ELEMENTARY PARTICLES

The search for the elementary constituents of matter is as old as physics itself, but any quantitative attempt at such a theory had to await the experimental discoveries of this century. Such a search is prompted by two considerations: the identification of the basic building blocks of nature and the hope that their laws of interaction would be essentially simple.

The atom had to yield its claim to be indivisible when it was found that electrons were constituents of all atoms; moreover, the electrons from various species of atoms were identical. Light, with its particle properties, seemed another universal entity connected with matter, since the photons (light quanta) which were emitted in atomic transitions appeared identical apart from their momenta. The electron and the photon were the first two elementary particles to be discovered, and a quantitative theory of the emission and absorption of photons by the electrons in an atom was possible only after the invention of quantum mechanics. The corresponding picture of the atom regarded the electrons in an atom as being subject to electrostatic attraction of the positively charged nucleus (and the mutual repulsion of the electrons), the photons having only a transitory existence being either emitted or absorbed in the transitions between the atomic states. The search for the structure of matter now became a search for the constituents of the nucleus.

A quantum theory of the nucleus (or rather nuclei) was made possible by the discovery of the proton and the neutron. The nuclear interaction which was responsible for holding the nucleus together (against the disruptive electrostatic repulsion of the protons) was found to be of an entirely new kind, much stronger than the electric interaction at short distances but decreasing very much more rapidly with distance. The various complex nuclei differ in the number of protons and neutrons they contain.

By that time, the theory of the interaction between electrons and photons had developed to the point where the electrostatic repulsion or attraction between electrically charged particles could be understood in terms of the exchange of photons between them. In the lowest nontrival approximation, it gave the Coulomb law for small velocities. The basic interaction was the emission and absorption of "virtual" photons by charged particles. A similar mechanism could be invoked to explain the short-range nuclear interaction; and essentially our present picture of the nuclear interaction is that it is due to the exchange of particles, which have nonzero masses which are a fraction of nuclear mass—the same approximation procedure used for deducing the static Coulomb force (from the electron-photon interaction) is no longer valid here; and the nuclear force has a rather complicated form. However, these theoretical considerations did predict the existence of a set of three particles called pions, which have since been discovered.

Another kind of particle and another kind of interaction were discovered from a detailed study of beta radioactivity in which electrons with a continuous spectrum of energies are emitted by an unstable nucleus. The interactions could be viewed as being due to the virtual transmutation of a neutron into a proton, an electron and a new neutral particle of vanishing mass called the neutrino. The theory provided such a successful systematization of beta decay data for several nuclei that the existence of the neutrino was "well-established" more than twenty years before its experimental discovery. The beta decay interaction was very weak even compared to the electron-photon interaction.

Meanwhile, the electron was found to have a positively charged counterpart called the positron; the electron and positron could annihilate each other, with the emission of light quanta. The theory of the electron did in fact "predict" the existence of such a particle. It has, since then, been found that the existence of such "opposite" particles (antiparticles) is a much more general phenomenon (see below).

Our present catalog of elementary particles and decay modes contains many more entries. These particles fall into five families: the photon family, the electron family, the muon family, the meson family and the baryon family. Most of these particles are unstable and decay within a time which is often very small by normal standards but which is many orders of magnitude larger than the time required for any of these particles to traverse a typical nuclear dimension. There is a wide variety of reactions between them, but they could be understood in terms of three basic interactions—the strong (or nuclear) interactions, the electromagnetic interactions and the weak interactions. The nuclear forces and the interaction between pions and nucleons belong to the first, the electron-electron and electron-photon interactions to the second, and the beta decay interaction to the third. The present theoretical framework enables us to handle more or less quantitatively the electromagnetic and weak interactions only. Despite this, it is possible to understand many aspects of strong (as well as the other) interactions in terms of conservation laws and invariance principles (see CONSERVATION LAWS AND SYMMETRY).

The classical conservation laws of energy, momentum and angular momentum are valid in the relativistic quantum theory of elementary particles also. The particles may possess intrinsic angular momentum or "spin" which expressed in natural units $\frac{h}{2\pi}$ of angular momentum is restricted to an integer or a half-odd integer. Angular momentum conservation holds only when this spin angular momentum is included. But one finds that to every particle, there corresponds an antiparticle with the same mass, same spin and same lifetime. (In the case of the photon and the neutral pion, they are their own antiparticles; they are strictly neutral particles.) The particle and antiparticle have equal and opposite electric charges, and the antiparticle of the antiparticle is the original particle. The conservation of electric charge is another familiar (although non-classical) conservation law satisfied by all known interactions. It is the prototype of a set of "additive" conservational laws which include the conservation of the baryon number, the muon number and the electron number. To the best of our knowledge, these conservation laws are still exact.

Incidentally, the conservation of baryon number is the refinement of the classical law of conservation of matter; and may be thought of as the fundamental law guaranteeing the stability of the physical universe.

In addition to these additive conservation laws which arise from continuous symmetries, there are a set of "multiplicative" conservation laws which are associated with discrete symmetries. It is possible to examine the invariance of the physical laws under space inversion, i.e., using a left-handed coordinate system instead of a right-handed coordinate system or vice versa; if the statement of the law is unaffected by this interchange, it is possible to show that a quantum number having the two values ±1 can be assigned to classify the quantum-mechanical states such that a state with the label +1 will not change to one with the label −1 due to any interaction. This quantum number is called "parity." Just as particles may possess intrinsic angular momentum (spin), particles may also have intrinsic parity. Table I lists the particles (and their corresponding antiparticles) with their respective additive quantum numbers, intrinsic parities and lifetimes. General principles of relativistic quantum theory imply that antiparticles of integral spin particles have the same parity as the particles; for half-odd-integral spin particles the antiparticle has the parity opposite that of the particle. All experimental checks are in accordance with this prediction.

In addition to invariance under space inversion, we may consider particle conjugation (replacement of particles by antiparticles) invariance, and time reversal invariance, or combinations of these transformations. It turns out that strong and electromagnetic interactions are invariant under each of these three transformations (and hence any product of these), but weak interactions are invariant only under combined inversion (product of particle conjugation and space inversion) and under time reversal. It can be shown that all interactions are invariant under the product of the three transformations of space inversion, particle conjugation and time reversal if some very general principles of the relativistic quantum theory of these particles are valid.

Even the statement that weak interactions are invariant under combined inversion has turned out not to be strictly true. In the decay of the neutral K meson we would have expected a short lived particle (even under combined inversion) called K_1^0 and a longer lived particle (odd under combined inversion) called K_2^0, provided combined inversion were strictly valid. We do observe such short- and long-lived components; but we also expect that the long-lived component K_2^0 cannot decay into two pions. Experimentally we find a small amount of decay into two pions. This violation of combined inversion (and, hence, of time reversal invariance) is only two-tenths of a percent, but it is definitely present. Thus none of the discrete symmetries (except the product of the three) seems to be strictly valid.

One notices that the various particles belonging to a family have the same spin and the same values of the additive quantum numbers except the electric charge. The photon has a universal interaction with all charged particles; it has been found possible to connect the conservation of electric charge and this universal interaction structure, on the one hand, to the vanishing mass and unit spin of the photon, on the other. The electron and muon partake of both electromagnetic and weak interactions, but do not exhibit any strong interaction. In fact the muon family appears to be simply a duplicate of the electron family except for a change in the unit of mass. At the present time, no basic reason has been found for this doubling, and it is perhaps the most fascinating puzzle of current elementary particle physics. The members of these two families are collectively known as leptons and they all have spin one-half. The neutral members (the electron neutrino, the muon neutrino, and their antiparticles) have extremely weak interaction with matter since they do not participate even in electromagnetic interactions.

The meson family consists of eight members which fall into a triplet of pions, a singlet eta, a doublet of kaons and a doublet of antikaons. They are all pseudoscalar (spin zero and odd parity) and exhibit strong interactions. The charged particles are of course coupled to the photon, but even the neutral members can participate in electromagnetic interaction by virtue of the large probability for virtual dissociation into charged particles. They participate in a variety of weak interactions including the nuclear beta decay interaction.

It is found that the kaons, the hyperons (baryons other than the neutron and proton) and their antiparticles, collectively known as "strange particles," can decay by weak interactions not involving leptons or photons with a lifetime which is large compared to the natural periods appropriate to strong interactions. On the other hand, these particles are produced copiously in high-energy nuclear collisions. These two circumstances can be understood in terms of the existence of another additive quantum number, called hypercharge, which is conserved in strong and electromagnetic interactions but violated in weak interactions.

The meson-baryon system exhibits further regularities as far as strong interactions are concerned. The neutron and the proton have very nearly the same mass and similar nuclear interactions although their electromagnetic properties are quite different. The three pions have different electric charges, but again they have approximately equal masses and similar nuclear interactions. This kind of multiplet structure is evident for other strongly interacting particles: the kaons form a doublet, the sigma hyperons form a triplet, the xi hyperons form a doublet, and the lambda hyperon remains a singlet. In view of the relative weakness of the electromagnetic interaction, it is tempting to ascribe all deviations from exact equality of the masses to the indirect action of the electromagnetic interaction. In this framework, it is possible to consider the members of a multiplet to be different states of the same particle corresponding to the values of a new quantum number. What is remarkable is that if one takes this point of view, it is possible to show that the strong interactions exhibit a remarkable invariance under a group of continuous transformations which may be viewed as the group of rotations in a fictitious three-dimensional space (or more correctly as the special unitary group SU(2) of transformations on two variables). The transformations act as follows: the singlet is unchanged, the doublet components

TABLE 1. CATALOG OF ELEMENTARY PARTICLES

Particle	Family*	Spin	Mass (MeV)	Lifetime† (sec)	Antiparticle	Parity‡	Charge	Hyper-charge	Baryon Number	Electron Number	Muon Number
Photon, γ	Photon	1			Photon, γ	—	0	0	0	0	0
Electron neutrino, ν_e	Electron	$\frac{1}{2}$			Antielectron neutrino, $\bar{\nu}_e$	Undefined	0	0	0	1	0
Electron, e^-		$\frac{1}{2}$			Positron, e^+	+	−1	0	0	1	0
Muon neutrino, ν_μ	Muon	$\frac{1}{2}$			Antimuon neutrino $\bar{\nu}_\mu$	Undefined	0	0	0	0	1
Muon, μ^-		$\frac{1}{2}$			Positive muon, μ^+	+	−1	0	0	0	0
Neutral pion, π^0	Meson	0			Neutral pion, π^0	—	0	0	0	0	0
Positive pion, π^+		0			Negative pion, π^-	—	+1	0	0	0	0
Neutral kaon, κ^0		0			Neutral antikaon, $\bar{\kappa}^0$	—	0	+1	0	0	0
Positive kaon, κ^+		0			Negative antikaon, $\bar{\kappa}^-$	—	+1	+1	0	0	0
Proton, p	Baryon	$\frac{1}{2}$			Antiproton, $\bar{p}$	+	+1	+1	+1	0	0
Neutron, n		$\frac{1}{2}$			Antineutron, $\bar{n}$	+	0	+1	+1	0	0
Lambda, Λ		$\frac{1}{2}$			Antilambda, $\bar{\Lambda}$	+	0	0	1	0	0
Positive sigma, Σ^+		$\frac{1}{2}$			Negative antisigma, $\bar{\Sigma}^-$	+	+1	0	1	0	0
Neutral sigma, Σ^0		$\frac{1}{2}$			Neutral antisigma, $\bar{\Sigma}^0$	+	0	0	1	0	0
Negative sigma, Σ^-		$\frac{1}{2}$			Positive antisigma, $\bar{\Sigma}^+$	+	−1	0	1	0	0
Neutral Xi, Ξ^0		$\frac{1}{2}$			Neutral antiXi, $\bar{\Xi}^0$	+	0	−1	1	0	0
Negative Xi, Ξ^-		$\frac{1}{2}$			Positive antiXi, Ξ^+	+	−1	−1	1	0	0
Omega, Ω^-		$\frac{1}{2}$			Anti omega, Ω^+	+	−1	−2	1	0	0

[*] Electron and muon families are collectively known as the lepton family. The proton and neutron are both nucleons; other members of the baryon family are the hyperons

[†] The neutral kaon has a long-lived component $K_2{}^0$ and a short-lived component, which are quantum mechanical superpositions of the neutral kaon and the neutral antikaon.

[‡] Electron, muon, proton, neutron and lambda parities are defined by convention.

INSERT "A"

$K^0\ K^+\ \bar{K}^0\ \bar{K}^-$

(the letter K
not kappa)

"A"

(5a)

Spin	Mass (MeV)	Lifetime†(sec)
	0	Stable
	0	Stable
	0.51098	Stable
	0	Stable
	105.66	2.20×10^{-6}
	135.0	0.84×10^{-16}
	139.6	2.60×10^{-8}
	497.8	0.86×10^{-10}
	493.8	1.24×10^{-8}
	938.3	Stable
	939.6	$0.93 \times 10^{+3}$
	1115.6	2.5×10^{-10}
	1189.4	0.8×10^{-10}
	1192.5	1×10^{-14}
	1197.4	1.5×10^{-10}
	1314	3.0×10^{-10}
	1321	1.7×10^{-10}
	1672	1.3×10^{-10}

transform like the components of a spinor, and the triplet components transform like the components of a vector. This property of strong interactions is called "charge independence"; and the corresponding conserved dynamical variable (with three components) is called the isotopic spin. It then turns out that hypercharge conservation is a consequence of isotopic spin conservation and electric charge conservation. While the conservation of isotopic spin is violated by the electromagnetic (and weak) interactions, the charge independence of nuclear interactions is still expected to be satisfied to within a few per cent and experimental tests confirm this. Since the symmetry associated with invariance under isospin transformations is not directly related to space-time properties, one often refers to it as an "internal symmetry."

On might now raise the question: Which of these particles are basic constituents of matter? For the case of the atom, say the simplest of them all, the hydrogen atom, it seems easy to say that it is a composite system made up of an electron and proton bound together by an electrostatic force. However, this answer is not completely satisfactory since the electrostatic force itself is due to the exchange of light quanta, and in the process of atomic transitions photons are emitted or absorbed. Yet we do not include them as constituents of the atom. In beta radioactivity, electrons and neutrinos emerge from the nucleus, yet the nucleus is not pictured as containing either of these varieties of particles but rather as made up of protons and neutrons. The beta electron and neutrino are rather assumed to be created at the moment of emission. With the mesons taking part in strong interactions, however, such distinctions are no longer obvious, and the question of whether a particle is elementary or is composed of several other particles cannot be answered except perhaps within the context of a more quantitative but limited model. A point of view that has gained some acceptance is that *none* of these particles are elementary and that each is a composite of several particles (including perhaps itself)!

This view, while by no means inevitable or even well-established, is a possible picture, because in the realm of elementary particles we can not only add particles together to construct a composite system, we can also "subtract" particles by adding antiparticles. The claim that particles A and B go to make up the particle C is difficult to distinguish from the claim that particles $\bar{B}$ (antiparticle to B) and C go to make up the particle A. Further, particles play a dual role. On the one hand, they are constituents of a composite system: on the other hand, they are the objects which are exchanged to generate forces between the constituents. In any case, in view of the very large number of entries in Table 1, it is not desirable to accept all of them as the ultimate constituents of matter.

This is even more forcefully brought to our attention by the recent discovery of a very large number of ultra short-lived particles. They appear as sharp resonances in multiparticle systems.

Since these "resonances" disintegrate within a short time (even on the nuclear scale!), it is difficult to view them as elementary particles, but they seem to play an important role in interaction phenomena and are produced as often as the more stable (and familiar) mesons and baryons included in Table 1. It appears at the present time that they ought to be included on more or less the same footing. A list of the better established resonances is given in Table 2 along with the mesons and baryons from Table 1. Since an unstable particle lives only for a very short time, its energy and consequently its mass cannot be sharp, and from elementary quantum mechanical considerations we would expect this "width" in the mass of a resonance to be inversely proportional to its lifetime. Since the width is what is measured experimentally, the width (rather than the lifetime) is usually quoted in connection with resonances.

Since these particles are coupled in the strong interactions, one would expect them to occur in isospin multiplets. This is in fact observed. It turns out that since strong interactions are invariant under particle conjugation and are charge independent, we could define a multiplicative quantum number called G-parity which has definite values ±1 for mesons and meson resonances. These values are also included in Table 2.

With these resonances included among the "elementary particles" we have a situation somewhat parallel to atomic spectroscopy <u>before</u> the discovery of quantum mechanics. The catalogue of the strongly interacting particles (collectively known as "hadrons") now contains well over a hundred entities and it would be sad to consider a hundred plus "elementary" constituents. Yet how are we to select the genuine subset of elementary constituents? We have already remarked about the picture in which <u>every</u> hadron is a composite system. We should then look for regularities amongst them including groupings into families, multiplets etc., as well as for systematic relations between masses, spins, multiplet sizes, etc.

There are also practical questions regarding the identification and interpretation of resonances. How wide a resonance is to be included? When a number of different reaction channels are open, a resonance may not be easily visible as a pronounced peaking in cross section or mass plot. When resonances overlap the problem is aggravated. A particularly curious example is given by the so-called A_2 resonance which corresponds to a meson with spin 2 even parity isospin 1 and odd G-parity in the neighborhood of 1300 MeV. The generally accepted picture views this as a double resonance, approximately coincident in mass and variable width. For example the data could be fitted with one resonance of width 80 MeV and another of width 10 MeV both at 1300 MeV. Equally well it could be fitted with two resonances both with width 25 MeV but one at 1290 MeV and another at 1310 MeV. Yet other experiments do not find any splitting at all! This is admittedly an extreme case, yet it highlights the kind of problem involved.

"B"

Mass (MeV)	Width (MeV)†
138.5	0
495.8	0
495.8	0
548.8	0
938.9	0
1115.6	0
1193.4	0
1318.4	0
765	125
893	50
893	50
1019	4
784	11
1236	120
1385	36
1530	7
1672	0

Table 2. Strongly Interacting Particles and resonances (as of ~~1964 summer~~ 1971 April)

Particle or Resonance	Spin	Mass (MeV)*	Width (MeV)†	Parity	Electric Charge	Hyper-charge	Isotopic Spin	G-parity	Unitary Symmetry Assignment
Pion, π	0			−	0, +1	0	1	−	Pseudoscalar meson octet
Kaon, K	0			−	0, +1	+1	$\frac{1}{2}$	Undefined	
Antikaon, $\bar{K}$	0			−	0, −1	−1	$\frac{1}{2}$	Undefined	
Eta, η	0			−	0	0	0	+	
Nucleon, N	$\frac{1}{2}$	INSERT #13"		+	0, +1	+1	$\frac{1}{2}$	Undefined	Baryon octet
Lambda, Λ	$\frac{1}{2}$			+	0	0	0	Undefined	
Sigma, Σ	$\frac{1}{2}$			+	0, +1, −1	0	1	Undefined	
Xi, Ξ	$\frac{1}{2}$			+	0, −1	−1	$\frac{1}{2}$	Undefined	
Rho resonance, ρ	1			−	0, +1, −1	0	1	+	Vector meson octet
Kaon resonance, K^*	1			−	0, +1	+1	$\frac{1}{2}$	Undefined	
Antikaon resonance, $\bar{K}^*$	1			−	0, −1	−1	$\frac{1}{2}$	Undefined	
Phi resonance, ϕ	1			−	0	0	0	−	
Omega resonance, ω	1			−	0	0	0	−	Vector meson singlet
Nucleon resonance, N^*	$\frac{3}{2}$			+	0, +2, +1, −1	+1	$\frac{3}{2}$	Undefined	Baryon resonance decuplet
Y resonance, Y^*	$\frac{3}{2}$			+	0, +1, −1	0	1	Undefined	
Xi resonance, Ξ^*	$\frac{3}{2}$			+	0, −1	−1	$\frac{1}{2}$	Undefined	
Omega minus resonance, Ω					−1	−2	0	Undefined	

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* The average mass of the members of the isotopic multiplet is tabulated.

† Since the unstable particles of Table 1 live "practically forever" on the nuclear time scale, the corresponding widths are several orders of magnitude smaller than one MeV; these are quoted here as "0".

One notes also that the meson and baryon multiplets seem to fall into further supermultiplets. Following the analogy of the isospin group, we may now ask what internal symmetry group is responsible for this interaction. We must also remember that whatever is responsible for the violation of this higher symmetry must itself be a part of the strong interaction. A scheme in which invariance under the special unitary group on three variables SU(3) holds approximately has been successful in correlating and predicting the spectrum of particles and their interactions. The isospin group, SU(2) is a subgroup of this unitary group. Just as for charge independence, no basic reason has been found for the origin of this "unitary symmetry." Still other symmetry groups, even wider than SU(3) and generally incorporating it, and which are even more significantly violated, are being studied. It appears that the complete understanding of these higher internal symmetries would involve not only their origin, but also the origin of their violation.

The hadron multiplets appear to have other regularities. We can discern, in analogy to atomic physics, subfamilies consisting of a lowest spin "ground state" and successive higher spin "excited states". The states listed in Table 2 maybe viewed as the ground states. If we plot the masses squared versus the spin for several of these subfamilies, we find them to lie approximately on straight lines with a universal slope of about

$1(\mathrm{GeV})^{-2}$. These may be thought of as the generalization of the bound state energy versus spin relation for potentials to the domain of resonances and, thus, as orbital excitations; and in this context they are known as Regge families.

The ground states themselves may be understood in terms of a generalization of the "internal symmetry" to include a spin aspect also so that instead of SU(3) we consider SU(6). The spin ½ even parity baryon octet and spin $\frac{3}{2}$ even parity baryon decuplet resonances together then form a single 56-dimensional representation of SU(6). The nine spin 0 odd parity mesons and the nine spin 1 odd parity vector meson resonances form a mixture of the 35-dimensional and the 1-dimensional representation of SU_6. We can combine this SU(6) structure together with the orbital excitations mentioned above to bring about a phenomenological SU(6)×0(3) classification for hadrons.

It is very tempting to think of this SU(6)×0(3) structure as pointing to a substructure of the hadrons in terms of 3 hypothetical entities with spin ½ and even parity which transform as a

3×2 dimensional representation of this group called "quarks". The simplet baryon resonances are then to be viewed as three-quark compounds and the meson resonances as quark-antiquark compounds. The spin, parity, and SU(3) quantum numbers of most hadrons are consistent with this picture and some quantitative understanding of the resonance masses and decay parameters can be obtained within this framework, sometimes referred to as the "quark model". It should be pointed out that so far no quarks have been discovered and physicists are not sure if they even expect them to exist.

We should also remark that the particles so far discovered all have either finite mass (Class I particles or tardyons), or zero mass (ClassII particles or luxons). It is an interesting question to ask if particles of imaginary mass (Class III particles of tachyons) can and do exist. It used to be thought that such particles could not exist since their existence would violate the principle of relativity, but now we know that such is not the case. If hadronic tachyons exist quantum theory of tachyons predicts that they will show up as fixed resonances in momentum transfer; experimentally the situation has not been conclusive. Leptonic tachyons (and photon-like tachyons) could probably be best detected in astronomical phenomena. If they exist they would provide for a substantial pressure in the interior of hot stars and thus provide a balancing force to alleviate gravitational collapse . Whether the concept of particles of imaginary mass, which is the relativistic counterpart of geometric size used in simpler nonrelativistic physics, is useful in elementary particle physics is not yet clear.

The theoretical description of the interaction of electrons and photons involves a relativistic quantum theory of the electron and photon fields (QUANTUM ELECTRODYNAMICS). While fundamental difficulties still remain, the computational techniques developed have enabled the accurate prediction of even the finer details of the electron's electromagnetic properties. Such a method of calculation completely fails for strong interactions, although there are reasons to believe that the correct theory should involve interacting quantized relativistic fields. The immediate correspondence between each kind of particle and a field as obtained in quantum electrodynamics is unlikely for the strongly interacting particles. On the other hand the answer to the question "What are the primitive fields?" is not obvious. The problem is made much more difficult by the appearance of meaningless divergent quantities in direct calculations. At the present time we have a number of ad hoc theoretical devices to extract some meaningful quantitative predictions in perturbation theory but at the loss of much physical intuition. Thus we are faced with a frustrating situation: there are reasons to believe that the basic theory should involve relativistic interacting quantized fields, but there is no immediate way of deciding the number or nature of the fields or of the law of their interaction.

The problem of divergences in local relativistic quantum theory may be seen to be a reappearance of the Rayleigh-Jeans divergence of the specific heat of the vacuum in the context of interacting fields. Basically it stems from the unqualified availability of the infinite number of degrees of freedom of a local field. Just as Planck's hypothesis of quanta was a drastic departure from usual theory such a natural, yet drastic departure is indicated to eliminate the divergences. To do this without departing from local interaction structure we may generalize the notion of the vector space of states to a mathematical space with indefinite metric. Within such an indefinite metric quantum field theory the various scattering and transition amplitudes can be calculated to a desired degree of approximation without the appearance of infinities. However we do have to deal with generalized probabilities which may be positive or negative. Negative probabilities cannot be reconciled with the physical interpretation of probabilities in quantum theory. This logical hurdle has been overcome with the discovery of shadow states. These are mathematical states which have no physical counterpart. They enter the dynamical theory but the probability is conserved amongst physical states only; there is no transition between physical states and shadow states. Quantum field theory with shadow states is the realization of a finite relativistic field theory. So far only perturbation theory has been worked out within this framework.

Since the quantum field theory framework has not so far yielded acceptible computational techniques for strong interactions, in recent years increasing effort has gone into attempts to make a theory of the reaction amplitudes ("scattering matrix elements") directly. The hope is that from the general principles of quantum field theory together with sufficient clues provided by the scattering experiment one can directly construct a theory for the scattering amplitude. This point of view has triggered a systematic effort to scan transition amplitudes in various kinematical regions and to higher and higher accelerator energies, and substantial amount of data has been accumulated. As an intermediate step in the groping for fundamental building blocks of the theory the investigation often appears to be the direct interpretation of scattering phenomena. We have gained some qualitative (and partially quantitative) understanding; but the goal is still beyond the horizon. Eventually, of course, we expect that this approach would include also an understanding of the leptons and the photon.

> To sum up, we find that we have now a very large number of "elementary" particles which, by their very number, forfeit their claim to be considered ultimate constituents of matter. We have some understanding of the regularities observed in their spectrum and their interactions, and we have discovered a variety of conservation laws. However, we still do not understand the multiplicity of these particles, nor do we have a quantitative theory of their interactions. Perhaps yet another level of discovery awaits us in our search for the constitution of matter.
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