partly predictable, patterns. In our research with the Bevatron and similar accelerators, we have been compiling a comprehensive record analogous to the detailed "energy level diagrams" of the spectroscopists of the early 1900's. And, just as their diagrams revealed seemingly "absurd" rules governing the behavior of electrons in the atom, so our experiments have laid bare a whole new set of "allowed energy levels" and "selection rules" for nuclear states. In a later article, when we review the experimental discoveries of recent years, you will be able to see for yourself that nature seems to choose these "allowed levels" in groups of one, eight, or ten, then repeats these whole groups at still higher energies. You will also be introduced to a few of the "selection rules" that have been unearthed so far.

It should be remembered that our problems in discovering and understanding these rules are complicated by the fact that we know so little about the strong interaction itself—the force that is involved in all these processes. (The electromagnetic interaction, on the other hand, had already been extensively studied prior to 1926, and could be more readily adapted to the new ideas of quantum mechanics.)

Physicists have temporarily gotten around this difficulty by constructing various theoretical approximations of the nucleus, known as the shell model, the square-well model, etc. These models work quite well within certain limits, though they leave much unexplained.

But even though the theoreticians have failed, so far, to explain nuclear physics, the experimentalists have forged ahead in their task of laying foundations for new theory. With the Bevatron and similar accelerators, they have again and again torn apart the nucleus, counted up the "pieces," and added still more fine detail to the increasingly explicit picture of its interior. Next month, we shall look more closely at this experimental evidence, and see where it appears to be leading.

Part III: The Seven Quantum Numbers

In previous articles in this series, we have discussed the four basic forces of nature, pointed out that many familiar systems and objects can be described as "states" of these four forces, and shown how, in the case of the electromagnetic force, empirical information about the states of the atom led scientists to the invention of quantum mechanics and to a rather complete understanding of the chemical world. After pointing out that experiments on nuclear matter are now leading to the discovery of an analogous pattern of nuclear "states," we expressed the hope that a rather complete understanding of nuclear physics will not lag far behind.

We are not quite ready, however, to turn our attention to these "experiments on nuclear matter" and lay before your admiring eyes an impressive list of the known strongly interacting states called "particles." First, we must embark on a brief excursion into the thickets of classification and nomenclature. We trust that you will not find our route too fraught with perils.

Quantum Numbers

Every nuclear particle, it goes without saying, is defined, or identified, by a set of individual characteristics—just as the various planets in the solar system are defined by such characteristics as their mass, their distance from the sun, their rate of rotation, etc. In the case of nuclear particles, the set of defining characteristics contains exactly seven properties, which are called "quantum

numbers." Each quantum number stands for a particular trait of the particle or state under consideration; taken together, they form the signature of that particular nuclear state. In fact, most particles (especially the more recently discovered ones) are referred to simply by their quantum numbers; some of the older and more familiar ones, like the proton, are called by their "pet names." By grouping the quantum numbers appropriately, physicists have arrived at a very useful classification of the particles into families, called multiplets.

Let us now look more closely at these all-important quantum numbers. Unfortunately, it will not be possible, within the scope of these articles, to present any comprehensive explanation of what each of the quantum numbers stands for. Instead, we shall have to be satisfied with a brief definition or formula for each, plus a discussion of the ways in which they are related. (Many quantum numbers, as you shall see, are defined in terms of other quantum numbers, so it is not easy to give individual definitions.) The table below lists and defines the seven quantum numbers in the order in which they are usually presented: Atomic Mass Number (A), Strangeness (S), alternatively

expressed as average charge ($\langle Q \rangle$), Isotopic Spin (I) alternatively expressed as Multiplicity (M), Electric charge (Q), Rest Mass (m), Spin (J), and Parity (P).

Multiplets and Multiplicity

A multiplet is a family of particles all having the same quantum numbers *except* for their electrical charge. Physicists have grouped them in this way because the electrical charge, Q , seems to play a superficial role as far as the strong interactions are concerned. Thus, we notice that although the neutron and the proton have different electric charges, their "nuclear" properties and behavior are similar (e.g., identical mass, identical interaction with pi mesons, etc.). It makes sense, therefore, to group neutrons and protons into a "doublet" called the "nucleon doublet N ," with N^+ standing for a positively charged N (the proton), and N^0 standing for an uncharged (neutral) N (the neutron). Similarly, the three pi mesons (the π^+ , the π^0 , and the π^-) have been found to be entirely identical in all traits except charge; they, therefore, are grouped into the " π triplet." Doublets, triplets and similar groupings are referred to collectively as "multiplets." A doublet is said to have a "multiplicity" of two, a triplet a multiplicity of three, etc. There are also known several singlets (only one particle in the group—multiplicity = 1) and two quartets (four particles in the group—multiplicity = 4). In the remainder of this series of articles, we shall usually speak

AS
PI
QM

NAME and SYMBOL		COMMENT	EXAMPLES The Proton π^- Meson	
MULTIPLY SYMBOL	Atomic Mass Number A	Stands for the number of basic mass units (mesons, A = 0; baryons, A = 1; nuclei, A = 2 or more)	I	0
	Strangeness S or Hypercharge Y or Average Charge... $\langle Q \rangle$	$\langle Q \rangle$ is the average charge of the multiplet. Y is defined as $2 \langle Q \rangle$; S is defined as $2 \langle Q \rangle$ minus A.	S = 0 Y = 1 $\langle Q \rangle = 1/2$	S = 0 Y = 0 $\langle Q \rangle = 0$
	Isotopic Spin I or Multiplicity..... M	Defined by a formula involving the multiplicity of the multiplet: $M = 2I + 1$.	I = 1/2 M = 2	I = 1 M = 3
	Electric Charge..... Q	Measured in units of charge on a proton	Q = 1	Q = -1
	Rest Mass m	Weight, expressed in MeV	938	140
	Spin J	Measures how fast a particle rotates about its axis, like daily rotation of earth. Basic unit of J is Planck's Constant.	1/2	0
	Parity P	An intrinsic property which can be +1 or -1. Not easy to explain in a line (or a volume!).	+1	-1
	(G-Parity) (G)	An extra intrinsic property of certain mesons. Since most particles don't have a well-defined G, we shall choose to ignore it.	Not defined	-1

Fig. 2.

of multiplets rather than individual particles.

After its multiplicity, the next property of a multiplet we wish to take up is its "average charge" $\langle Q \rangle$. When we add up the charges of the N doublet (one for the proton plus zero for the neutron) and divide by two to get the average, we find that it equals $\frac{1}{2}$; similarly the average charge for the π triplet is zero. Another multiplet, called the cascade doublet, consists of a negatively charged cascade (the Ξ^-) and a neutral one (called Ξ^0), so the average charge is $\frac{1}{2}$. In contrast to the individual charges, which are superficial, these average charges are important.

By Any Other Name . . .

So far we have mentioned three quantum numbers, A, M, and $\langle Q \rangle$. Actually, each of the latter two has an alternative name. For historical reasons, M is often expressed by another name, the isotopic spin, I, defined by $I = M/2 - 1$. And $\langle Q \rangle$ is frequently expressed either as "hypercharge," Y (where $Y = 2 \langle Q \rangle$) or as "strangeness," S ($S = 2 \langle Q \rangle - A$). The name isotopic spin has little to do with the physical property we associate with spinning. The name comes, perhaps misleadingly, merely from an analogy with certain properties of the actual spin (quantum number J.)

Multiplet Symbols

As indicated on the table, these first three quantum numbers, A, M, and $\langle Q \rangle$ (or A, I, and S) are often grouped by

convention into a single "multiplet symbol." Thus the single symbol "N" (nucleon) stands for a particle with $A=1$, $S=0$, and $I=\frac{1}{2}$. Since the neutron-proton doublet N has a mass (quantum number m) of 938 MeV, we can represent this doublet, once and for all, by the symbol "N(938)." The "N(1688)" symbol, it follows, stands for an excited state of this doublet at 1688 MeV, and so on. (It might be well to remind the reader that mass values, in nuclear physics, are expressed in terms of "rest energy," measured in MeV. This is the amount of energy which would be released if it were possible to convert the particle entirely into energy according to Einstein's equation $E=mc^2$.) Although it is usually redundant, the isotopic spin number is often, again through convention, written in as a subscript; thus the official name of the nucleon doublet is $N_{\frac{1}{2}}(938)$.

Cars and Colors

We might summarize, and perhaps clarify, this system of notation by making an analogy to the classification of, say, automobiles. Here the "superficial" quantity, instead of being charge Q , is color. Thus, within the general class of Fords, the "multiplet name" Falcon might stand for a quartet (multiplicity = 4) of small cars sold in four colors, which might show up as blue Falcons, red Falcons, green Falcons, and yellow Falcons. Despite differences in color, 1963 Falcons are all really similar, and are all related in the same special way to

1962 Falcons, just as the excited state N(1688) is related to N(938).

Back to particles! It will be necessary for you to digest one more classification before we are ready to proceed to a discussion of known particles. A particle can be classed as either "stable" or "unstable" against decay through the strong interaction. Particles that are unstable break up quickly into lighter groupings of strongly interacting particles—after going a distance equal to a few nuclear sizes. Particles that are stable, on the other hand, are immune to strong-interaction decay forces. This is not to say that such particles undergo no changes. All of them, except the proton, decay eventually via the weak interaction or other forces. (We don't have to worry about confusion between strong-interaction decays and other kinds, since the time-and-distance scales involved are vastly different.) From now on, for purposes of simplicity, we shall refer to all nuclear states which are immune to strong-interaction decay as "stable particles." States which are NOT so immune we shall call "unstable states" or "resonances." The origin of this rather curious term will become clear in a later article; for the time being, let us agree to think of the word "resonance" essentially as an alternate spelling of the word "unstable."

Now that this *antipasto* of classification and nomenclature has been digested, let us retire for a nap before we return next month for the main course—a table loaded with the "elementary" particles.

Part IV: Nuclear States

So far in this series, we have talked about forces of nature, atomic states, quantum numbers, and a variety of other topics whose relevance to the avowed subject of the series—the “elementary” particles—may have, at times, seemed to you farfetched.

Today, as we promised in our preceding article, we present the main course—a well-appointed table of the nuclear states known as “particles” or “resonances.” Before turning to the table, let us briefly review last month’s discussion. You will recall that we introduced you to the seven quantum numbers which serve to identify each nuclear state, or particle, and showed how—on the basis of these quantum numbers—particles are grouped into “charge multiplets.” We also explained how the “official name” of a particular state is derived, being made up of the “multiplet symbol” (N, Y, π , etc.), followed by the isotopic spin number (written as a subscript), followed by the mass (in parentheses). Thus the “official name” of the neutron-proton doublet at 938 MeV is $N_{\frac{1}{2}}(938)$. (Does anyone care to exercise by formulating the official name of the pion triplet at 140 MeV?)

A Well-Appointed Table

With this system of classification and nomenclature firmly in mind, we should be ready to turn our attention to the table on the opposite page. You will notice immediately that we have given up referring to individual particles at all; instead, each bar on our table stands for a whole charge multiplet—i.e. one of those groups composed of particles identical in every property except their electric charge. Beginning at the bottom of the table, the multiplets are listed in an ascending scale according to their mass. Stable multiplets are drawn as heavy marks; resonances (i.e., unstable multiplets) as light wavy lines. Baryons are drawn to look like wavy lines, mesons are drawn as plain bars.

The most familiar particles are the lighter ones, so from the historical point of view as well as the weight scale, it makes sense to discuss our table from the bottom up.

The first three entries you see (the neutrino, the electron, and the muon) are the “leptons”; as pointed out in previous articles, the leptons don’t enter into our present discussion at all, since they are not subject to strong-interaction forces. Passing by them and the pho-

ton, and continuing up the table, we next meet the pion (or π meson) triplet, at 140 MeV. Since this multiplet is stable, and therefore lives for a long time without decaying, it was discovered and studied long before our history gets under way with the commissioning of the Bevatron in 1954.

Climbing the Ladder

Next on our way up the ladder comes the K-meson doublet. “K” is a multiplet symbol we have not met before; it stands for a multiplet in which $A=0$, $S=+1$, and $I=\frac{1}{2}$. The K and anti-K doublets were also known before the commissioning of the Bevatron.

Next comes the eta meson, a singlet. Though stable against the strong interaction, this meson decays electromagnetically after going only about 10^{-16} cm. Because of this speedy electromagnetic decay, the eta was the only *stable* particle that escaped detection before the Bevatron and the bubble chamber came along. (Actually, the π^0 , the neutral member of the pion triplet discussed earlier, also decays electromagnetically after only 10^{-16} cm, but, luckily for physicists, it was betrayed by its two charged siblings, π^+ and π^- , both of which go hundreds of feet and are thus easy hunting.) The η is the heaviest of the stable mesons. Above it, we see several more meson multiplets, all of which happen to be resonances (i.e., unstable), and which therefore eluded discovery until the last few years.

Baryons

At mass 938 we come, finally, to the lightest of the baryons, the nucleon doublet. (Baryons, let us remind you, are states with atomic mass number $A=1$; i.e., states with one fundamental building block of nuclear matter.)

The five lightest baryon multiplets [nucleon, lambda, sigma, xi, and the $N(1238)$ quartet] were all discovered before 1954. Four of them are stable, but $N(1238)$ is unstable. Since it was the first unstable baryon to be found, it was originally thought to be something special, and was christened “the pion-nucleon resonance.” Since that time however, five other pion-nucleon resonances have turned up.

Apart from $N(1238)$, all the resonances shown on the table have been discovered since 1954, mainly at the Bevatron and mainly with hydrogen bubble chambers. In *all* cases except two, the Bevatron has played some role in the

discovery. Thus, the eta was first identified at Johns Hopkins University, but the team there used film from LRL’s 72-inch bubble chamber, as well as the data analysis system developed by the Alvarez group. The rho meson was another particle that turned out to be hard to pin down; several laboratories, including LRL, did the necessary experiments that resulted in the final identification of the rho in 1961.

You will notice that several of the resonances are called K^* or N^* or Y^* . Don’t bother to try to figure out what that star means; it is a historical vestige left over from the days when there were so few resonances known that we thought that we could get away with using asterisks instead of writing the mass.

Room at the Top

We have lopped off the top of the ladder, rather arbitrarily, at 1815 MeV. Actually, three resonances above 1815 are already established, and many more are expected. But there is a kind of symbolic value in cutting off our list at a point already past: it reaffirms our thesis, expressed in an earlier article, that it is not necessary to identify *all* possible nuclear states in order to deduce the laws that govern them.

A few still-undiscovered particles, on the other hand, are of crucial importance. One such particle is included in the table, even though it has not yet been found. It is the final stable baryon, predicted at mass 1676 MeV and already named Ω baryon (omega for “the end”—not to be confused with ω meson, lower down on the table).¹

Save the Table!

There has not been room, in this article, to do more than list the known particle states and give a few words of comment on each. I suggest, however, that you hold on to the table for future reference. We shall have occasion to look at it again in our next article, when we shall compare it with similar tables for atomic and nuclear physics, and examine certain intriguing symmetries in the table which led to the idea of “occurrences and recurrences” and to the postulate of “the Eightfold Way.”

¹ Researchers at Brookhaven National Laboratory announced the discovery of this particle in February, 1964.

Nuclear States ("Particles")

Shown below are the known strongly interacting charge multiplets with mass less than 1850 MeV. Not shown are the antiparticles, which have the same mass, multiplicity, and spin, but opposite strangeness and electric charge. Light marks represent unstable states ("resonances"), which fall apart after going only a few nuclear diameters; heavy marks represent stable states —i.e., states that are immune to decay via the strong interaction. Baryons are shown as wavy lines, mesons as straight bars.

Fig. 3.

Part V: Occurrences and Recurrences

In the preceding part of this series, we presented an energy-level diagram (or "laundry list") of the known strongly interacting nuclear states (charge multiplets, or "particles"). Our list included a total of nine mesons and fourteen baryons with mass less than 1850 MeV, arranged in a "ladder" of ascending mass.

Today, we shall show you some of the same "particles" arranged in a rather different way. In Figure 6 on the following page you will be able to see (as physicists themselves have seen only within the past few years) that the 23 nuclear states arranged last month in a "laundry list" can be re-grouped into only two "supermultiplets" (which we shall call "occurrences"), and that each of these supermultiplets recurs (in groups called "recurrences") at higher values of the quantum number J (spin).

At the same time, we shall take the opportunity to point out to you the striking similarity between energy-level diagrams for enormous systems like the solar system, for small systems like the atom, and for tiny systems like nuclei, mesons, and baryons.

A Solar System

Let us start by considering the energy of a space ship cruising around the sun in a circular orbit. Such a ship cannot escape from the gravitational pull of the sun unless energy is supplied in the form of rocket fuel. We say, therefore, that the ship is bound in an "attractive well," with a certain binding energy "B" (i.e., the energy required to release it from the sun's attractive force). Another term we need to define before proceeding is an important one which you may recall from a high school course in elementary physics: "angular momentum," usually written as a lower case letter " l ." Angular momentum is the measure of the amount of spin of any object: the faster a wheel rotates, the greater its angular momentum. If two similarly shaped objects are rotating at the same speed, the one with the greater mass has the greater angular momentum.

For later analogy with states in particle physics, remember that energy and mass are related, so B will correspond to the energy of an atomic state, and to the mass of a particle. Angular momentum (l), on the other hand, will correspond to the spin, quantum number J . We can

thus describe the "state" of the space craft-sun system by specifying two quantum numbers, B and l , just as in Part III of this series we described a strongly interacting state by listing its seven quantum numbers. As long as our rocket ship burns no fuel and just circles in a constant orbit with constant B and l , its state does not change. If we supply fuel and have it climb to a different B or l , we then say it is in a new state. You may object that this is a silly way to describe a space ship in solar orbit—why not list something more descriptive than l : for example, the radius of the orbit and the mass of the craft? The answer is that neither of these quantities has easily measured analogous properties in atomic or nuclear states, whereas l does. So let us agree that each combination of B and l will, for our purposes, specify a different state of our space craft-sun system.

An Important Equation

Let us now return to that space ship, which we left orbiting the sun a few sentences back. In the same elementary physics course, you may have learned that the binding energy, B, and the angular momentum, l , are related by the simple equation $B \propto m^3 / l^2$, where m is the mass of the space craft. Thus the tightly-bound orbits close to the sun have the smallest l .

In Figure 4, on the following page, we have plotted B vertically vs. l horizontally for a one-ton (Russian) space ship in circular orbit at the radius (i.e., the distance from the sun) of each of the planets of our solar system. A dashed curve joins these possible "states" of the space ship. Note that once we know the relation between B and l for one circular orbit, we can calculate the mass of the space craft involved, and then we can go on to calculate B and l for all possible circular orbits. In the language of particle physics, we would say that all the high-orbit states are just "recurrences" of the innermost state (i.e., that with lowest angular momentum). If we now consider a lighter (American) space ship (this time with $m = 1/2$ ton) at the orbit of Mercury, we now get a new relation between B and l (drawn as open circles in Figure 4, which in turn generates new recurrences, also shown joined with a solid curve.

Thus, though we began with many dots ("states") in Figure 4, we now see

(with our understanding of recurrences) that all these dots are not independent. There are, in fact, only two independent series of states of the space ships.

[In Figure 4, the main scales are plotted in "earth units" (i.e., Earth's B and Earth's l are the unit of measurement), since these are the most natural units for mortals to use. However, for those inclined to space engineering, we have put a more practical vertical scale on the right: namely, the number of tons of rocket fuel needed for our one-ton rocket to escape from the solar system if only it could burn this fuel in a completely efficient manner. (Actual rockets' efficiencies run about 1/2 (%).)]

An Atomic System

We now leave the solar system and turn our attention to another kind of system—governed by a different one of the four fundamental forces of nature (see Part I of this series, pages 1-2). Figure 5 is taken from a text in *atomic physics*, and shows the similarity between an atomic system (the lithium atom) and the solar system. Of course, there are several important differences. The operating force in the solar system is gravity; in the atom it is electromagnetism. Furthermore, because the atom is so small, quantum mechanics becomes important, and we find that nature permits only certain "quantized" values of l to exist—those which are multiples of Planck's constant. However, if we consider the system as consisting of an electron orbiting around the nucleus just as the space ship was orbiting around the sun, certain important similarities become apparent.

For example, in Figure 5, just as in Figure 4, the dashed line connects the lowest angular-momentum state of the electron (labelled 1S) with all its recurrences. A little further up the chart we see a second state, labelled 2S, which can be thought of as representing a lighter space ship; it recurs as the states labelled 3P, 4D, 5F, etc. It is apparent that we could make sense out of all the information contained in Figure 5 simply by answering two questions: (1) Why do certain low-angular-momentum states occur? and (2) Why do these states recur? For the field of atomic physics, both these questions have, in fact, been answered. They were answered simultaneously, back in 1926, when quantum mechanics was first applied to the prob-

Fig. 4.

Fig. 5.

ENERGY LEVELS OF POSSIBLE ASSIGNMENTS OF POSITIVE-PARITY BARYONS

Fig. 6.

lem of an electron electrically attracted to a nucleus. But almost identical questions now face us in the field of particle physics, and it may be quite a long time before they are answered satisfactorily.

A Nuclear System

We are now ready to turn to the field of particle physics, and to the diagram (Figure 6) which presents nuclear states in the same form as we have used to represent a solar system and an atomic system. Before turning to Figure 6, however, let us review one important definition—that of the quantum number J , or spin. When we first introduced you to J , back in Part III of this series, we defined it, loosely, as “a measure of how fast a particle rotates about its axis, like the daily rotation of the earth.” You will perceive, then, that J is a property very closely related to the property l (angular momentum) which we have been discussing in regard to space ships and electrons. The slight difference between the two is that J , unlike l , includes the “intrinsic spin” of the whole system (i.e., sun plus space ship in our first example, nucleus plus electron in our second example). The value of J turns out to mark an important distinction between the two basic strongly interacting states, baryons and mesons. J for baryons is always a “half-integral value” (i.e., an integer plus a half), such as $1/2, 3/2, 5/2, \dots$, and so on. J for mesons always turns out to be a simple integral value, such as $0, 1, 2, 3, \dots$, and so on. The reason for this is the fact that each of the fundamental mass units of nuclear matter (A) has an intrinsic J value of $1/2$. Since baryons are defined as states with one fundamental mass unit ($A=1$), it follows that they must start out with a J of at least $1/2$. Mesons, on the other hand, are defined as nuclear states without any fundamental mass units ($A=0$); therefore, they are not endowed with the intrinsic half-integral J value of A .

In our simplified table of nuclear states (Figure 6), we have not included *all* the baryons and mesons presented in last month's "laundry list." Instead, for purposes of simplicity, we have chosen only *some* of the baryons—those which happen to have positive parity. (Parity, you will remember, is another of those intrinsic properties known as quantum numbers. Its value can be either $+1$ or -1 .) We have plotted rest mass, m , vertically *vs.* spin, J , horizontally for each of the baryon multiplets under consideration.

Let us turn to Figure 6 and identify on it the eight multiplets that seem to be independent "occurrences" (corresponding to space ships of differing weights). We find them on the left-hand side of the wavy line, four of them at $J = 1/2$ and four more at $J = 3/2$. (The other two

"supermultiplets" are not shown in our figure, since they have minus parity.) The supermultiplet at $J = \frac{1}{2}$ consists of the familiar stable baryons N (nucleon), Λ (lambda), Σ (sigma), and Ξ (xi); we have drawn them as solid dots. The supermultiplet at $J = \frac{3}{2}$ consists of three known resonances, $N^*(1238)$, $Y^*(1385)$ and $\Xi^*(1530)$ (each separated in mass from its neighbor by 146 MeV) plus one stable singlet, $\Omega^-(1676)$. We have used triangles to represent this supermultiplet: solid triangles for the three known states and an open triangle waiting for the Ω^- .

Now on to recurrences! You will remember from our discussion of atomic physics that it was found that nature permits recurrences of electron orbits only at certain, specific "quantized" energy levels. A similar phenomenon is operative in particle physics. It turns out that a nuclear state can recur only every time J increases by *two* (not by one). Thus we can expect occurrences at $J = \frac{1}{2}$ to lead to recurrences only at $J = \frac{5}{2}$, $J = \frac{9}{2}$, etc. Similarly, occurrences which start out at $J = \frac{3}{2}$ can generate recurrences only at $J = \frac{7}{2}$, $J = \frac{11}{2}$, etc. If

you will turn again to Figure 6, you will see that there are indeed two resonances known whose J 's are $\frac{5}{2}$: the "pion nucleon" resonance doublet $N^*(1688)$ and a singlet $Y^*(1815)$. We have drawn them as dots and labelled the lower dot N^{II} to indicate that it is probably the recurrence (i.e., the second occurrence) of the nucleon doublet N . $Y^*(1815)$ similarly is labelled Λ^{II} . Above these two solid dots are two open dots waiting for Σ^{II} and Ξ^{II} to show up.

More Recurrences

Referring back to our "rules of nature," we would expect the next dot recurrences (N^{III} , Λ^{III} , Σ^{III} , Ξ^{III}) to fall at $J = \frac{9}{2}$. Again, sure enough, another resonance $N^*(2190)$ may have $J = \frac{9}{2}$; we have optimistically labelled it N^{III} . The other possible members of this $\frac{9}{2}$ supermultiplet are shown as open dots. We have drawn a solid line through N , N^{II} , and N^{III} . This line (which corresponds to the curve with which we connected the possible "states" of our space ship) is called a "Regge trajectory" after T. Regge, who, in 1959-60, made the first careful theoretical study of the relations between recurring states.

A Theory to Test

The admirable thing about Regge trajectories is that they make so many specific predictions that it should be possible to prove or disprove the whole theory experimentally within a very short time. Note, for example, that the resonance $N(1238)$, first shown as a filled-in triangle at $J = \frac{3}{2}$, should recur at $J = \frac{7}{2}$ and $J = \frac{11}{2}$. Its recurrence at $J = \frac{7}{2}$ has already been demonstrated experimentally, and the recurrence at $J = \frac{11}{2}$ is now being studied.

Earlier we spoke of the only independent $J = \frac{3}{2}$ "occurrence" which has still eluded the experimenters—the stable singlet Ω^- .¹ In our next article, "The Eightfold Way," we shall attempt to show just why the existence of this singlet is predicted by current theory—and why high-energy physicists at LRL and all over the world are running their atom-smashers 'round the clock in the search for this highly significant speck of matter.

¹ Discovered at Brookhaven National Laboratory, February, 1964.

Part VI: Supermultiplets

In the course of our discussion of elementary particles, a progressive simplification has begun to take shape. (You mean to say you haven't noticed?)

Beginning with a motley collection of empirically discovered "particles," we first showed, back in Part III, that it is not necessary to distinguish between particles that are similar in every property except their electric charge, since charge plays no role in the strong interaction. Consequently, we were able to stop referring to individual particles and to begin talking instead about "charge multiplets" (e.g., the nucleon doublet: neutron and proton).

Having come this far, we were then able to arrange these charge multiplets in a simple "laundry list" according to increasing mass.

Supermultiplets

Then, in Part V, we carried our simplification a step further. We pointed out that multiplets can be grouped into "supermultiplets" on the basis of the important quantum properties known as spin (J) and parity (P). A supermultiplet was defined as a group of charge multiplets with identical values of J and P . We illustrated two of those supermultiplets—the positive-parity baryons with a J value of $1/2$, and the positive-parity baryons with a J value of $3/2$. At the same time we pointed out that six more supermultiplets exist: two for the minus-parity baryons and four for the mesons.

Recurrences

All other multiplets (i.e., those with higher values of J) we then agreed to consider as simply recurrences of one of the root multiplets contained in the eight basic supermultiplets. We saw, for example, that the "nucleon doublet," a member of the supermultiplet at $J = 1/2$, has a recurrence at $J = 5/2$ and another likely one at $J = 9/2$. We called the line which connects various recurring states a "Regge trajectory," after the man who first studied these relationships.

(It should be stated here that no certified recurrences have so far been found among the minus-parity baryons or among mesons. However, we can point to some striking recurrent series among the heavy nuclei, which we shall take up in more detail later.)

In this month's installment, we are going to rearrange our "laundry bundle"

of particles once again. This time, however, we shall narrow our field of interest still further, and look only at those supermultiplets which we have identified as "root" or "ground state" occurrences. (Obviously, if we are able to deduce the laws which govern the root states, they will also govern the recurring states.) Our purpose here is to see if, by further rearrangements and reshufflings of the particles, we can shed some light on the forces that cause particles to occur in supermultiplets.

Ground States

Let us turn our attention, then, to the eight independently occurring supermultiplets (of which two were shown in our Figure 6 last month). In all, the eight root supermultiplets are as follows: the positive-parity baryons at $J = 1/2$, the positive-parity baryons at $J = 3/2$ (both illustrated last month), the minus-parity baryons at $J = 1/2$, the minus-parity baryons at $J = 3/2$, and four equivalent groupings for mesons. All nuclear states which occur at higher values of J (for example, the baryons at $J = 5/2$) can be dismissed as recurrences of one of these eight supermultiplets.

A Familiar Octet

Now let us take one of these supermultiplets, the positive-parity baryons at $J = 1/2$, and try rearranging its component particles to see if any patterns emerge. The supermultiplet at $J = 1/2$ should be an old friend by now: it is the octet containing the familiar stable baryon multiplets N , Λ , Σ , and Ξ . Since all these multiplets have, by definition, the same values of spin, J , parity, P , and, of course, A , we can eliminate those three quantum numbers from any further rearrangements. That leaves us with four nuclear properties still unexplored: (1) electric charge, Q ; (2) hypercharge, Y , alternatively expressed as twice the average charge, $\langle Q \rangle$, or in terms of the strangeness, S ; (3) isotopic spin, I , alternatively expressed as multiplicity, $M = 2I + 1$; (4) mass, m . (See Part III for further definitions of these quantum numbers.)

The Plots Thicken

What illuminating relationships can we find among these four remaining numbers? Let us start by making more plots, and let us arbitrarily pick Q as one variable, which we shall plot, say, horizontally. For our vertical scale, we

can now choose between I , Y , and m . Our first choice might easily be I , but we leave it to the reader to experiment and convince himself that we don't see anything very striking on such a figure. That leaves us Y or m , and since we want to discuss m in detail in the next installment, we shall choose Y . (Also, to permit our plots to come out a little more symmetrical and striking, we are going to adjust the horizontal scale to read $Q - \langle Q \rangle$ rather than simply Q . This adjustment introduces nothing new, but makes for a much prettier picture.)

Plotting Patterns

When we arrange the eight baryons which form the $J = 1/2$ supermultiplet on these Y vs. Q scales, a striking design appears. It is a hexagon, with two particles at the center and the remaining six particles forming the six corners of the figure (Figure 7, Sketch A). Now let us try arranging another supermultiplet on the same scales. This is the octet of stable mesons found at $J = 0$. Voila! Another hexagon, again with two particles at the center and the remainder outlining the perimeter (Figure 7, Sketch B). And exactly the same pattern appears again for the unstable mesons at $J = 1$ (Figure 7, Sketch C).

A different pattern, but one strikingly symmetrical in its own fashion, appears when we plot the unstable baryons at $J = 3/2$. The figure is a triangle containing ten particles—a multiplet of four baryons at the base, a multiplet of three forming the next row, a doublet forming the next, and a singlet (predicted but not yet discovered) at the apex.

Hexagons and Triangles

If we continue to plot all of the eight ground-state supermultiplets on these Y vs. Q scales, we find that all of them form either hexagons of eight particles or triangles of ten particles—except for two puny supermultiplets which are singlets, and therefore cannot form any pattern, and one which either doesn't form particles at all or is just now being discovered. We can sum up, then, by stating that the particles of all known supermultiplets, when plotted on scales of Y vs. Q , can assume only three patterns: single points (singlets), hexagons (octets), or triangles (decuplets).

In our previous installment, we spoke of the only independent $J = 3/2$ baryon

which has still eluded the experimenters—the Ω^- at 1676 MeV. If you will glance at the triangle decuplet in Sketch D of Figure 7, you will see why this particle is considered so important just now. In the first place, it is the only member of a root supermultiplet still undiscovered; furthermore, it falls at a crucial point, since it forms the apex of the triangle decuplet. Until it is discovered experimentally, we are not strictly justified in calling this baryon supermultiplet a triangle decuplet, even though most physicists feel confident that it is—and that the missing Ω will be discovered soon.¹

The Eightfold Way

The symmetry of the supermultiplet

¹Discovered at Brookhaven, Feb. 1964.

arrays—singlets, triangles, and hexagons—is so striking that it is difficult to escape the conclusion that some important message of nature is hidden in these patterns, could we but read the code. The most successful attempt so far to do just that is found in the theory known as the Eightfold Way, conceived independently in 1961 by theoretical physicists Murray Gell-Mann, at Cal Tech, and Y. Ne'eman, at Imperial College, London. On the basis of the ideas contained in the Eightfold Way, Gell-Mann and Ne'eman were able to predict the existence of all the nuclear states shown in our figure—even though, at that time, the membership of only one octet was complete (cf. solid black dots in Sketch A).

Of Gell-Mann, this sort of dramatic insight was to be expected; he had already

been the first to understand many (perhaps most) of the important relations in particle physics. Colonel Ne'eman, on the other hand, was previously unheard of in particle physics. An Israeli, he was, at the time of his discovery, military attaché at the Israeli embassy in London, working at Imperial College in his spare time.

What Gell-Mann and Ne'eman did in formulating the Eightfold Way had two important results. First, it provided a means of organizing a great mass of experimental data and predicting the results of further experiments. Second, it shed new light on an important question we broached early in this series—the question of whether or not some really “primitive” or “elementary” states of matter do exist. In our next article, we shall take up these questions in more detail.

Part VII: The Eightfold Way

In recent installments of this series, we have grouped the well-known, lowest-mass strongly interacting particles into groups called "supermultiplets" composed of particles having identical spin J and parity P . We observed that each of these supermultiplets contained either one, eight, or ten particles; accordingly, we named the groups singlets, octets, and decuplets respectively.

Then, in last month's article, we plotted each of these supermultiplets, using as scales Y (hypercharge) vs. Q (electric charge). We saw that supermultiplets arrayed in this fashion form several striking designs. The three octets appeared as hexagons, and the decuplet appeared as an unfinished triangle. The singlets, of course (of which we have three or four), cannot form any pattern.

A Prophetic Guess

Just as striking as the symmetry of these arrays is the fact that they were predicted, by Murray Gell-Mann and Y. Ne'eman, in January, 1961, when the membership of only one octet was complete. (The sketch shown last month, you will remember, had 19 solid dots, representing states known before the independent contributions of Gell-Mann and Ne'eman, 14 open dots, representing states predicted and later verified experimentally, and one "dashed" dot, representing the state still awaiting "discovery.")

How were Gell-Mann and Ne'eman, on the basis of such sketchy evidence, able to formulate a theory that has proved so fruitful in particle physics? One clue that doubtless aided them was the familiar example of the "periodicity" (of 2, 8, 18, 36, etc.) in the "elements" of chemistry, represented in the well-known periodic table of the elements.

Hints from Chemistry

In the case of the periodic table, we know that certain physical laws, acting on the electrons and nucleus of the atom, are responsible for the periodic character of atomic states. Really, the complete explanation of the atom involved both a force law and a symmetry principle. The force law is that of the electrostatic attraction between the electrons in an atom and the nucleus of the atom, according to the laws of quantum mechanics. The symmetry principle was discovered by Pauli in 1925; it states that no two electrons can share the same state.

We can picture Gell-Mann and Ne'eman's reasoning proceeding something like this: If an atom can be explained as a composite of nucleus and electrons acting together under certain physical and mathematical laws, let us see if we can similarly visualize "elementary" particles as composites, or bound states, of even more primitive particles.

But How Many?

To pursue this radical idea, they next asked what would be the *absolute minimum number* of such primitive particles needed in order to form all the known baryons and mesons—i.e., to construct arrays (like hexagons) on a plot where the variables are electric charge Q and hypercharge Y . Now, we know that the real proton and the real neutron have the same Y but different Q 's, so we shall have to invent at least *two* primitive

particles, one neutral (which we could call n') and one charged (which we could call p'). That much would be fine for all the common "nonstrange" parti-

cles, with a hypercharge number of $+1$, but it doesn't take us far when we try to construct (or plot) particles with different hypercharges (related like n and Λ). To construct these particles, we'll need a third primitive particle (which we could call Λ'). Actually the symbols p' , n' , and Λ' are misleading, since they suggest that we can actually discover new primitive particles with the quantum numbers of the p , n , and Λ . We'll see later that this is an oversimplification, so let us instead choose three primitive states called $P(1, 0)$ (where the P stands for Primitive, the 1 for $Y = 1$, and the 0 for $Q = 0$, i.e., neutral), and $P(1, +)$ and $P(0, 0)$. Then the law of particle-anti-particle symmetry tells us that there must also exist three anti- P 's called $\bar{P}$, namely $\bar{P}(-1, 0)$, $\bar{P}(-1, -)$, and $\bar{P}(0, 0)$.

Now we can construct all the real mesons as $\bar{P}P$ combinations; thus π^- can be thought of as a composite of $\bar{P}(-1, -)P(1, 0)$, K^- could be $\bar{P}(-1, -)P(0, 0)$, $\bar{K}^0$ as $\bar{P}(-1, -)P(0, +)$, K^0 as $\bar{P}(0, 0)P(1, 0)$, etc. (Convince yourself that three P 's are just the right number: two is too few, four is redundant.)

Note that the P 's can have any value of atomic mass number A . Since the mesons are made out of $\bar{P}P$ pairs, and since

$\bar{P}$ and P have opposite values of A , the atomic mass number of the mesons is guaranteed zero, as it must be.

Finally we have to make baryons, and to do this we'll need one more primitive particle that carries one unit of A ; in fact let's call it $A(0, 0)$ to indicate that it has the essential properties of a baryon ($A = 1, J = \frac{1}{2}$), and all other quantum numbers zero except for its mass, which doesn't matter, since the A is unobservable anyway. Now, in our thinking we can go two ways, it doesn't matter which one. We can think of *real* baryons as composites of A with real mesons—thus $p = A\pi^+$, etc.—or we can visualize the A combined with our three P 's to make three primitive baryons $B(1, 0)$, $B(1, +)$, and $B(0, 0)$; and then think of making real baryons out of pairs of B and P . As long as you realize that there are many alternatives, you won't get the misleading idea that the theory is going to predict specific primitive particles that will soon be discovered.

Given this arsenal of a few primitive particles interacting strongly according to unknown laws, how many different sorts of composite states can we expect them to form? To hint at the answer we shall have to mention Group Theory, the branch of mathematics that deals with symmetries—i.e., such questions as "What are all the regular arrays you can draw on the surface of spheres in 2, 3, 4, ... dimensions?"

The Uses of Mathematics

As an example, let us present a rather corny version of a symmetry argument, involving currency instead of geometry. Suppose we asked a cashier for change of a dollar, and suppose further that she has a particularly aesthetic sense of symmetry, so that (depending on the contents of her cash register) she will always give us two coins, or four, or ten, or twenty, or one hundred, but never one, or three, or seventeen, or any number greater than one hundred. If she chooses to emphasize symmetry in this way, we can obviously learn some principles of currency by observing the numbers of coins she gives us.

Now, group theory isn't this trivial—but, at times in the past, it may have seemed just as divorced from practicality. In the nineteenth century, Sophus Lie studied symmetry operations with different numbers of basic objects. Later it was shown that the simplest appropriate "Lie Group," called $SU(3)$, or Special Unitary

Group of size 3 by 3, must contain one, eight, ten, or twenty-seven members, and that the "representation" with eight members should be arranged as a hexagon. Back in the nineteenth century, nobody bothered very much about whether there would ever be a physical example of such arrays, but, in our own time, noted these clues, specifically that the "3" in $SU(3)$ is related to the three P's.

The Noble Truth?

At the time (1961), you will remember, the only known supermultiplets were octets (one complete, one seven-eighths completed), so Gell-Mann christened the whole scheme the Eightfold Way (if "christened" is the right word to use in connection with a venerable term borrowed from Buddhist and Taoist philosophy²).

The basic assumption, then, of the Eightfold Way is that the four primitive states, in combinations governed by the laws of the Lie Group, $SU(3)$, are involved in the formation of all nuclear states, or particles. With this tentative formulation in mind, Gell-Mann and Ne'eman then proceeded to push ahead and exploit to the limit all known properties of the $SU(3)$ group.

Meanwhile, as you know, the experimentalists did their bit by finding nine-tenths of the ten-group, the decuplet (though they have not as yet uncovered any recognizable fraction of a 27-plet). It was gratifying to note that Lie's rules for $SU(3)$ relationships predicted that

² Now this, O monks, is the noble truth of the way 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. — Buddha, "The Four Noble Truths," circa 500 B.C. [W. Durant, "The Story of Civilization," 1,430 (1954)].

the decuplet should be arrayed as a triangle, and, sure enough, that's exactly how it turned out.

Formation of Multiplets

To give a physical explanation to supermultiplets, Gell-Mann and Ne'eman took a hint from the fact that the strong interaction doesn't seem to "care very much" about the quantum number Q (electric charge), so that, as we have seen, as long as states have all of their other quantum numbers in common, they have the same mass and hence form a charge multiplet (see Part III). Further, from this hint, they went on to guess that the strong interaction also doesn't "care very much" about the quantum numbers I and Y (in fact, it mixes them in an interesting way), so that, as long as our primitive objects pair up with the same A , J , and P , they are found in supermultiplets, with each member having nearly the same mass.

Moreover, Gell-Mann and Ne'eman showed that three primitive objects interacting according to the rules for the Lie Group $SU(3)$ should show a certain special relationship between their masses; let us call these relationships a "mass rule."

Mass Rules

The mass rule for decuplets is particularly simple: it says that the mass spacing should be equal. When the decuplet supermultiplet was predicted, only the $N^*(1238)$ charge quartet was known; in Figure 7, this quartet was shown under its more modern name, $\Delta(1238)$. After that Y^* and Ξ^* were discovered, and were found to have the same J and P as Δ . $Y^*(1385)$ lies 147 MeV above $\Delta(1238)$, and $\Xi^*(1530)$ lies 145 MeV above Y^* . No wonder we expect to find $\Omega^-(1676)$ 146 MeV above Ξ^* !

The mass rule for the octets is a little more complicated, but it has been very exciting in the past year or so to watch

it predict all the open circles shown in the sketches earlier. The Eightfold Way has also had other successes—and also a few failures—but they are not so easy to describe here.

It should be pointed out that the Eightfold Way conflicts with experiment in a few serious places, so we should not assume that this theory can tell us the whole story of particle physics. Like so many useful theories in the past, it is only a useful approximation. It contains gaps and areas of vagueness: What does it really mean, after all, to say that the strong interaction "doesn't care 'very much' about Q , I , and Y ? Notwithstanding such imperfections, most physicists now accept the basic concept that any strongly interacting particle must to a great extent be viewed as a composite of all other strongly interacting particles.

Are They Real?

The time has now come to face up to the question that we have so carefully evaded in our previous articles: Do the "primitive" states postulated in the Eightfold Way really exist? And are they "elementary" in any fundamental sense? Possibly, but not necessarily. They may be just convenient ways of picturing properties of the strong interaction, just as lines of force are a good way to picture electric and magnetic fields. In any case, they certainly interact so strongly that one cannot easily conceive of "discovering" them in a pure, untarnished form. And, since modern physics stubbornly refuses to define as "real" any object that is in essence undiscoverable, the question becomes more of a philosophical one than a matter for the experimental scientist.

This brings us pretty close to the end of our story (for the time being, at least). In the final installment, we will look back to review what we have learned, and forward to see what the immediate future may hold in the field of "elementary particle" physics.

Part VIII: Summary & Conclusions

The significance of the term "elementary particle" has varied enormously as the scientist's view of the physical universe has become more detailed and precise: the changes in its meaning mirror the history of modern physics.

In the time of Newton and for almost a century thereafter, the connection between the structures of different materials was not understood, and there were, in this view of our world, as many elementary particles as there were kinds of matter: water, salt, oxygen, iron, quartz, etc.—an immense number.

The uncovering of a finer structure of matter, mainly in the nineteenth century, revealed that all matter, with all its different sorts of molecules, was composed of fewer than 100 kinds of atoms; these became the elementary particles of last century's physicists.

Wrong Again?

Early in this century we had our first look inside the atom—and our first recognition that these 100 atoms were again not the elementary particles of our universe, but were each made up of a very small core, the nucleus, surrounded by one or more electrons, whose configurations determined the chemical properties of the atom. Moreover, these electrons could have many possible configurations. Thus, in Fig. 5 of Part V of this series, we displayed an energy level diagram of the lithium atom, showing that the substance we call "lithium" is really much more than one single state of matter: in addition to the familiar ground state, with the electron bound by 5.37 volts, there are hundreds of other possible states. Thus lithium is really the name of a whole family of states or "particles."

More than three decades ago the tiny nuclei were themselves split open. Observations were difficult, fuzzy, approximate, but clearly showed that all nuclei are composed of combinations of protons and neutrons.

A Closer Look

For nearly a decade following this discovery, the number of accredited "elementary" particles of our universe stayed reasonably small; the particles were the proton, the neutron, the electron, the photon, and the neutrino. But as soon as instruments were able to resolve still finer detail, protons and neutrons revealed a substructure involving a host of new strongly interacting particles. This new breed of elemen-

tary particle started a violent population explosion, mitigated only slightly by the recognition, about 1955, that there is an antiparticle corresponding to every particle, so that one can divide the head count by two.

In this series, we have tried to show that, if we systematize what we know, the population explosion in elementary particles can be brought under reasonable control. Some people still ask if *some* of the strongly interacting particles are not "more fundamental" than others. This is a perfectly sensible question, but there are, as yet, no facts that suggest an answer. IRL theoretician Geoffrey Chew, one of the leaders in the field of high energy physics theory, likes to counter this question with another one: "Why not just assume *democracy* among the strongly interacting particles?" Why not assume, that is, that they are all equally fundamental creatures of the strong interaction.

This brings us to the last new idea in this series: the idea of the "bootstrap" explanation of the strong interaction. Physicists have for years explained "action at a distance" in terms of the exchange of particles ("field quanta") between the interacting objects. Thus, Sketch 1 on the following page shows our picture of the solar system held together by "gravitons" exchanged between the sun and a planet. By "exchange" we imply that gravitons are emitted by planets and absorbed by the sun, and vice versa. Using this model, we would say that "the solar system is held together by the graviton force."

Sketch 2 shows an atom, held together by the exchange of photons, and Sketch 3 shows a nucleus, held together by mesons. (Before 1961, we would have said that "nuclear particles are glued together mainly by π mesons"; now, since the discovery of other kinds

of mesons, we would have to add "... by π , η , ω , ρ , ϕ , etc. mesons.") Since these mesons are exchanged over very small distances in very short times, it makes no difference whether they are stable (like the π and the η) or unstable (like the ρ , ω , etc.). Again, we visualize the meson as emitted by the neutron and absorbed by the proton, and vice versa.

An Incestuous Affair

All very reasonable and straightforward, you will probably agree—but here comes the not-so-reasonable part. Figure 8 shows another system, the ρ meson, again held together by the exchange of mesons. The rho itself is mainly a semistable state of two very strongly interacting π mesons; eventually, it usually breaks up into these two pions. Now it turns out that certain considerations of spin and parity forbid two pions from exchanging another pion, so that the most important contributor to the pion-pion forces must be none other than the ρ meson itself. So for this system we would have to say that the ρ meson is glued together mainly by the exchange of ρ mesons! "Exchange" implies that ρ 's are emitted by one pion and absorbed by the other, and vice versa. In other words, this somewhat incestuous picture shows a ρ pulled together by its own bootstraps. (Perhaps now you can see more clearly why we have made such a fuss about strongly interacting particles being considered creatures of the strong interaction.)

Theoretical physicists hope soon to have enough data on strongly interacting states to be able to calculate a self-consistent picture of each of them as a delicately balanced composite, held together by itself and by all other states. Some theoreticians even guess that there will turn out to be only one self-consistent solution, which will then explain all the properties of the strong interaction. In any case, it is easy to see that just any old force would not have a chance of satisfying all the coupled conditions imposed by the bootstrap idea. Bootstraps, therefore, gives us a "handle" for learning a lot more about the special complicated force we call the strong interaction.

Summing Up

Let us summarize very briefly what we have said in this series.

First, we discussed the four basic

forces of nature. We pointed out that science does not yet understand how these four forces are related, nor why some states of matter, or "particles," feel only one force, some two, some three, and some all four. But the strong interaction is so powerful that those states which *do* feel it (or, as we would say, "are coupled to it") are influenced by it almost to the exclusion of any other force, and are so moulded by it that it is best to think of them as being "creatures" of the force itself.

Quantum Numbers

In Part III, we saw that strongly-interacting states are characterized by seven quantum numbers: atomic mass number (A), hypercharge (Y), multiplicity (M), electric charge (Q), mass (m), spin (J), and parity (P). Some mesons have, in addition, an eighth quantum number, G -parity (G). Not all quantum numbers, however, play equally important roles in the strong interaction. Most significantly, the strong interaction seems to ignore Q , the electric charge. Thus we were able to organize the states into charge multiplets, members of which could have different values of Q as long as their other six numbers were shared in common. As an example we offered the "nucleon charge doublet," consisting of the neutron (charge = zero) and the proton (charge = plus one).

Recurrences

In Part V, we considered some familiar stable composite systems: the solar system, the atom, and the nucleus. We showed that low-energy states, with low angular momentum ("spin") tend to breed higher-energy "recurrences" at higher angular momentum. In particle physics, these recurrences are said to lie on a "Regge trajectory." Thus we reduced our organizational task to a consideration of those charge-multiplets which lie at the roots of Regge trajectories; these roots all have spin of less than $3/2$. For mesons there are only four such root values of J and P : $J^P = 0^+, 0^-, 1^+,$ and 1^- . For baryons there are again only four: $J^P = 1/2^+, 1/2^-, 3/2^+,$ and $3/2^-$.

Supermultiplets

In Parts VI and VII, we saw that corresponding to each of these eight root values of J^P we find either one or four

Action at a Distance: Field Quanta

Fig. 8.

charge multiplets, and that, if we count all the charge states in a multiplet, we find states occurring in groups of either one, eight, or ten (called "supermultiplets"). And we saw how Gell-Mann and Ne'eman first pointed out the remarkable connection between this fact and the mathematical properties of Lie groups.

Since we have seen that the application of the adjective "elementary" is merely a reflection of our current thinking, perhaps we could say that now the number of "elementary" strongly interacting particles has reached a temporary new low: four supermultiplets for the mesons, four for the baryons, with some chance of accounting for the arrangements within the supermultiplets by means of the Eightfold Way and its possible "primitive" subparticles. And of course we view the higher- J resonances just as Regge recurrences. But surprises are doubtless lurking in half-processed experiments, and our count of elementary states may soon start to rise again.

So much for progress up to the present. What of the future? The most natural thing for scientists to do next is to push experiments up to higher energies, using the 25-plus BeV available at the proton synchrotrons of Brookhaven and CERN, and higher energy machines as they are built. We may very well discover some new quantum numbers at these higher energies. After all, at the time the construction of the Bevatron was begun, we knew nothing of hypercharge, so that we were working in a space where some of the dimensions were not even known. (Imagine, for example, how difficult it would be to visualize the real three-dimensional world if one knew of only two dimensions, and could conceive of things only as they look projected on a plane!)

At very high energies we also know that the weak interaction becomes more

important, so perhaps the new high-energy machines can give us a clue concerning the relationship between weak, electromagnetic, and strong interactions. And we might find that space-time itself turns out to be "quantized" at these very high energies—that is, space and time may come in "grainy" bundles like the other quantum numbers we have been familiar with. (Note that within the last few hundred years many things that seemed smooth and continuous have turned out to be available only in grainy packets or units.) And, finally, there is always the possibility that we might find even more primitive particles.

A Better Mousetrap?

Will all this lead to the construction of a "better mousetrap"—a still unforeseen practical application that will revolutionize technology as the splitting of the atom did two decades ago? That is hard to say. We think that we are working on a frontier remote from mousetraps, just learning about the architecture of nature and hoping one day to relate all four basic forces of nature. On the other hand, in the past most new knowledge *has* led to unexpected applications. History could very well repeat itself.

In closing, I'd like to express my thanks to two indispensable members of this expedition across the frontiers of elementary-particle physics. Our cartographer, technical illustrator Bob Stevens, provided the sketches, diagrams, and tables which served as maps through those dangerous verbal swamps we encountered on the way. Our interpreter, MAGNET Editor Judith Golwyn, pointed out landmarks along the route, reassured the explorers with pious exhortations, kept the whole wagon train heading in the right direction, and—like any good interpreter in a strange land—dealt firmly but fairly with the native guide.

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