ELEMENTARY PARTICLES?

By Geoffrey F. Chew

In this brief survey I am going to borrow some ideas from a lengthy review prepared in collaboration with Murray Gell-Mann and Arthur Rosenfeld for publication elsewhere.* In the title of our article we have used the term "particle" but have carefully avoided the adjective "elementary". Had the title of my paper here today been of my choosing, I should similarly have avoided such a modifier, because if there is a discernible trend in current high-energy physics it is the *decline* of the elementary particle concept. A major purpose of my report to you is to describe this decline of an ancient idea and the beginnings of a new idea that may fill the void.

Particle proliferation

A well publicized facet of the present position in subatomic physics is the proliferation of nuclear particles. The number of particles discovered during the past five years is so large that there is little point in an enumeration here. Those of you not already familiar with the list would only be bewildered, not enlightened. What was the source of the spectacular increase in the rate of particle discovery?

There were at least three ingredients. To understand these you must realize that most nuclear particles are unstable and have rest mass energies of the order of a billion electron volts. Some, with longer lifetimes, were found in cosmic rays but the majority are so short lived that they must be created in the laboratory if they are to be seen. Accelerators in the billion-volt range became operative during the last ten years; this was a necessary first ingredient for the population explosion among established particles.

A second ingredient was the invention and development of the bubble chamber. This marvelous instrument allowed the complete study of almost all the particles produced in a given nuclear reaction, under conditions where thousands of events could be accumulated in a reasonable time. Unstable particles with lifetimes as short as 10^{-22} sec thereby revealed themselves through their decay products, which could be followed in detail and analyzed on a statistical basis. The third ingredient was the development of high-speed data analysis systems capable of handling tens of thousands of events in individual experiments. Without such systems the output from bubble chambers would overwhelm human capacities.

By no means all of our information about nuclear particles is coming from bubble chambers. Spark chambers and sophisticated electronic arrangements continue to be essential in situations where the number of events to be analyzed runs in the hundreds of thousands or more. A substantial number of the new particles have revealed themselves in such experiments.

What can be said to summarize the vast amount of particle information now available? First of all,

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proliferation has occurred only among "strongly interacting particles". These are particles like the neutron and proton that mutually interact through powerful short-range forces. All particles discovered to date, with the exception of the photon, electron, muon, and the neutrinos, are of this type. The latter four particles are called leptons and this lepton family has not increased in number over the past thirty years. Recently it was discovered at Brookhaven that there are two kinds of neutrinos, one associated with muons and one with electrons, but this cannot be considered proliferation in the sense observed for strongly interacting particles.

A second generalization is that there are no strongly interacting particles of mass very small compared to the average, which is ~ 1 billion electron volts in order of magnitude. The lightest is the pion whose mass is $\sim 1/7$ BeV. Compare this to the electron whose mass is $\sim 5 \times 10^{-4}$ BeV, or to the neutrino whose mass is believed to be zero. A plausible inference from these two circumstances is that strongly interacting particles are in some sense dynamical structures, owing their existence to the same forces through which they mutually interact. Such a mechanism can be imagined to produce a spectrum of energy levels (i.e., particle masses of the type observed, with no sharp upper bound, and with the ground state not differing qualitatively from excited states.

In contrast, the origin of the leptons cannot be dynamical in the same sense. The necessary forces here have never been found and the bizarre spectrum of states, beginning with one of zero energy and terminating sharply at the muon, bears no resemblance to any dynamical spectrum seen before. There have been many discoveries of simplicity and regularity in lepton properties in recent years but nothing yet to suggest a deep explanation of why these particles exist. I shall concentrate the remainder of this report, therefore, on the strongly interacting particles—where the accumulated weight of experimental evidence promises soon to produce a major increment of understanding.

It will be easy for you to grasp one reason for the current optimism regarding strong interactions. The point is that the very magnitude of the particle population is transforming high-energy physics into something like spectroscopy, as it was at the beginning of the century. Regularities are being discovered that allow the particles—or energy levels—to be grouped into families. Some of these groupings already have been given a dynamical motivation by the theorists, others remain at present empirical. But if the current rate of experimental discovery continues it seems inevitable that major aspects of the underlying fundamental principles will reveal themselves.

Yukawa forces

A second reason for optimism is that hundreds of painstaking measurements over the past thirty years have by now convincingly verified the Yukawa hypothesis concerning the forces acting between strongly interacting particles. Expressed in modern language, this hypothesis associates nuclear forces with the existence of antiparticles through the key concept of "crossing". Consider a reaction leading from the two-particle "channel" (a,b) to the "channel" (c,d):

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

the probability of the reaction occurring being given by the absolute square of the reaction amplitude $A(E_a,\ E_b,\ E_c,\ E_d)$, which is a function of the four particle energies. The principle of crossing states that this same function also describes two "crossed" reactions that correspond to replacing ingoing particles by outgoing antiparticles, and vice versa:

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

These three different reactions are distinguished by the signs of the energy variables, which are positive or negative according to whether ingoing or outgoing particles are involved, but if the controlling amplitude is known for one reaction it can be obtained for the two others by smooth extrapolation (continuation) in energy.

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

(a) $\quad n + p \longleftrightarrow n + p$

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

both described by the same reaction amplitude, an important part of which is represented by Fig. 1. The first way of drawing the arrows in this diagram (which physicists will recognize is related to a Feynman diagram, though it has not quite the same meaning) is appropriate to reaction (a) and the second to reaction (b). The two figures differ, of

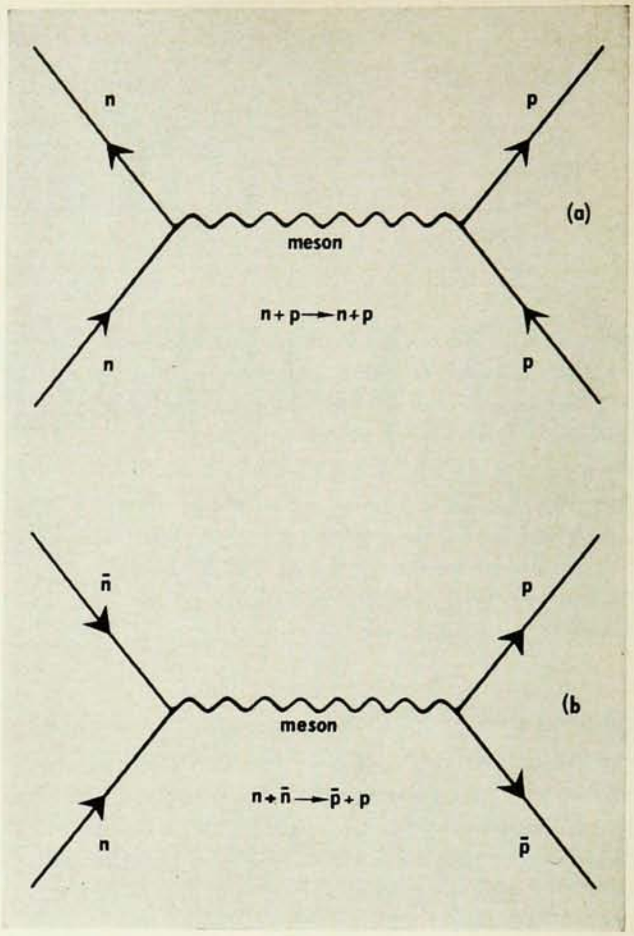

Fig. 1

course, only in the direction we read them, as indicated by the arrowheads.

The second way of drawing the figure can be interpreted as the contribution from the meson "intermediate state" in reaction (b):

$$n + \bar{n} \rightarrow \text{meson} \rightarrow p + \bar{p}\,.$$

In general, whenever there exists a particle whose quantum numbers permit it to "communicate" with both sides of a reaction, the contribution from such a diagram as (b) is necessarily present in the reaction amplitude. This contribution is given by the so-called Breit-Wigner formula and depends on the mass (or energy) of the intermediate state and the coupling between this state and the initial and final channels. Physicists refer to such coupling strengths as "partial widths".

The first way of drawing Fig. 1 has an entirely different interpretation. Here we say that a meson is "exchanged" in a scattering collision between a neutron and a proton and it can be shown that this exchange constitutes a "force" acting between these particles. This, of course, is the Yukawa force, its range and magnitude being determined by the Breit-Wigner parameters. In general we may say that forces arise from the exchange of particles that can act as intermediate states for crossed reactions. If the masses, spins, and partial widths of these particles are known, the details of the forces can be predicted.

I have already stated that there has been accumulated ample experimental verification for the existence of these Yukawa forces, with the predicted strength and range. It is important to add, however, that no evidence for *additional* forces has been found. It is possible to believe, in other words, that *all* the forces between strongly interacting particles arise by the Yukawa mechanism. This situation should be contrasted with that of conventional electrodynamics where the photon interacts by direct absorption and emission in a manner that cannot be described as due to the exchange of particles communicating with crossed reactions. (It is of course true that electromagnetic interactions between *charged* particles *are* of the Yukawa type, arising from the exchange of photons.) In the strongly interacting family we see no indication of particles subject, like the photon, to direct emission and absorption. For many years it was believed that the π-meson might be such a particle, but experiments indicate nothing unusual about the forces felt by the π. Suggestions have been made that the spin-1 mesons may have a special status, but again there is nothing in the data to support such an idea.

Nuclear particle democracy

I am led now to a third reason for optimism about strong interactions. This is the success achieved in understanding the existence and properties of certain particles, assuming them to be dynamical composites (bound states) of other particles, held together by the Yukawa forces. A well-known example is the deuteron, which in a first approximation can be considered a neutron-proton composite held together by the exchange of various mesons. It is of great importance to realize, however, that the deuteron is not exactly composed of one proton plus one neutron. In quantum mechanics it is more accurate to say that *most of the time* the deuteron consists of these two particles. The deuteron communicates with a great variety of channels in addition to $p + n$, and according to quantum theory any state consists part of the time of each of the channels that communicate with it. If one neglects other channels such as $n + p + \pi^0$ in calculating deuteron properties, one does not get an exact result. Nevertheless there is a general belief that, since the simplest channel successfully accounts for the bulk of the observed deuteron properties, it should eventually be possible to improve the predictions systematically by inclusion of more channels.

A similar situation holds with respect to the Δ particle (often called the 3,3 resonance), whose properties have been qualitatively understood, assuming it to be a composite of pion plus nucleon, held together primarily by exchange of a nucleon. The predictions here are cruder than for the deuteron because the neglected channels play a larger role. For most particles, in fact, a single-channel approximation is not adequate even to achieve qualitatively correct results. Many channels must simultaneously be included, which poses a grave calculational task. The problem of including all the significant channels is in most cases still too difficult for us, but suppose we could solve it. The question is would we then get a correct description of each particle? Would the quantum numbers and the mass come out right? Or do we need to put into our calculation some *special extra* parameters pertaining to certain particles? Until recently there was an almost universal belief that a few strongly interacting particles, such as the nucleon, would have to play a special role; but during the past two years the notion of *democracy* among strongly interacting particles—that is to say, the notion that no strongly interacting particle is more elementary than any other—has been gaining adherents.

The revolutionary character of nuclear-particle democracy is best appreciated by contrasting the aristocratic structure of atomic physics as governed by quantum electrodynamics. No attempt is made there to explain the existence and properties of the electron and the photon; one has always accepted their masses, spins, etc., together with the fine structure constant, as given parameters. There exist atomic particles, such as positronium, whose properties are calculable in the sense described above, but so far one does not see a plausible basis, even in principle, for computing the properties of photon and electron as we compute those of positronium. In particular, the zero photon mass and the small magnitude of the fine structure constant appear most unlikely to emerge from dynamics of the Yukawa type.

What has happened to make some of us think that all strongly interacting particles are composite, with properties that are dynamically calculable? I have already mentioned the systematic absence of very small masses. For a long time we have known of certain particles, such as the deuteron and Δ, for which there has been qualitative success in calculating the properties from Yukawa forces; but a presumed analogy with electrodynamics inhibited theorists from attempting similar calculations for the nucleon—which from the time of its discovery had been accorded a status parallel to that of the electron. Gradually, however, it was realized that this select status was dubious—that no observed properties of the nucleon justify the belief that it differs in a fundamental way from other strongly interacting particles. And so, finally, an attempt was made to calculate nucleon properties from Yukawa forces: the same qualitative success was achieved as for Δ! The status of these two particles, N and Δ, now appears completely parallel. It seems, furthermore, on the basis of recent theoretical developments, that in all such dynamical calculations no distinction need be made on the basis of the spin or other quantum numbers of the particle involved. To sum up, if there is no need for aristocracy among strongly interacting particles, may there not be democracy?

Once suggested, the notion of nuclear particle democracy appears plausible, but one cannot yet say it is established. Some physicists continue to believe, for example, that certain spin-one mesons are not ordinary citizens but play a role like that of the photon. The most promising experimental tests of the democracy principle involve careful measurement of nuclear reactions at very high energies, but currently available energies from the Brookhaven and CERN accelerators are insufficient to make such a test decisive. A further increase by at least a factor of five is required, necessitating the construction of still larger machines.

Even if accepted, the democracy principle leaves unanswered some major questions. One is why the photon and the leptons are excluded. Perhaps one should take comfort here in the historical circumstance, emphasized recently by Dirac, that up to now nature has revealed her secrets in a remarkably well-separated sequence of installments and that human intellect has been able to grasp only one installment at a time. Why nature should be so considerate to scientists no one understands, but she has been so in the past and at the moment she seems to be inviting us to understand strong interactions as a more or less isolated collection of phenomena. A unified picture of the entire subatomic world may not appear until a later and quite separate installment.

Many physicists feel unhappy about the prospect of a separate theory for strong interactions because Yukawa's idea about nuclear forces arose in the first place from a presumed analogy with electromagnetism, as also did Fermi's picture of the weak interaction. By the same token, however, there are many points of analogy between electromagnetism and *gravitation,* and nearly all of us believe it is too soon to invoke general relativity in subatomic physics. Eventually such a step will be taken, but human science proceeds one step at a time. How many separate steps will be required it is impossible to predict.

Bootstrap dynamics

I conclude this report by mentioning a second major question, this one of immediate concern: the origin of the special symmetries and the associated conservation laws that characterize strong interactions. I am thinking here of isotopic spin and strangeness as well as the newly discovered eightfold way. For those of you hearing these terms for the first time, it is sufficient to say that they describe an empirical classification of the observed particles into families, all the members of a given family having similar properties. The analogy with the atomic periodic table is evident. No explanation has yet been given for the symmetries underlying these subatomic families but many physicists believe that the secret will emerge from the "bootstrap" mechanism.

The bootstrap concept is equivalent to the notion already developed of a democracy governed by Yukawa forces. Each strongly interacting particle is conjectured to be a bound state of those channels with which it communicates, owing its existence entirely to forces associated with the exchange of particles that communicate with "crossed" channels. Each of these latter particles in turn owes *its* existence to a set of forces to which the original particle makes a contribution. In other words, each particle helps to generate other particles, which in turn generate it. In this circular and violently nonlinear situation it is possible to imagine that no free parameters appear and that the only self-consistent set of particles is the one we find in nature. Needless to say, vigorous efforts are being made to investigate this possibility.

Now if the system is in fact self-determining, perhaps the special strong interaction symmetries are not arbitrarily to be imposed but will emerge as necessary components of self-consistency. Perhaps their origin is destined to be understood at the same moment we understand the pattern of masses and spins for strongly interacting particles—*both* aspects of the system flowing from the dynamics of the bootstrap.

On this optimistic note I close my survey.