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CURRENT PROBLEMS IN RESEARCH

Elementary Particles of Modern Physics

The properties of the 30 particles and antiparticles, their forces and conservation laws are summarized.

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In popular usage, the term *elementary particle* signifies an ultimate constituent out of which all matter is compounded. In physics, the usefulness of the concept depends very much on our state of knowledge, the hierarchy of forces with which one is dealing, and the order which is introduced into the description of the empirical facts.

From one point of view, any particle with a well-defined mass, charge, and intrinsic angular momentum (or spin) is an elementary particle and, in this context, even a molecule could be regarded as elementary. However, when the electromagnetic law of force was established between the atoms in a molecule and also between the electrons and the positively charged nucleus of the atom, it was much more convenient at that stage to think of the electron and the various types of atomic nuclei as the elementary particles. When quantum mechanics was developed and the wave-particle dualism became an essential ingredient of our understanding of all atomic phenomena, it was proper to add the photon to the list of elementary particles. When the neutron was discovered and the existence of a distinct nuclear force was established, it became more advantageous to think of the neutron and proton as the elementary particles out of which atomic nuclei are built up. Within this context, for example, the completely stable deuteron, with a well-defined mass, charge, and spin, is considered a composite structure, whereas the unstable neutron is treated as an elementary particle. The reason for this anachronistic point of view is that within the hierarchy of strong (or nuclear), electromagnetic, and weak forces, the neutron lives for a very long time (10^3 seconds) on the nuclear time scale of 10^{-23} second.

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The situation is even more curious. If we restrict ourselves to low-energy nuclear phenomena, the only elementary particles which enter the picture are the electron, positron, proton, neutron, photon, neutrino, and antineutrino. When some of these particles acquire sufficient kinetic energy (either as components of the cosmic radiation or in high-energy accelerators), many new varieties of particles are created which, at this stage of our understanding, are added to the list of elementary particles. Some of these particles, which result from the conversion of kinetic energy into mass, in turn create new particles through decay or through secondary production.

As a result, the following additional particles (and antiparticles) have been observed and must be added to the list of elementary particles: the positive and negative muons; the positive, negative, and neutral pions; the positive and negative kaons and two kinds of neutral kaons; the antiproton and the antineutron; the neutral Λ-hyperon and the anti-Λ-hyperon; the positive, negative, and neutral Σ-hyperons; and the negative and neutral Ξ-hyperons. For reasons which will become apparent, it is quite certain that the three anti-Σ-hyperons and the two anti-Ξ-hyperons will be observed when the proper experiments are performed (*1*). We thus end up with 30 particles and antiparticles, of which seven (the photon, neutrino, antineutrino, electron, positron, proton, and antiproton) are genuinely stable. The remaining 23 particles and antiparticles possess such a slight degree of instability (on the nuclear time scale) that we are justified in treating them on an equal footing with the seven genuinely stable particles and antiparticles.

Properties

The properties of an elementary particle which can be directly measured are the charge, mass, spin, and, if the particle is unstable, the lifetime. These properties are listed for all 30 particles and antiparticles in Table 1. The charges, masses, spins, and lifetimes of the antiparticles are not listed separately; the reason for this is that if the laws of special relativity apply to all physical processes involving the elementary particles, as we believe they do, it can be shown that the charge of the antiparticle must be the negative of that of the particle, and that the mass, spin, and lifetime of the antiparticle must all be identical with those of the particle. The neutral kaon is an exception to this statement where we have listed two distinct lifetimes for two particles which are called the K_1^0 and K_2^0 particles; the K_1^0 and K_2^0 particles are opposite mixtures of the neutral kaon and its antiparticle, and the exception occurs because the neutral kaon and its antiparticle can convert into each other through the weak force.

It will also be noted that antiparticles for the neutral pion and the photon are placed in parentheses; this is because there is no known property by means of which the antineutral pion and the antiphoton could be distinguished from the respective particles. This also explains why the list in Table 1 contains 16 particles and 14 antiparticles; of these, four particles (proton, neutrino, electron, photon) and three antiparticles (antineutrino, positron, antiproton) are stable and the remaining 12 particles and 11 antiparticles are unstable.

Mass and Charge

The particles in Table 1 have been ordered chiefly according to their mass; the one ambiguity, between the photon and the neutrino, has been resolved by placing the photon first on the list. This mass ordering leads to a remarkable grouping of the particles into four classes: photon, lepton, meson, and baryon. The names *lepton, meson,* and *baryon* were originally invented to denote light, intermediate-mass, and heavy particles, respectively, but we now know that the particles in each of these three classes have certain important properties in common which are distinct from the properties characterizing the members of the other two classes.

If we further examine Table 1, we find that the (electric) charge number Q for the particle (the Q for the antiparticle is the negative of the Q for the particle takes on the values 1, 0, and -1 (e being the fundamental unit) and that for no elementary particle is $|Q| > 1$. Also, the range of masses of the particles listed in Table 1 is not completely arbitrary; there appear to be some important mass groupings, within at least the meson and baryon classes, of particles which bear a direct relationship to the charge numbers. Within the meson class, the charged pion is only 4.6 Mev heavier than the neutral pion, and the neutral kaon is only 3.9 Mev heavier than the charged kaon. In the baryon class, the neutral nucleon (that is, the netutron) is only 1.3 Mev heavier than the charged nucleon (the proton); the negatively charged Σ-hyperon is only 6.8 Mev heavier than the positively charged Σ-hyperon; this, in turn, is only 2.4 Mev lighter than the neutral Σ-hyperon; and the masses of the negative and neutral Ξ-hyperons are within 8 Mev of each other (this is experimental error). By the same token, it may be meaningful to consider the neutrino and electron, which differ in mass by only 0.5 Mev, as the neutral and negative "light" leptons in contradistinction to the "heavy" lepton, which is the muon. These mass differences are all small compared to the mass differences between the average masses of the "light" and "heavy" leptons (within the lepton class), between the average masses of the pion and kaon (within the meson class), and between the average masses of the nucleon, Λ-hyperon, Σ-hyperon, and Ξ-hyperon (within the baryon class).

It seems, therefore, that in some sense the particles which differ only slightly in mass are different charge states of the same particles, so that the distinct elementary particles whose properties and interactions we must understand are the photon, the "light" lepton, the "heavy" lepton, the pion, the kaon, the nucleon, the Λ-, Σ-, and Ξ-hyperons, and all the antiparticles of these particles. The slightly different masses associated with the different charge states of each of the above particles are then attributed to electromagnetic self-energy effects produced by virtual interactions with the electromagnetic field. While no quantitative theory of these mass differences exists, the electromagnetic approach appears plausible and involves no difficulty of principle except possibly for the "light" lepton.

Spin

The regularities among the spins of the particles listed in Table 1 are even more striking than the regularities in the charge and the mass. Except for the photon, which is in a class by itself and possesses spin 1 (in units of $\hbar$, Planck's constant divided by 2π), all

Table 1. Properties of elementary particles. Masses and mean lifetimes are taken from the Berkeley compilations.

	Particle	Antiparticle	Spin	Mass (Mev)	Charge No. Q	Baryon No. B	Lepton No. L	Strangeness No. S	Mean life (sec)	Decay modes
						Photon				
Photon	γ	(γ)	1	0	0	0	0	0	Stable	
						Leptons				
Neutrino	ν	$\bar{\nu}$	½	0	0	0	+1	0	Stable	
Electron	e^-	e^+	½	0.510976 ± 0.000007	−1	0	+1	0	Stable	
Muon	μ^-	μ^+	½	105.70 ± 0.06	−1	0	+1	−1	$(2.261 \pm 0.007) \times 10^{-6}$	$e^- + \nu + \bar{\nu}$
						Mesons				
Pion	π^+	π^-	0	139.63 ± 0.06	+1	0	0	0	$(2.56 \pm 0.05) \times 10^{-8}$	$\mu^+ + \nu$; $e^+ + \nu$
Pion	π^0	(π^0)	0	135.04 ± 0.16	0	0	0	0	$<4 \times 10^{-16}$	2γ
Kaon	K^+	K^-	0	494.0 ± 0.2	+1	0	0	+1	$(1.224 \pm 0.013) \times 10^{-8}$	$\mu^+ + \nu$; $\mu^+ + \nu + \pi^0$; $e^+ + \nu + \pi^0$ $\pi^+ + \pi^0$; $2\pi^+ + \pi^-$; $\pi^+ + 2\pi^0$
Kaon	K^0	$\overline{K}^0$	0	497.9 ± 0.6	0	0	0	+1	K_1^0: $(1.00 \pm 0.038) \times 10^{-10}$	$\pi^+ + \pi^-$; $2\pi^0$
									K_2^0: $(6.1 \pm 1.3) \times 10^{-8}$	$\pi^+ + \pi^- + \pi^0$; $3\pi^0$ $\mu^+ + \nu + \pi^-$; $\mu^- + \bar{\nu} + \pi^+$ $e^+ + \nu + \pi^-$; $e^- + \bar{\nu} + \pi^+$
						Baryons				
Nucleon	p	$\bar{p}$	½	938.213 ± 0.01	+1	+1	0	0	Stable	
Nucleon	n	$\bar{n}$	½	939.506 ± 0.01	0	+1	0	0	$(1.04 \pm 0.13) \times 10^3$	$p + e^- + \bar{\nu}$
Λ–Hyperon	Λ	$\bar{\Lambda}$	½	1115.45 ± 0.12	0	+1	0	−1	$(2.505 \pm 0.086) \times 10^{-10}$	$p + \pi^-$; $n + \pi^0$ $p + e^- + \nu$
Σ–Hyperon	Σ^+	$\bar{\Sigma}^+$	½	1189.55 ± 0.21	+1	+1	0	−1	$(0.84 \pm 0.07) \times 10^{-10}$	$p + \pi^0$; $n + \pi^+$
Σ–Hyperon	Σ^-	$\bar{\Sigma}^-$	½	1196.39 ± 0.34	−1	+1	0	−1	$(1.59 \pm 0.10) \times 10^{-10}$	$n + \pi^-$
Σ–Hyperon	Σ^0	$\bar{\Sigma}^0$	½	1191.94 ± 0.53	0	+1	0	−1	$<0.1 \times 10^{-10}$	$\Lambda + \gamma$
Ξ–Hyperon	Ξ^-	$\bar{\Xi}^-$	?	1319.1 ± 0.5	−1	+1	0	−2	$(1.9 \pm 0.5)\ 10^{-10}$	$\Lambda + \pi^-$
Ξ–Hyperon	Ξ^0	$\bar{\Xi}^0$	?	1311 ± 8	0	+1	0	−2	1.5×10^{-10} (1 event)	$\Lambda + \pi^0$

the particles in the meson class possess spin zero, whereas all the particles in the lepton and baryon classes possess spin 1/2. (The spin of the Ξ-hyperon has not been measured as yet, but it is rather likely that this will also turn out to be 1/2.) Thus, all the elementary particles (with the exception of the photon) possess the lowest half-integral (1/2) or integral (0) spins that are possible.

Quantum Numbers B and L

We have also listed in Table 1 the values of two quantum numbers—the baryon number B and the lepton number L—which have been assigned to each elementary particle (B and L for the antiparticles are discussed below). The introduction of these quantum numbers and the imposition of conservation laws involving them help greatly to reduce the multiplicity of processes in which the elementary particles might otherwise participate. It is to be hoped that the future fundamental theory will provide a natural basis for these quantum numbers, but at this stage they must be regarded as essentially having a phenomenological origin. The baryon and lepton quantum numbers have already been anticipated in the names assigned to two of the classes of elementary particles: each member of the baryon class is assigned $B = 1$ (the antibaryon is assigned $B = -1$), while the particles (and the antiparticles) of the other three classes—photon, lepton, and meson—are assigned $B = 0$. The particles in the lepton class are assigned $L = 1$ (the antiparticles are assigned $L = -1$), whereas the particles of the other three classes—photon, meson, and baryon—are assigned $L = 0$.

The conservation laws for baryon number and lepton number (like the conservation of charge number) are absolute conservation laws which hold for all three types of interaction (strong, electromagnetic, and weak) which operate among the elementary particles. Also, the conservation laws for baryon, lepton, and charge numbers are similar in character in the sense that a quantum number is assigned to the particle and its negative is assigned to the antiparticle and the conservation law is stated in terms of the requirement that the algebraic sum of the values of the quantum number for a system of particles and antiparticles stay constant for any physical process. A quantum number with this property is called an "additive" quantum number, so the charge number, the baryon number, and the lepton number are all "additive" quantum numbers which must be absolutely conserved.

We can now understand why the photon and neutral pion are their own antiparticles whereas the other neutral particles are not. In the case of all but one of the other neutral particles, one of the additive quantum numbers B or L distinguishes between the particle and the antiparticle. Thus, the neutrino and antineutrino are distinguished by the lepton number L, and the neutron, neutral Λ-, Σ-, and Ξ-hyperons and their antiparticles, by the baryon number B. We shall see below that the neutral kaon and neutral antikaon are distinguished by another "additive" quantum number called the strangeness number.

The absolute conservation law for baryon number has immediate consequences for the production and annihilation of antibaryons. For example, it is evident that if in the initial state there are two baryons and no antibaryons present, then the production of one antibaryon in the final state by any physical process whatsoever will necessitate three baryons in the final state. Conversely, if there are one antibaryon and one baryon present in the initial state, then the disappearance (annihilation) of the antibaryon by any physical process whatsoever can only take place if we end up with no baryons. As far as the empirical evidence for the absolute conservation law of baryon number is concerned, the most incisive evidence comes from studying a possible instability of the lightest of the baryons—namely, the proton. If the baryon number is absolutely conserved, there should be no physical process by means of which the proton can decay into lighter particles. Various experiments (*2*) carried out with this purpose in mind have set a lower limit for proton decay by any mode (for example $p \rightarrow 2e^+ + e^-$) of about 10^{23} years. This is a very long lifetime and implies that the conservation law for baryon number, which is responsible for the stability of atomic nuclei, is even more absolute than charge conservation insofar as the experimental evidence is concerned (where a lower limit of 10^{19} years has been found for the reaction $e \rightarrow \nu + \gamma$).

The conservation of lepton number also appears to be an absolute conservation law. The best (albeit rough) check of this conservation law has come from the study of neutrino interactions with atomic nuclei. In accordance with out assignment of lepton number, a neutron should emit an antineutrino with the electron, and a proton in the nucleus should emit a neutrino with the positron. It follows that the neutrinos produced in a nuclear reactor must be antineutrinos (since the fission of heavy nuclei leads to fission fragments with an excess of neutrons, and thus to electron-unstable nuclides), and therefore the process $\bar{\nu} + p \rightarrow e^+ + n$ is possible, whereas the process $\bar{\nu} + Cl^{37} \rightarrow e^- + Ar^{37}$ must be impossible. The cross section for the first process has actually been measured and found to be $11 \pm 4 \times 10^{-44}$ cm^2 (in agreement with the theoretical prediction), whereas the upper limit on the cross section for the second process has been found to be $0.1 \pm 0.6 \times 10^{-45}$ cm^2, at least ten times smaller than would be expected if the neutrino and antineutrino were not distinguishable particles. All the other weak interaction processes involving leptons, including the decays of the strange particles, are consistent with the conservation of the lepton number (within an experimental error of 10 percent).

Stable Particles

There are several points to note in connection with the lifetimes listed in Table 1. First of all, the stable particles are the photon, the two "light" leptons (neutrino and electron), and the lightest of the baryons (that is, the proton) and their antiparticles. The conservation of momentum, energy, and angular momentum prevents the decay of the photon into two neutrinos. Conversely, the conservation of angular momentum is enough to ensure the stability of the neutrino with respect to decay into photons. Conservation of charge number guarantees the stability of the electron with respect to decay into neutrinos and photons. The stability of the proton is a more subtle phenomenon and requires for its explanation the conservation of a new quantum number—to wit, the baryon number. The assignment of baryon number 1 to the proton and of 0 to the photon, the leptons, and the mesons and the requirement of baryon number conservation then "explains" the stability of the proton. It is to be hoped that a deeper theoretical foundation will be found for the empirical principle of conservation of baryon number, since, in a sense, it is this principle more than any other which is responsible for the stability of the universe as we know it.

Unstable Particles

We see that the principles of conservation of angular momentum, charge number, and baryon number (in addition to energy and momentum) are sufficient to ensure the stability of the photon, neutrino, electron, and proton. These principles are not sufficient to ensure the stability of the "heavy" lepton (that is, the muon), the mesons, and the baryons heavier than the proton. In actual fact, all of these particles turn out to be unstable. In Table 1 we have also tabulated the observed decay modes of the 12 unstable particles. We have not listed the decay modes of the antiparticles because the decay products must be the antiparticles of the decay products of the particle. Of the 12 unstable particles (and 11 unstable antiparticles) listed in Table 1, only two particles (the neutral pion and the neutral Σ-hyperon) and one antiparticle (the neutral anti-Σ-hyperon) emit photons in the dominant decay mode. It is to be noted that the lifetime of the neutral pion is less than 4×10^{-16} second and the lifetime of the neutral Σ-hyperon is less than 10^{-11} second (this is an upper limit obtained by a rather crude experiment). These are the shortest lifetimes in Table 1, and it is expected on theoretical grounds that both will lie in the range of 10^{-19} to 10^{-17} second. These extremely short lifetimes which are predicted for the two observed electromagnetic decays (as well as for the as-yet-unobserved neutral anti-Σ-hyperon) are still long on the nuclear time scale (by a factor of 10^4 or more, since the characteristic nuclear lifetime is 10^{-23} second—a nuclear dimension of 10^{-13} centimeter divided by the velocity of light) and justify the inclusion of these particles in the list of elementary particles. None of the other unstable particles shown in Table 1 emits photons in its dominant mode of decay.

The unstable particles whose dominant modes of decay do not involve emission of photons have lifetimes which range from 10^{-10} second to 10^3 seconds, a factor of 10^{13}. This enormous range in lifetime would appear to indicate a great diversity in the types of forces which are responsible for the corresponding decay processes. In actual fact, it seems possible to explain all of these decays by essentially a single type of interaction, which is called the universal weak force. The enormous range in lifetime is explained by a very sensitive dependence of the lifetime for weak decays on available energy (that is, the so-called Q value), ranging from a lifetime of 0.8×10^{-10} second and a Q value of 115 Mev for the Σ^+ lifetime to a lifetime of 10^3 seconds and a Q value of 0.75 Mev for the neutron. It is important to note that not all weak decay processes which are consistent with the conservation of angular momentum, charge number, baryon number, and lepton number are actually observed. For example, the decay process $\mu \rightarrow 3e$ has never been observed, although this process satisfies all the conservation laws satisfied by the well-known decay process $\mu \rightarrow e + \nu + \bar{\nu}$. Other examples could be given of weak decay processes which are not observed and which are as consistent with the absolute conservation laws and have as much available energy (so that the phase space factors are not unfavorable) as those which are observed. It appears necessary to introduce additional selection rules, other than those already cited, in order to understand this phenomenon.

Since the lifetimes of the three unstable particles and antiparticles whose dominant modes of decay involve the emission of photons are much shorter than the lifetimes of the 20 other unstable particles and antiparticles, whose dominant modes of decay do not involve the emission of photons, the question naturally arises as to why these electromagnetic modes of decay do not prevail for all unstable particles. Since an electromagnetic lifetime is almost certainly shorter than 4×10^{-16} second (the upper limit for the lifetime of the neutral pion), there is at least a factor of 10^6 in favor of an electromagnetic decay process over a nonelectromagnetic decay. The failure to take advantage of such a large factor can only be explained by some sort of selection rule which forbids the fast electromagnetic decays of the particles within each class (of leptons, mesons, and baryons). For example, within the baryon class, the potentially fast electromagnetic decays like $\Sigma^+ \rightarrow p + \gamma$ and $\Xi^- \rightarrow \Sigma^- + \gamma$ do not take place, whereas the fast electromagnetic decay process $\Sigma^0 \rightarrow \Lambda + \gamma$ does take place. Within the meson class, the potentially fast electromagnetic decay processes like $K^0 \rightarrow 2\gamma$ and $K^+ \rightarrow \pi^+ + 2\gamma$ do not take place, whereas the fast electromagnetic decay $\pi^0 \rightarrow 2\gamma$ does take place. Within the lepton class, the absence of the potentially fast electromagnetic decay process $\mu^- \rightarrow e^- + \gamma$ has to be understood.

Strangeness Quantum Number

We are therefore faced with the necessity of introducing a new quantum number in order to forbid the fast electromagnetic decay processes which could otherwise take place in accordance with the absolute conservation laws of angular momentum, charge number, baryon number, and lepton number. This new quantum number is the strangeness number S, and both the observed and unobserved electromagnetic decays can be understood if we make a suitable assignment of this quantum number S to each of the elementary particles and insist upon the conservation of S in all processes involving the electromagnetic force. In Table 1 we have listed the assignments of the strangeness number for each of the elementary particles. It is convenient to assign the value $S = 0$ to the lightest particle within each of the four classes—that is, to the photon, the "light" lepton, the pion, and the nucleon. Such an assignment, plus the requirement of S conservation, allows the fast electromagnetic decay process $\pi^0 \rightarrow 2\gamma$. It then seems appropriate to change this quantum number by one unit as one proceeds to the heavier members of each class of particles. In this fashion, one assigns a strangeness quantum number, $S = -1$, to the muon, although such an assignment is actually not needed in order to explain the absence of the fast electromagnetic decay $\mu^- \rightarrow e^- + \gamma$. An assignment of $S = +1$ to the kaon, $S = + -1$ to the Λ- and Σ-hyperons, and $S = -2$ to the Ξ-hyperon would then allow the fast electromagnetic decay $\Sigma^0 \rightarrow \Lambda + \gamma$ and forbid the fast electromagnetic decay of all the other particles within the meson and baryon classes. The strangeness number S, like Q, B, and L, is an "additive" quantum number, so that S for the antiparticle is the negative of S for the particle.

It is interesting to note that while the weak decay processes are consistent with the absolute conservation laws of angular momentum, charge number, baryon number, and lepton number, they are not consistent with the conservation of strangeness number, as the fast electromagnetic decays are. Examination of the decay modes in Table 1 shows that in the weak decays, the strangeness number may remain unaltered (compare the neutron decay) or may change by one unit (compare the Λ decay or the K decay); it appears that the selection rule for the weak decays is $\Delta S = 0 \pm 1$. In the case of the Ξ-hyperon, where a weak decay with $\Delta S = 2$ could take place (for example, $\Xi^- \rightarrow n + \pi^-$), there is no evidence for such a process despite the fact that more phase space is available than for the decay $\Xi^- \rightarrow \Lambda + \pi^-$ which does take place. It appears that a change of ΔS by as much as two units is not allowed even for the processes governed by the weak force.

Of course, it is not remarkable that the conservation of the strangeness number S explains the observed facts concerning the fast electromagnetic decays of the elementary particles since, in a sense, we have simply introduced this new quantum number in order to account for these facts. What is remarkable is that the same conservation law of strangeness number holds for the strong or nuclear-type forces between mesons and baryons and has been confirmed in a wide variety of ways for physical processes governed by these strong forces. First of all, we have an explanation of the reason why decays such as $K^+ \rightarrow \pi^+ + \pi^0$, $\Lambda \rightarrow p + \pi^-$, $\Sigma^+ \rightarrow p + \pi^0$, and so on, do not take place extremely rapidly (with lifetimes of the order of 10^{-23} second—the nuclear lifetime—by virtue of the strong forces); they all violate the conservation of the strangeness number. The much longer lifetimes which are observed correspond to decays which occur through the weak forces and are permitted even though the strangeness number is not conserved. It is to be noted that all of the above reactions are consistent with the conservation laws of charge, baryon, and lepton numbers (in addition to energy, momentum, and so on).

A second important consequence of strangeness conservation for the strong forces is that the production of particles with $S \neq 0$ (called strange particles) must take place at least in pairs if the initial state only involves ordinary particles (that is, particles with $S = 0$, such as pions and nucleons). Thus, in nucleon-nucleon and in pion-nucleon collisions, the production of Λ- and Σ-hyperons requires the simultaneous production of the K^0 and K^+ mesons. The production of Ξ-hyperons requires the simultaneous production of two kaons with positive strangeness number. In other words, there is associated production of strange particles. Moreover, strangeness conservation implies that the production of the K^- or $\overline{K^0}$ meson can only take place if there is sufficient energy to produce simultaneously the K^+ or K^0 meson; this provides an immediate explanation of the much lower energy threshold observed for production of K^+ mesons than for K^- mesons, a difference that exists despite the fact that the masses of the positive and negative kaons are identical. It is found that the imposition of the requirement of conservation of the strangeness number is consistent with all physical processes which occur by virtue of the strong and electromagnetic forces but is not consistent with all the weak processes.

Three Types of Forces

In commenting upon the properties of the elementary particles I have referred to three types of forces which are responsible for the various types of processes in which the elementary particles are involved. The three types of forces (which at this stage, do not seem to bear any relationship to each other) are, to repeat, the strong or nuclear force, the electromagnetic force, and the weak force. Of the four classes of elementary particles—photon, lepton, meson, and baryon—the photon is the carrier, so to speak, of the electromagnetic force and does not exert a weak or strong force on any of the other particles. The charged members of the lepton class of particles experience electromagnetic forces due to the other particles (the neutrino does not, because it possesses no charge and no magnetic moment), whereas all the members of the lepton class interact weakly with each other and with the members of the meson and baryon classes. As regards the meson and baryon classes, we can say that, in general, the members of these two classes interact strongly with each other, interact electromagnetically with all the elementary particles, and interact weakly with each other and with the members of the lepton class.

As I have stated, the three forces under consideration are, in order of decreasing strength, strong or nuclear force, electromagnetic force, and weak force. It is useful to give a quantitative estimate of a dimensionless constant which is characteristic of each of the forces. The most familiar of the forces, the electromagnetic, is the one of intermediate strength, where the dimensionless constant which crops up whenever any electromagnetic process is calculated is the fine-structure constant

$$\alpha = \frac{e^2}{4\pi\hbar c} = \frac{1}{137}$$

where e is the elementary charge, $\hbar$ is Planck's constant over 2π, and c is the velocity of light. It is important to note that the charge e, which enters into the fine-structure constant, is a measure of the strength of the interaction of a charged particle with the electromagnetic field. The analog of the fine-structure constant in the case of the strong or nuclear force is a dimensionless constant $g^2/4\pi\hbar c \cong 15$, where g is the pion-nucleon coupling constant. The pion-nucleon coupling constant has been chosen because its value is much better known from pion scattering experiments (on nucleons) and from the nuclear force between two nucleons (which is attributed chiefly to the pion field).

For both the electromagnetic and strong forces, a dimensionless constant emerges in a natural way by considering e or g, which measures the strength of the corresponding force. In the case of the weak force, the characteristic coupling constant has a different dimension, and it is necessary to perform some manipulations in order to obtain a dimensionless constant characteristic of the weak force. The coupling constant for β decay, G, which is the most extensively studied of the weak forces, has the value 1.4×10^{-49} erg $\times$ cubic centimeter. A dimensionless constant characteristic of the weak force is then obtained by taking $G^2 \times (\hbar c)^{-2} \times (\hbar/\mu c)^{-4} \simeq 5 \times 10^{-14}$ (μ is the pion mass). In order to obtain a dimensionless constant, we have used the pion Compton wavelength ($\hbar/\mu c$); however, it is clear that the result which would be obtained by utilizing the Compton wavelength of some other particle would not alter the essential conclusion, which is that the weak force is extremely weak (by many powers of 10) as compared to the electromagnetic and strong forces.

There is one further force which is extremely important for the macroscopic world, to which no reference has thus far been made—namely, the gravitational force. However, the dimensionless constant characteristic of the gravitational force, which is obtained by using the (large) baryon mass, is $KM^2/\hbar c \simeq 2 \times 10^{-39}$ [K ($= 6.7 \times 10^{-8}$ dyne cm^2/gm^2) is the gravitational constant]. This extraordinarily small number justifies the complete neglect of the gravitational force in discussing the elementary particles.

I have already indicated that certain absolute conservation laws (of energy, momentum, angular momentum, charge number, baryon number, and lepton number) govern all three types of force which are of importance for the elementary particles. I have also referred to at least one conservation law which holds for some of the forces but not all—that is, the conservation of strangeness number is supposed to be valid for the electromagnetic and strong forces but not for the weak forces. There is at least one additional absolute conservation law (time reversal invariance) which holds for all three types of force, and there are at least three approximate conservation laws (parity conservation, charge conjugation invariance, and isotopic spin conservation) which hold for at least one of the forces but not for all. It appears that the strong forces are governed by the largest number of conservation laws (and therefore are subject to the largest number of invariance principles), with the electromagnetic interactions governed by fewer and the weak interactions subject to the least number of conservation laws. The correlation between the strength of the interaction and the number of conservation laws is certainly one of the important problems in the field of elementary particle physics.

Conservation of Parity, Charge Conjugation, Time Reversal

In conclusion, I shall comment briefly on the conservation laws of parity, charge conjugation, and time reversal. These conservation laws were accepted as a priori principles for many years. Then in 1956 came the shocking demonstration of parity breakdown in beta-decay processes, and since then all three conservation laws have been reinvestigated experimentally under all types of conditions. We can summarize the experimental situation at the present time as follows. In the domain of strong forces, an experimental search for parity nonconservation has been made in connection with ordinary nuclear forces, the πN (pion-nucleon) force, and the ΛKN force. No evidence has been found for parity nonconservation. There is similarly no experimental evidence for parity nonconservation in electromagnetic transition in atoms and nuclei. We may conclude that, just as for the strong forces, there is no experimental evidence for parity nonconservation in electromagnetic forces.

The situation is spectacularly different for the weak forces. There are literally dozens of experiments where parity nonconservation has been demonstrated in an unambiguous fashion. Indeed, one of the most striking aspects of all of these experiments is that the parity breakdown is usually complete. Parity nonconservation effects have been found in all types of weak processes: in connection with the leptonic decays of the nucleon, muon, pion, and kaon and the nonleptonic decay modes of the hyperons. We are thus led to the over-all conclusion that there is absolutely no experimental evidence for the nonconservation of parity for the strong and electromagnetic forces but that there is overwhelming evidence for the maximum nonconservation of parity for all the weak forces, whether they involve leptons, mesons, or baryons, strange or non-strange.

Next, consider the experimental evidence for the charge conjugation invariance of the strong, electromagnetic, and weak forces among the elementary particles. In order to decide whether a force is invariant under charge conjugation, we must compare a given physical process governed by this force with the charge conjugation transform of this physical process—namely, the physical process obtained by replacing every particle by its antiparticle. If the physical process and its charge conjugation transform governed by a given force are not identical (with respect to their cross sections, properties of the decay products, and so on), we can conclude that the force is not invariant under charge conjugation. It turns out that the experimental situation with regard to charge conjugation invariance is similar to that for parity conservation. Both the strong and electromagnetic forces are invariant under charge conjugation, whereas there is unequivocal experimental evidence for the breakdown of charge conjugation invariance in physical processes governed by the weak force. In the case of the weak force, direct experimental evidence for the failure of charge conjugation invariance comes from the observation that the helicities (that is, left- or right-handedness) of the electron and positron are opposite from the μ^- and μ^+ decays, respectively; that the helicities of the μ^- and μ^+ are opposite from the π^- and π^+ decays, respectively; and that the helicities of the neutrino and antineutrino are opposite in all decays in which they are involved. If these weak decays were invariant under charge conjugation, the particles and antiparticles would have to come out with the *same* zero helicity. Since the particles come out with *opposite* finite helicities, the breakdown of charge conjugation invariance is proved for the weak force.

A serious effort has also been made to ascertain whether time reversal invariance breaks down for any of the three forces. All the available evidence is in favor of the time reversal invariance of all physical processes—those governed by the weak force as well as those governed by the strong and electromagnetic forces.

Now there is a famous (*"CPT"*) theorem which says that if physical processes obey Einstein's laws of special relativity, then they will be invariant under the product of the operations of charge conjugation (C), parity (P), and time reversal (T). We therefore reach the interesting conclusion that since all the forces among the elementary particles (strong, electromagnetic, and weak) appear to be invariant under the time reversal operation, they must be invariant under the product of the charge conjugation and parity operations (that is, we have CP invariance). This is a trivial statement for the strong and electromagnetic forces, since they are separately invariant under C and P. However, the weak forces are separately *noninvariant* under C and P, but nevertheless it turns out (as a result of the CPT theorem and their invariance under T) that they are invariant under the product of the two operations C and P. An understanding of the fact that all forces among the elementary particles are CP-invariant, with the weak force separately noninvariant under C and P, is another intriguing problem of elementary particle physics.

Note

1. The Russians have recently produced an anti-Σ-hyperon with their 10 Bev accelerator at Dubna.
2. These experiments are discussed in G. Feinberg and M. Goldhaber, *Proc. Natl. Acad. Sci. U.S.* **45** (1959).