An Elementary(?) Guide to Elementary(?) Particles

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

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INTRODUCTION

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 to matter, mainly in the nineteenth century, revealed that all matter, with all its different kinds of molecules, was composed of fewer than 100 kinds of atoms; these became the elementary particles of last century's physicists. 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 various configurations determined the chemical properties of the atom.

More than three decades ago the tiny nuclei were themselves split open. Observations inside the nucleus were difficult, fuzzy, and approximate, but they clearly showed that all nuclei are composed of combinations of protons and neutrons. 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—and very oddly behaving—particles. This new breed of elementary particle started a violent population explosion, doubly compounded by the confirmation (with the discovery of the antiproton in 1955) that there is an antiparticle corresponding to every particle. In this article we try to show how, by systematizing what we have learned about the elementary particles, the population explosion can perhaps be brought under reasonable control. In order to do so, we shall have to begin by reviewing some rather basic discoveries and ideas of natural science.

I. THE FOUR FORCES OF NATURE

Throughout this immense and diverse universe, scientists have been able to discover only four basic ways in which objects can interact with each other—four fundamental forces that account for all the various forms of matter and action found in the universe. Two of these forces are reasonably familiar, the other two are still new and mysterious even to physicists. The four forces are gravity, electromagnetism, the strong interaction, and the weak interaction. They are summarized in Table I. Let us examine each of them in turn.

1. Gravity is the force that causes all objects to attract one another with a force proportional to their mass or energy. Gravitational force is exerted by all forms of matter, but 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 that holds the earth together, binds the sun and the planets into the solar system, and grips solar systems into vast galaxies. Strangely enough, despite its tremendous and impressive effects, gravity is actually the weakest of the four forces of nature.

2. Electromagnetism is the force that 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. Electromagnetism is about 10^{36} times stronger than gravity; it is the electromagnetic attraction which governs all of chemistry and biology.

3. The strong interaction, which will concern us most in this article, is the force that glues nuclear particles together, binding subnuclear "building blocks" into the nuclei of all elements. It is by far the strongest force in nature. For example, electromagnetism binds an electron to a proton with an energy of 13 units called electron volts (eV), forming a hydrogen atom. Compare this with typical binding energies of 10 million electron volts (MeV) for neutrons and protons in nuclei. The nuclear force is so strong, in fact, that high-energy accelerators and reactors were needed to break nuclear bonds and bring about, for the first time, man-made nuclear reactions. The "particles" of nuclear matter which figure in strong-interaction processes are called mesons, baryons, and clusters of baryons

Table I. The four forces of nature, and the system they create.

Force:	1. Gravity	2. Electro-magnetic	3. Weak	4. Strong
Acts On:	All particles with mass	Particles with electric charge, and photons	Leptons, mesons, baryons	Mesons, baryons
Relative Strength	10^{-36}	1	10^{-12}	100 to 10^6 (depends how you measure it).
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

called nuclei. Mesons and baryons differ from each other in certain important ways which will become clear later, when we discuss those properties of nuclear particles known as quantum numbers.

4. The weak interactions is the force that causes certain very light particles known as "leptons" to interact with each other and with mesons, baryons, and nuclei. These curious leptons—the electron, the neutrino, and the muon—seem to be immune to the strong interaction; instead, their activities seem to be wholly dependent upon the still-mysterious force that physicists call the weak interaction. It is this force which is responsible for the well-known "decay" of radioactive elements, as in the gradual 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 distances. In this respect it differs from gravity which, while also weak, can extend its effects over vast distances. Because of this deficiency the weak interaction does not "form" a stable organization of matter in the sense that the gravitational force can "form" a solar system, the electromagnetic force can "form" an atom, or the strong interaction can "form" a nucleus.

Most physical objects and systems, it should be remembered, are governed by more than one of the four forces of nature. Thus, both gravity and electromagnetic forces act on solar systems; gravitational, electromagnetic, and strong forces act on heavy nuclei, etc. If more than one force is acting, the effect of the weakest will often be masked beyond detection, so that we are ordinarily aware of only one force at a time.

II. ELEMENTARY VS COMPOSITE PARTICLES

In the light of the preceding discussion, perhaps we can now understand why physicists have, in the past few years, decided that it makes little scientific sense to call any objects "elementary." We have seen how gravity acts on certain basic objects (sun and planets) to form a composite entity--the solar system. Gravity and the electromagnetic force, in turn, act on other basic objects (atoms and molecules) to form the composite entities known as the sun and the planets. Electromagnetic forces, similarly, act on other objects (nuclei and electrons) to form composite entities earlier thought indivisible—the atom and the molecule. The strong interaction, in its turn, acts on mesons and baryons to form nuclei, and may act on even more primitive objects ("quarks") to form mesons and baryons themselves. Since the terms "elementary" and "composite" obviously have shifting meaning depending on one's point of view and the force being considered, physicists have decided that it makes more sense simply to refer to all physical entities as "states" of the force which forms and maintains them. In this language, a solar system would be considered a state of the gravitational force (since it is this force which is primarily responsible for maintaining it), an atom would be considered a state of the electromagnetic force, and a nuclear particle would be a state of the strong interaction. Aggregates of matter which are "elementary" in one system are, of course, "composite" in another, but both terms are, in this language, superfluous, and can be omitted entirely.

You may object that this sort of renaming is a matter of semantics only, and of no fundamental importance. But scientists have found that, simply by freeing themselves of old-fashioned and constricting notions about "elementary" and "composite" they have been able to make great progress in organizing and understanding the great mass of information discovered experimentally in recent years.

Population Explosion. The beginnings of the population explosion in elementary-particle physics may be traced as far back as 1932, the year in which two important new particles were discovered–the neutron, by Chadwick in Cambridge, and the positron, by Anderson in Pasadena. Yet neither of these new particles did much to disturb the comfortable models of the nucleus that had been erected around the previously known "elementary particles"—the proton, the electron, the photon, and the neutrino. The bewildering discoveries began in 1947, when physicists found so-called "strange" particles (so-called because they lived almost a million million times longer than scientists expected them to) in cloud-chamber pictures of cosmic rays. Within the next few years, seven new strange particles had been discovered, and theoretical physicists had developed a fairly reasonable explanation for their "strange" long-lived behavior. It appeared that these particles are produced in pairs through the strong force, but cannot decay by the same force once they are separated from each other. When they do break up, it is only through the workings of the weak force, which is a far slower process.

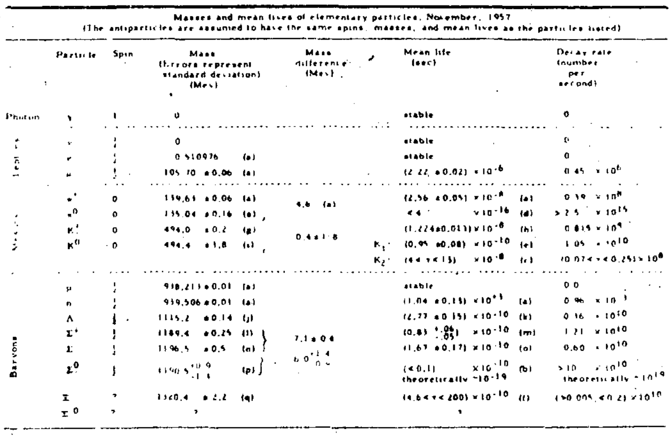
Particle discoveries continued to grow during the fifties, with the discovery of several more strange particles. Finally, in 1960, the flood gates were opened with the discovery of the first of the "strange-particle resonances" in film from the 15-inch bubble chamber at the University of California's Lawrence Radiation Laboratory. A resonance is a strong-interaction state that is so short-lived that physicists were at first reluctant to class it with the particles. More recently, however, it has been recognized that the distinction between "particle" and "resonance" is no more helpful than that between "elementary" and "composite," and all these states are now lumped together. Since 1960, the particle population has grown so enormously that it would be futile, in this present context, to try to present any kind of "complete list" of known particles. Instead, the reader may be interested in referring to Tables II and III, which illustrate more clearly than any words the great progress of the past few years. In Table II, you see a wallet card prepared in 1958 as a convenient way for physicists to carry around all the data on all the known particles. Since then, the wallet "card" has grown to a booklet, with mesons and baryons each occupying several pages. Table III shows half of the 1969 meson table, half being as much as will fit on one page of this article.

III. MULTIPLETS AND THEIR SIGNATURES (QUANTUM NUMBERS)

You will notice that the 1958 wallet card had plenty of space to list each electric-charge state, e.g. Σ^+, Σ^0, Σ^-, separately. Now, however, we group them all into a single entry Σ, called a particle multiplet. This change in terminology reflects a convenient convention that physicists adopted when they noticed that one of the characteristics of particles, electric charge, appears to be a very superficial one so far as subnuclear forces are concerned.

Table IIa: The 15 "elementary particles at 1958."

From W. H. Barkas and A. H. Rosenfeld, UCRL-8030.



Masses and mean lives of elementary particles, November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)	Mass difference (Mev)		Mean life (sec)	Decay rate (number per second)
Photon	γ	1	0			stable	0
Leptons	ν	$\frac{1}{2}$	0			stable	0
	e	$\frac{1}{2}$	0.510976 (a)			stable	0
	μ	$\frac{1}{2}$	105.70 ± 0.06 (a)			$(2.22 \pm 0.02) \times 10^{-6}$	0.45×10^{6}
Mesons	π^+	0	139.63 ± 0.06 (a)	4.6 (a)		$(2.56 \pm 0.05) \times 10^{-8}$ (a)	0.39×10^{8}
	π^0	0	135.04 ± 0.16 (e)			$< 4 \times 10^{-16}$ (d)	$> 2.5 \times 10^{15}$
	K^+	0	494.0 ± 0.2 (g)	0.4 ± 1.8		$(1.224 \pm 0.013) \times 10^{-8}$ (h)	0.815×10^{8}
	K^0	0	494.4 ± 1.8 (i)		K_1:	$(0.95 \pm 0.08) \times 10^{-10}$ (e)	1.05×10^{10}
					K_2:	$(4 < \tau < 13) \times 10^{-8}$ (f)	$(0.07 < r < 0.25) \times 10^{8}$
Baryons	p	$\frac{1}{2}$	938.213 ± 0.01 (a)			stable	0.0
	n	$\frac{1}{2}$	939.506 ± 0.01 (a)			$(1.04 \pm 0.13) \times 10^{+3}$ (a)	0.96×10^{-3}
	Λ	$\frac{1}{2}$	1115.2 ± 0.14 (j)			$(2.77 \pm 0.15) \times 10^{-10}$ (k)	0.36×10^{10}
	Σ^+	$\frac{1}{2}$	1189.4 ± 0.25 (l)	7.1 ± 0.4		$(0.83\ ^{+.06}_{-.05}) \times 10^{-10}$ (m)	1.21×10^{10}
	Σ^-	$\frac{1}{2}$	1196.5 ± 0.5 (n)			$(1.67 \pm 0.17) \times 10^{-10}$ (o)	0.60×10^{10}
	Σ^0	$\frac{1}{2}$	$1190.5\ ^{+0.9}_{-1.1}$ (p)	$6.0\ ^{+1.4}_{-0.9}$		$(< 0.1) \times 10^{-10}$ (b) theoretically $\sim 10^{-19}$	$> 10 \times 10^{10}$ theoretically $\sim 10^{19}$
	Ξ^-	?	1320.4 ± 2.2 (q)			$(4.6 < \tau < 200) \times 10^{-10}$ (r)	$(> 0.005, < 0.2) \times 10^{10}$
	Ξ^0	?	?			?	

Table IIb: The one known resonance (unstable particle) of 1958.

(3/2, 3/2) πp Resonance

Center-of-mass momentum: p_π = 230 MeV/c

Lab-system momentum: P_π = 303 MeV/c (T_π = 194 MeV)

They found, for example, that two particles—like the proton and the neutron, or three mesons, π^+, π^0, π^- — are exactly the same in all their "nuclear" properties (i. e. , mass, interaction with other nuclear particles, etc.) even though they have different electric charges. Reasonably enough, physicists decided that they could group the particles into families, called "charge multiplets," which ignore electric charge. Each charge multiplet is assigned a family name, or "multiplet symbol." For example, the "nucleon" (N) is the multiplet that contains the proton (p) and the neutron (n). The π meson (called "pion" for short) is the multiplet that contains the π^+, π^0, and π^- mesons.

Table III. Mesons—the first half of the 1970 list of mesons.

[From Review of Particle Properties, Rev. Mod. Phys. Jan. 1970.]

Name	$I^G(J^P)C_n$ ⊢⊣ estab. ? - guess	Mass M (MeV)	Width Γ (MeV)	M^2 ±ΓM[(a)] (GeV)^2	Partial decay modes: Mode	Fraction %	p or p_{max}[(b)] (MeV/c)
$\pi^+(140)$ $\pi^0(135)$	$1^-(0^-)+$	139.58 134.97	0.0 7.2 eV ±1.2 eV	0.019483 0.018217	See Stable Particles Table		
$\eta(549)$	$0^+(0^-)+$	548.8 ±0.6	2.63 keV ±.64 keV	0.301 ±.000	All neutral $\pi^+\pi^-\pi^0 + \pi^+\pi^-\gamma$	71 29 } See Stable Particles Table	
$\eta_{0^+}(700)$ "ε" → ππ	$0^+(0^+)+$	≈ 700	≫100	≈ 0.5	ππ	100	≈ 320
	δ_{00} seems to stay near 90° from 650 to 900 MeV; see note in listings						
$\rho(765)$	$1^+(1^-)-$	$765^{(c)}$ ±10	$125^{(c)}$ ±20	0.585 ±.095	ππ $\pi^\pm\pi^+\pi^-\pi^0$ $\pi^+\pi^-\pi^+\pi^-$ $\pi^\pm\gamma$ $\eta\pi^\pm$ e^+e^- $\mu^+\mu^-$	≈ 100 < 0.2 < 0.15 < 0.2 < 0.8 .0060±.0006 (d) .0062±.0011 (e)	356 243 243 370 141 382 368
$\omega(784)$	$0^-(1^-)-$	783.7 ±0.4 S = 1.8*	12.7 ±1.2	0.614 ±.010	$\pi^+\pi^-\pi^0$ $\pi^+\pi^-$ $\pi^0\gamma$ e^+e^- For upper limits, see footnote (f)	87 ± 4 > 0.3 (95% confidence) 9.4 ± 1.7 0.0066±.0017 S = 1.4*	328 366 380 392
$\eta'(958)$ or X^0 See note (h), on name η'	$0^+(0^-)+$ $J^P = 2^-$ not excluded; see note in listings	957.7 ±0.8	< 4	0.917 < .004	ηππ $\rho^0\gamma$ γγ [note (g)] For upper limits see footnote (i)	66 ± 4 S = 1.1* 30 ± 3 S = 1.2* 4.7 ± 2.9	231 173 479
δ(962)	≥1 ( )	962 ±5	< 5	0.927 < .005	ηπ possibly seen		305
} These two could be related, see listings							
$\pi_N(1016)$ → $K\bar{K}$	$1^-(0^+)+$	1016 ±10	≈ 25 } if res.	1.032 ±.025	$K^\pm K^0$ ηπ	Only mode seen < 80	111 342
Resonance, virtual bound state, or antibound state, still not distinguished							
φ(1019)	$0^-(1^-)-$	1019.5 ±0.6 S = 1.5*	3.9 ±0.4	1.039 ±.004	K^+K^- K_LK_S $\pi^+\pi^-\pi^0$ (incl. ρπ) e^+e^- $\mu^+\mu^-$ For upper limits see footnote (j)	45.5 ± 3.3 S = 1.1* 36.4 ± 3.4 S = 1.3* 18.1 ± 4.9 S = 1.5* 0.036±.003 $0.035^{+.035}_{-.018}$	126 110 462 510 499
$\eta_{0^+}(1060)$ "S*" → K_SK_S	$0^+(1^+)+$ if res.	1062 ±20§	≈ 80(?) see note (k)	1.13 ±.09	ππ $K\bar{K}$	< 65 > 35	513 190
Resonance and scattering length both possible							
A1(1070)	$1^-(1^+)+$	1070§ ±20	95§ ±35	1.14 ±.10	3π see note (ℓ) $K\bar{K}$	≈ 100 < 0.25	488 201
Interpretation still slightly in doubt; $J^P = 2^-$ not excluded						$[G = (-1)^{\ell + I}$ forbids $K\bar{K}]$	
B(1235)	$1^+(1^+)-$	1235 ±15§	*102* *±20§*	1.53 ±.13	ωπ ππ $K\bar{K}$ For other upper limits see footnote (m)	≈ 100 < 30 } Absence suggests J^P = Abn. < 2	350 602 371
f(1260)	$0^+(2^+)+$	1264 ±10§	151 ±25§	1.60 ±.19	ππ $2\pi^+2\pi^-$ $K\bar{K}$ indic. seen	≈ 100 < 4 ≈ 3	616 553 389
D(1285)	$0^+(A)+$ $J^P = 0^-, 1^+, 2^-$, with 1^+ favored	1288 ±7 S = 2.3*	33 ±5 S = 1.1*	1.66 ±.04	$K\bar{K}\pi$ [mainly $\pi_N(1016)\pi$] ππη ππρ	Seen Possibly Large Not seen	307 485 354
$A2_L(1280)$	$1^-(2^+)+$	*1280* *±4* *S = 1.7**	22 ±4	1.64 ±.028	ρπ (and π + neutrals) $K\bar{K}$ ηπ	Dominant Seen Indication seen } See note (n)	395 405 511
$A2_H(1320)$	$1^-(2^+)+$	*1320* *±5* *S = 2.1**	21 ±4	1.74 ±.028	ρπ (and π + neutrals) $K\bar{K}$ ηπ	Dominant Seen Indication seen } See note (n)	423 436 535
E(1422)	$0^+(0^-)+$ $J^P = 1^+$ not excluded See note in listings	1422 ±4	69 ±8	2.02 ±.10	$K^*\bar{K} + \bar{K}^*K$ $\pi_N(1016)\pi$ ππη ππρ	50 ± 10 } (so 100% $\bar{K}K\pi$) 50 ± 10 < 60 Not seen	153 326 568 457
f'(1514)	$0^+(2^+)+$	1514 ±5	73 ±23 S = 1.8*	2.29 ±.11	$K\bar{K}$ $K^*\bar{K} + \bar{K}^*K$ ππ ηππ ηη	72 ± 12 10 ± 10 < 14 18 ± 10 < 40 } See note (o)	570 294 744 624 521

Although the nuclear force is blind to electrical charge, and so cannot distinguish neutron from proton, it appears that it can count very well. Thus, the number of possible family members in a charge multiplet turns out to be a very significant property. Physicists classify the nucleon as having a "multiplicity" (M) of 2 (neutron and proton) and the pion as having a multiplicity of 3 (π^+, π^0, π^-). Often for convenience, multiplicity is translated into a closely related quantity known as isotopic spin–under which name we will meet it again below in our discussion of the quantum numbers.

Identification via Quantum Numbers. What are the characteristics that "identify" a particular particle? Or, to put it another way, how do physicists know when they have discovered a new particle—one that is different in significant ways from the ones already known? Each particle can be identified by a set of seven individual properties known as the quantum numbers and commonly referred to by the symbols I, Q, $\overline{Q}$, A, m, J, and P. Each quantum number stands for a particular trait of the particle under consideration; taken together they form the unique signature of that particle. Within the limits of this presentation, a short definition of each quantum number will have to suffice.

I: Isotopic spin, as we have already said, is the way in which physicists usually discuss the multiplicity, M, introduced two paragraphs earlier.

Q: Electric charge has also been discussed, and we have seen that it is the least significant of the quantum numbers—at least as far as the strong interaction is concerned.

$\overline{Q}$: Average charge, on the other hand, is very significant in strong-interaction phenomena. This quantum number refers to the average of the charges in the multiplet; thus, it is 1/2 for the N(n or p), 0 for the pion, and so on.

For convenience, $\overline{Q}$, like multiplicity is sometimes translated by simple mathematical manipulations into other closely related quantities known as hypercharge (Y) or strangeness (S).

A: Atomic mass number, familiar to all students of chemistry, is a fundamental quantity used to describe the atomic nucleus. It defines what we might call the number of basic nucleon building blocks in the nucleus. Thus, the "A" number of one isotope of the element uranium is 235, indicating that the nucleus of this isotope can be broken down into 235 neutrons and protons, each of which has an A value of 1. Atomic mass number is used to define the fundamental difference between the three kinds of strongly interacting particles. Particles with an A value of more than 1 (like the uranium-235 nucleus) are defined as nuclei; particles with an A value of exactly 1 are defined as baryons; particles with an A value of zero (i.e., no basic nuclear building blocks in the particle!) are defined as mesons.

m: The mass of the particle at rest in units of MeV (millions of electron volts).

J: Spin is a measure of how fast a particle rotates about its axis, expressed in natural "quanta" of angular momentum, $\hbar$. For baryons, J is always a "half integer", 1/2, 3/2, 5/2, ··· ; for mesons, it is an integer, 0, 1, 2, 3,··· .

P: Parity, the seventh and last of the currently recognized quantum numbers, is an intrinsic property having to do with nature's treatment of "left-handed" and "right-handed" phenomena. For all strongly interacting particles, P can be either +1 or -1.

Stable Particles vs Resonances. Apart from the quantum numbers, there is only one other property that need be mentioned in order to describe a particle. We say that a particle is either "stable" or "unstable" against decay through the strong interaction. Most strongly interacting particles decay very soon into lighter particles, and hence are called unstable particles or "resonances." Thus, the rho meson, with a rest mass of 750 MeV, decays into two pions, each of 140 MeV, with 470 MeV to spare. But suppose that the rho happened to weigh less than two pions. Then it would be unable to decay by the strong interaction, and would be called "stable." Of course, it might eventually decay via electromagnetism into a pion and a gamma ray, or via the weak interaction into two leptons. We see from the above example that stability is really an accidental property (depending on the availability of final states), although of course it is very important to the experimenter who has to deal with the particle.

Multiplet Signatures. In discussing the concept of isotopic spin, or multiplicity, we have already mentioned, that each of the charge multiplets has received a family name, or multiplet symbol by which it is generally known. This symbol is simply the first three significant quantum numbers $(A, \overline{Q}, I)$. Thus, for the nucleon, the single symbol N stands for the information $A = 1$, $\overline{Q} = 1/2$, and $I = 1/2$. The charge is written as a superscript; thus, N^+ is the proton, N^0 is the neutron, and so on. Finally, the mass, spin and parity are written in parenthesis. The convention is to write the parity as a superscript to the spin, as follows: J^P. Thus, the full seven parameters for the proton are written $N^+(938,\ 1/2^+)$.

IV. SUPERMULTIPLETS OF STRONGLY INTERACTING PARTICLES

We have now set a stage with the following particles, each with its antiparticle:

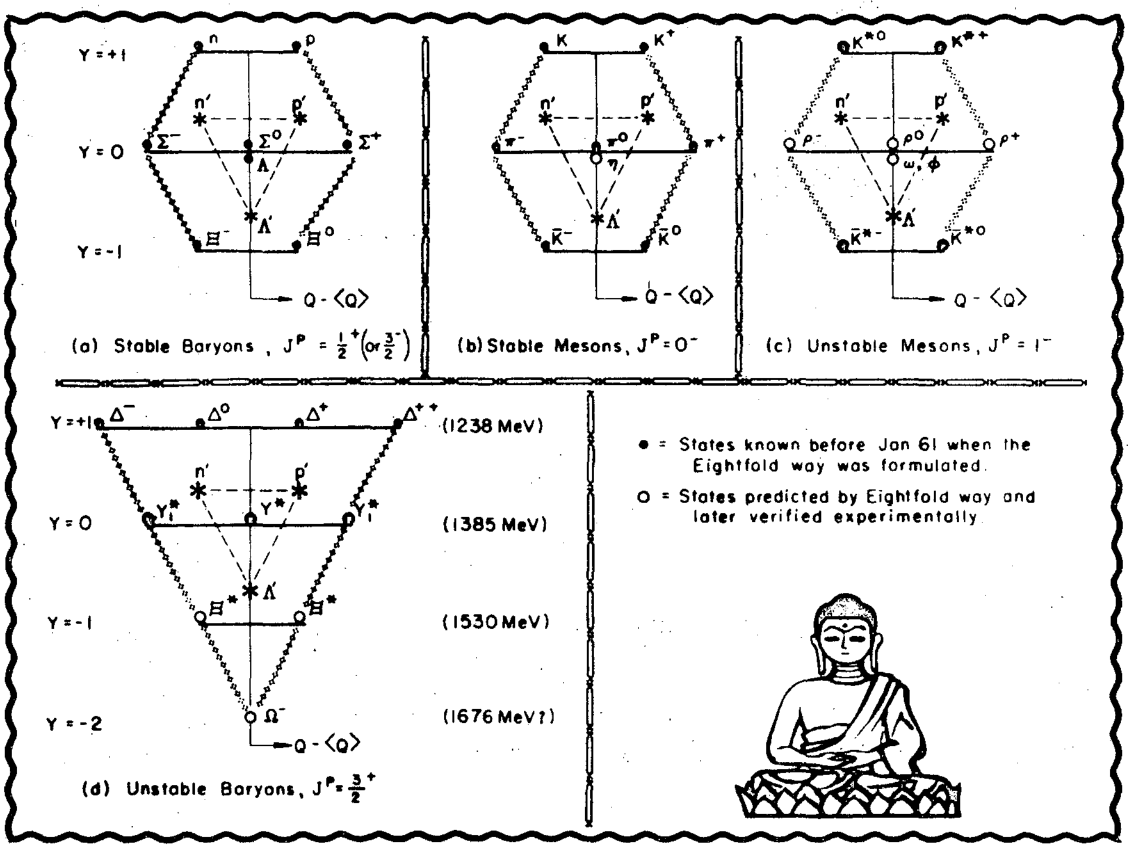
1. For the electromagnetic interaction, the photon.

2. For the weak force, three leptons: the electron, the muon. and the neutrino. Hundreds of experiments have looked for evidence of structure or complexity in the leptons, but none has been found so far.

3. For the gravitational force, the graviton. Although physicists have long believed in gravitons, the first experimental evidence for them came only in 1969, so it is premature to say more about them at this point.

4. For the strong interaction, there remain the hundreds of particles we have briefly mentioned. We have already made some progress in reducing their number by grouping them into charge multiplets, resulting in about two dozen meson multiplets, and about 10 each of six different kinds of baryon multiplets. The remainder of this article describes the progress that has been made in further organizing these 75 multiplets into a periodic table of "elementary" particles.

Hexagonal Arrays. Let us start purely empirically with the eight stable baryons that were known in January 1961, when the classification scheme known as the "Eightfold Way" was first suggested. In part (a) of Figure 1, each of these eight baryons has been plotted as a black dot. The electric charge (Q) increases along the horizontal axis; thus, the top entry is the N doublet, with the neutron (n) at the left and the proton (p) one unit to its right. Six quantum numbers remain; we might pick any one of them to serve as our vertical axis. Many physicists tried many combinations during those early years of particle proliferation, and we leave it to the reader to try some for himself and find,



(a) Stable Baryons, $J^P = \frac{1}{2}^+ (\text{or } \frac{3}{2}^-)$ (b) Stable Mesons, $J^P = 0^-$ (c) Unstable Mesons, $J^P = 1^-$

(d) Unstable Baryons, $J^P = \frac{3}{2}^+$

● = States known before Jan 61 when the Eightfold way was formulated.

○ = States predicted by Eightfold way and later verified experimentally

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Figure 1. Supermultiplets—octets and decuplets. The dots represent known particles; the asterisks labeled n′, p′, and Λ′ are a possible set of primitive particles called "quarks," from which the mesons and baryons can be formed. The symbol ⟨Q⟩ means the average electrical charge of the multiplet; in the text it is written $\overline{Q}$.

as we did, that nothing very suggestive arises out of the various combinations of quantum numbers until we choose the quantity known as "hypercharge" ($2\overline{Q}$) as our vertical axis. (Remember that we introduced $\overline{Q}$ as the average charge of a multiplet, and said that it was also related to hypercharge Y, which in fact is just $2\overline{Q}$.)

Now let us return to Figure 1a, noting now that hypercharge, or $2\overline{Q}$, has indeed been used as the vertical axis for the plot. A striking hexagonal snowflake has emerged, with six dots at each corner and two at the center. Is nature trying to send us a signal by displaying such startling symmetry?

Let us try the same game with the seven stable mesons that were known at the same time (January 1961). Another hexagon emerges—the one shown in Figure 1b. Moreover, during 1961 an eighth stable meson, called η, was discovered. In fact, one of the authors of this chapter (Rosenfeld) led the team that determined all of the quantum numbers of the η and showed that it belonged at the center of the hexagon.

Which particles do we have left to form still another hexagon? We have run out of the stable states, so we shall need to find some new criteria for grouping the unstable states known as the resonances. We take as our clue the fact that the eight stable baryons of Figure 1a all had the same spin and parity ($J^P = 1/2^+$), and the eight stable mesons of Figure 1b all had the same $J^P = 0^-$. So, let us try to make a new plot, Figure 1c, using mesons which share some new value of spin and parity. At the time of which we are writing, two meson doublets, the K^* and the $\overline{K}^*$ were available, yielding the four black dots so labeled in Figure 1c. In 1961 the ρ-meson triplet was discovered, filling out the hexagon, and the present author was again among the group that discovered the ω singlet, again completing the count of eight.

Since the next "octet" of mesons was not filled in until 1964, let us turn our attention back to baryons for a moment. By January 1961 we already had groupings for all the stable baryons with $J^P = 1/2^+$, and we had left over two multiplets with $J^P = 3/2^+$. One of them, the $\Delta(1238, 3/2^+)$ had been around for a long time. It was, in fact, the state discovered by Fermi and his co-workers in the 1950's and listed as "the resonance" in the 1958 Table IIb. $\Delta(1238)$ is a quartet, appearing as Δ^-, Δ^0, Δ^+, and Δ^{++}, so it was clear to physicists that it would not fit into our hexagonal array, which can seat at most three dots abreast. You see it plotted at the top of Figure 1d. Then another baryon multiplet, the $Y^*(1385)$, now called the $\Sigma(1385)$ was discovered, hinting at a triangle. This turned out to be enough of a clue for two very bright theoreticians to build a scheme on.

V. THE EIGHTFOLD WAY AND QUARKS

The elementary forms of ordering that we have been doing in the preceding paragraphs brings us to the formulation, in January 1961, of the "Eightfold Way." The scheme was derived independently by Murray Gell-Mann, at the California Institute of Technology, and Yuval Ne'eman, at Imperial College, London. Their treatment was mathematical, and had as a key result the equation

$$3 \otimes 3 = 9 = 8 \oplus 1 .$$

Now, the $3 \otimes 3 = 9$ part is easy to understand, and so separately is the $9 = 8 \oplus 1$ part, but how do the two parts relate to each other, and what does it all have to do with elementary particles? In the simplest terms, we might say that the equation relates the combinatorial possibilities of three basic objects ($3 \otimes 3 = 9$) to the physical manifestations these combinations may take in the real world ($9 = 8 \oplus 1$). We shall try to explain with pictures and an analogy.

An Example: Combining Spins. We shall start with an example known to all students of atomic physics. Consider the simplest atom, hydrogen, with a proton at the center and an electron cloud around it. The proton has an intrinsic spin of $1/2\ \hbar$. Now, if we put the proton in a magnetic field, it can take either of two possible alignments: parallel (↑) or opposed (↓) to the field. The electron also has an intrinsic spin of $1/2\ \hbar$, and it also can line up in the same two ways in respect to the magnetic field. Then for the atom as a whole (the proton and the electron), there are four possibilities ($2 \otimes 2 = 4$). This situation is pictured on the left of Figure 2 and is summarized

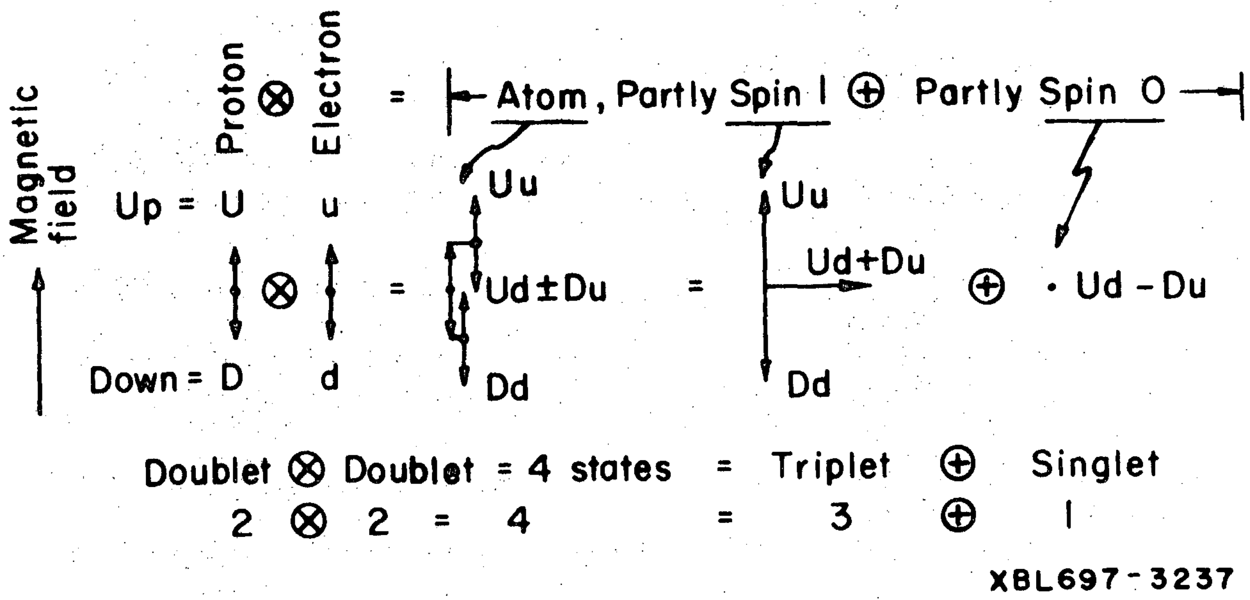

Figure 2. Illustration of how the four alignment states of p and e^- in a hydrogen atom combine to give three alignments of spin 1, and one of spin 0.

by the left-hand part of the equation

$$2 \otimes 2 = 4 = 3 \oplus 1 .$$

Now for the right-hand part. There, the point of view is to say that two objects, the proton and the electron, each with spin $1/2\ \hbar$ can add like ↑↑ , to make a total spin for the atom of $1\ \hbar$, or oppose, like ↑↓ , to make a total spin of 0. But quantum mechanics tells us that an object with a spin of $1\hbar$ can assume any of three alignments in a magnetic field (+1, 0, or −1)—not two like the original objects, the proton and electron. On the other hand, if the spins add up to zero, the combined object can have only a single alignment, zero. Thus, all possible combinations of proton and electron spin may be summarized as three possible alignments of spin 1 (that is, a triplet) and one possible alignment of spin 0 (that is, a singlet). Other theoretical combinations of spin $1/2\ \hbar$ objects simply cannot be made in the physical world. The triplet, incidentally, can be shown to have $J^P = 1^+$; the singlet has $J^P = 0^+$. If you've not yet glanced at Figure 2, please do so, because it will help us when we get to combining "quarks" instead of electrons.

A Discovery: Combining Ispins. When we combine electron and proton spin into a triplet and a singlet, it seems so natural that it's hard to think of each of the three triplet states as a different particle, although strictly speaking, in the language of particle physics, they could be so designated. So now let's use our knowledge of how to combine spins to get something new. Let's combine two nucleons (n or p), each of atomic number A = 1, to get a nucleus with A = 2. This nucleon can have three charges, 0 (nn) or 1 (np) or 2 (pp). That's odd, each nucleon is a member of a doublet. Since $2 \otimes 2 = 4 = 3 \oplus 1$, have we overlooked something? Yes, we have overlooked a singlet. The situation is sketched in Figure 3. Nature in fact recognized four states, three of which are members of a triplet and all have the same mass, and a fourth, which is more tightly bound and hence is plotted at a lower mass. The three related states plotted on top are unstable resonances; the singlet is the stable nucleus called the deuteron. When physicists recognized the fact that charge multiplets combine according to the same mathematics as spin multiplets they invented a new sort of spin called "Ispin" or "isotopic spin", and interpreted the electrical charge (+1 for proton, 0 for neutron) as the alignment I_z of the Ispin along the "charge" direction. This point of view has made many important predictions and explains why physicists introduce the jargon "Ispin" to describe the multiplicity of a state.

The Eightfold Way: Combining Quarks. In the preceding examples, there were two "original objects" or primitive building blocks from which we made up our atoms—the proton and the electron—or, in the explanation of the deuteron, two nucleons. Now let us go on to see how Gell-Mann and

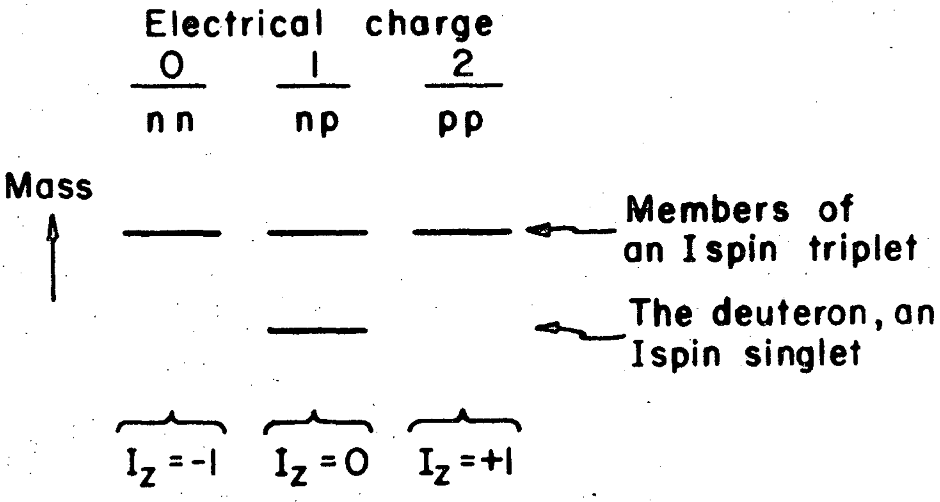

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Figure 3. Another illustration of $2 \otimes 2 = 3 \oplus 1$, this time combining nucleons to make two sorts of deuterons. This figure is a nuclear "level scheme" with mass plotted vertically. This means that "charge alignment" cannot be plotted vertically, as was "spin alignment" in Figure 2, but instead is plotted horizontally.

Ne'eman's Eightfold Way relates the strongly interacting particles to combinations of three "primitive objects" known as quarks. In returning to Gell-Mann and Ne'eman, let us also take a liberty with history: they actually took an intermediate step to get to the result that we are going to arrive at by a more direct "hindsight" route.

Consider the three asterisks at the center of each pattern in Figure 1. These are the quarks. They are redrawn in Figure 4, and are labeled n',p' and Λ', along with their antiquarks $\bar{n}'$, $\bar{p}'$, and $\bar{\Lambda}'$ Now, assume that the quarks are the original objects, or primitive building blocks, of strongly interacting matter. What possible combinations may we encounter in the real world? Well, first we might visualize all nine possible combination of quarks with antiquarks—$n'\bar{n}'$, $n'\bar{p}'$, $n'\bar{\Lambda}'$, $p'\bar{p}'$. . .($3 \otimes 3 = 9$). Let us plot these combinations in the same graphic way that we did in Figure 2 for the proton and the electron, except that this time the quarks will have to be plotted in two dimensions instead of one for the alignment of spin. No matter, the same rules hold. Suppose that one quark is a p' and the antiquark is any of the three possibilities—n', p', or Λ'. We display this by drawing the triplet centered on the p' asterisk (Figure 4) thus generating three dots labeled 1, 2, and 3. If we take the case where the quark is an n' instead of a p', we must redraw the quark triplet around the asterisk n', thus generating points 4, 5, and 6. Point 6, you will note, falls on top of point 2 in the previous triangle. Points 7, 8, and 9 are of course centered on Λ', with 7 falling on top of 2 along with 6. Behold, we have generated a hexagon, with three more points inside. And, by reasoning as we did for Figure 3,

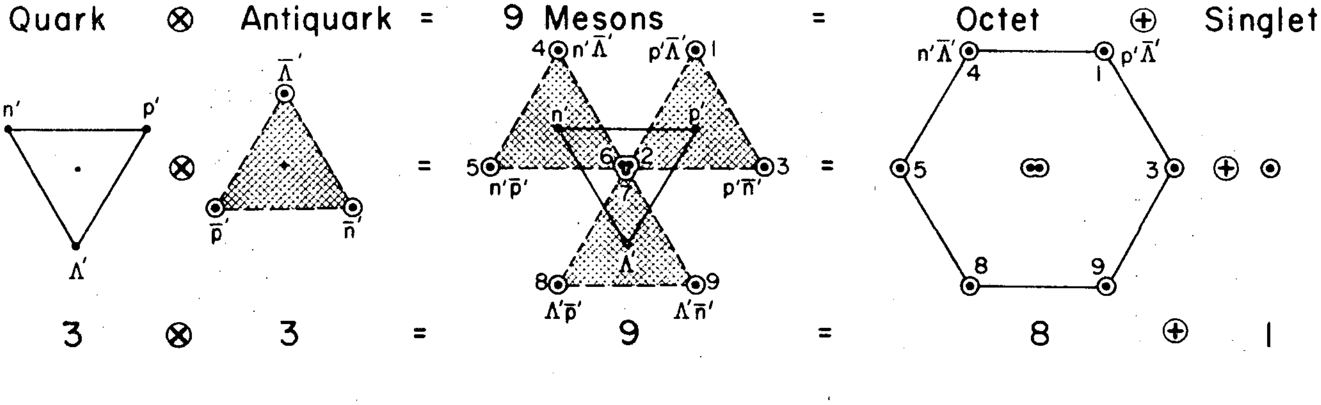

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Figure 4. Combining quarks. Three hypothetical quarks and three hypothetical antiquarks combine to form nine real mesons, which groups into an octet plus a singlet.

Gell-Mann and Ne'eman managed to show that eight of these nine dots belong to an "octet" with a physical manifestation (i. e., eight possible combinations that can occur in the real world), and the ninth corresponded to an additional singlet. (This ninth singlet meson has since been discovered.) Hence $3 \otimes 3 = 9 = 8 \oplus 1$, as promised above.

Now let us see if we can explain the baryons in a similar way. The mesons, we have seen, are combinations of quarks and antiquarks. What other possibilities do we have among our six primitive objects? The baryons, we shall now see, are formed out of three quarks. Since each quark can be either n', p', or Λ', we have $3 \otimes 3 \otimes 3$ or 27 possible combinations. By mathematical manipulations similar to those we have done above, using the branch of mathematics known as "group theory," one can show that the physical interpretation of these 27 combinations will be one singlet, two octets, and a group of ten (decuplet):

$$3 \otimes 3 \otimes 3 = 27 = 1 \oplus 8 \oplus 8 \oplus 10,$$

and furthermore, that the decuplet should be arrayed as shown in Figure 1d. Several people made predictions about the undiscovered multiplets (shown as open dots in Figure 1d) labeled Ξ^* and Ω^-. Both of these were later discovered and were found to have the predicted masses and quantum numbers.

Gell-Mann christened the scheme the "Eightfold Way" (if christened is the right word to use in connection with a venerable term borrowed from Buddhist and Taoist philosophy). Actually, the mathematics behind the Eightfold Way explains much more than the mere fact that we should find meson "supermultiplets" of 8 and 1, baryons in supermultiplets of 10, 8, and 1, and so forth. It gives relations between masses and decay modes of all members of these supermultiplets. The Eightfold Way is in fact probably the greatest single achievement in a very long list of brilliant ideas which earned Gell-Mann the Nobel Prize in December 1969.

Analogy with Theory of Relativity. In the formulation of special and general relativity, physicists treat space and time symmetrically, and do their thinking and their mathematics in a four-dimensional space. This recognition of the connection between space and time was clearly a big advance in physics. Now glance back at the symmetric quark triangles in Figures 1 or 4, in a space where the x axis is the charge, (or alternatively a component of Ispin) and y is the hypercharge. Until the formulation of the Eightfold Way, we saw no connection between charge and hypercharge. The analogy with relativity is clear; we have again advanced by recognizing a fundamental relation between apparently unrelated quantities.

Quarks. What about the hypothetical primitive objects that we used to explain the Eightfold Way? (They are called quarks by Gell-Mann after a passage in Finnegan's Wake; they were also conceived independently by another physicist, George Zweig.) Naturally, physicists would like to find the physical particles that correspond to these objects. We have looked for them very hard in a number of recent experiments; an Australian physicist, Brian McCusker, even thinks he may have preliminary evidence for them. But so for nobody has really found a quark. It may or may not be relevant that physicists are also looking hard for another particle, called the magnetic monopole. In nature, we find isolated electrical charges (called poles), such as the unit of plus charge on the proton, or the equal but opposite minus charge on the electron. But we have never succeeded in isolating a unit of magnetic charge; magnetic poles always seem to come in plus-minus pairs, i. e., like tiny magnets each with a north and a south pole. Some physicists suspect that the missing magnetic monopole and the missing quark are connected. Accordingly, every time a new higher-energy accelerator is turned on, you can expect a frantic search for quarks and magnetic monopoles.

VI. PRESENT AND FUTURE

We have shown you that high-energy physics has made great progress in the last 5 to 10 years. Hundreds of particles have been discovered and assigned to supermultiplets. But we still don't fully understand the law of force that makes hypothetical quarks combine to form particles, or particles combine to form other particles. And we are not sure if the laws of quantum mechanics (which apply very well to the domain of atoms) apply unchanged at tiny distances and ultrahigh energies. We hope that we are in the position of atomic physicists in 1910-20, when the whole periodic tables of the elements was known, and the great theoretical breakthrough of quantum mechanics was just around the corner.

Applications? Will practical applications arise from current research? Of course, particle physicists have developed some useful apparatus (spark chambers, Cerenkov counters) and have made ingenious contributions to computer systems and computer equipment. Spark chambers (developed for particle physics) installed at the bottom of a pyramid near Cairo have been used by Professor L. W. Alvarez and his Egyptian colleagues to "x-ray" the pyramid with cosmic rays and look for hidden chambers. And, for a few days back in 1956, we in the Alvarez group in Berkeley believed that we might have stumbled upon the solution to the problem of thermonuclear power. We were capturing μ^- leptons in liquid hydrogen, and observed that occasionally they catalyzed a thermonuclear reaction. But we could never get them to release enough power to come close to paying the cost of producing the μ^- lepton. So we gave up that idea.

But so far, most of our results in high-energy physics are conceptual. We have discovered that the neutron and the proton are not elementary — that they are just two complex members of a family of eight. It is rather like discovering that the sun is not the center of the universe: it has brothers and sisters, some bigger, some smaller, some older, some younger, some dead. It remains to be seen whether this recent insight will have as great an impact on the course of human understanding as Galileo's earlier insight had. Only time can tell.