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Particles and principles

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PARTICLES and PRINCIPLES

By Murray Gell-Mann

We know that there are two frontiers in the study of the basic laws of natural science: the frontier of the very large, the cosmos, and the frontier of the very small, the structure of the elementary particles out of which the entire universe is constructed, including us. The combination of these two (at the present time theoretically unrelated, although we hope that this situation won't persist) gives us the basic scientific laws that form the foundations for our discussions of science. The research in both of these fields is necessarily a close partnership of theory and observation, and the availability of numerous experiments in the study of the very small is what has made progress in that field more rapid and more exciting in recent years than progress at the other end. But, as interesting observations of the cosmos accumulate, cosmology too should flourish. One thing that makes the adventure of working in our field particularly rewarding, especially in attempting to improve the theory, is that at this basic level of science a chief criterion for the selection of a correct hypothesis, even more than elsewhere in science, seems to be the criterion of beauty, simplicity, or elegance.

I would like to try to describe today the current status of theory in this rapidly changing field. Because of the solemnity of the occasion and the impressive size of the audience, it would be out of place to put in purely personal prejudices. So, I shall try to cram in as many as possible. The description of the basic microscopic laws at the present time involves a split of the natural forces into four types. This multiplicity is something that we don't particularly relish. We would like to see a unifying principle that would tie all the forces together; in fact, in the long run, that is our basic aim. But there is no sign of such a principle at the moment, and so we discuss separately gravitation, electromagnetism, the strong nuclear forces, and the weak forces, which lead, for example, to beta decay. Right now we concentrate mostly on trying to understand the detailed laws of the strong and the weak interactions, in order to reach a theoretical situation somewhat comparable to the one for gravity and electromagnetism.

The fundamental structures of theory of the 20th-Century, relativity and quantum mechanics, remain essentially unchallenged. We seem to have no reason today to abandon either of them. They give us the basic framework of relativistic quantum mechanics, or field theory in the abstract, if you want to call it that. These seem to me indistinguishable. The methods that theoreticians use today are not unique, but they seem to me to be all in harmony with these same principles. The more usual, traditional, method of describing relativistic quantum mechanics uses the formalism of field theory. But the reformulation of the basic postulates with the aid of dispersion theory (employing the mathematical theory of analytic functions) has been extremely useful and appears to be highly desirable for some purposes.

Murray Gell-Mann's development of SU_3 symmetry received strong support when the omega minus particle was discovered last winter. He is professor of physics at the California Institute of Technology.

Within this framework of quantum mechanics and relativity, to which there is no experimental challenge at the moment, we want to find a description of the four forces. The most satisfactory theory, and the one that is used frequently as a model for everything else, is quantum electrodynamics. It is simply a quantum version of the electromagnetic theory that has long been familiar in classical physics. The agreement of quantum electrodynamics with experiment is awesome. Q.E.D. is an example of a really successful theory; I suppose it is our only example of a genuinely successful theory. The quantum description of electromagnetism involves, of course, the photon, the carrier of the force. Einstein's theory of gravitation can be looked at, actually, from the same point of view. It has been pointed out by several people, including Feynman, that if we were to start today from quantum field theory to explain gravity, we would end up quite soon with Einstein's theory. That Einstein was able to obtain his theory 50 years ago is as astonishing as ever, but if today we formulated a quantum theory of gravity with a spin-2 graviton, we would end up with Einstein's equation in the classical limit. Unfortunately, at the present time there is no foreseeable experimental check of the quantum aspects of gravity.

Both of the theories we have just discussed are characterized by a long-range force, by zero mass for the carrier particle, and by exact gauge principles—the famous gauge invariance of electromagnetism and the gauge invariance of gravity, which is called general relativity. Each is also characterized by an exact conservation law—the conservation of charge in the case of electromagnetism and the conservation of energy and momentum in the case of gravity. The survival of our oldest intuitive concepts about electromagnetism is remarkable, particularly the modern form of Ampère's hypothesis of minimal electromagnetic interactions, that all electromagnetic phenomena arise simply from the interaction of electric charges. The electromagnetic interaction does not have arbitrary extra terms to do special jobs. Of course, this is not a perfectly confirmed hypothesis, but everything seems to be consistent with it.

Now, what can we say about the two 20th-Century interactions, the strong interaction and the weak one? The strong interaction is remarkable in being restricted to the strongly interacting particles, a special group of particles, which includes all the atomic nuclei as well as the baryons, which are atomic nuclei of atomic mass number one; the mesons, which are nuclei of mass number zero; the antibaryons, which are nuclei of mass number minus one; and so on. All these nuclei are strongly interacting particles and because of the strong interaction exhibit a very rich spectroscopy. In recent years this has become apparent also in the simplest nuclei, that is, the ones with atomic mass number minus one, zero, and plus one. This spectroscopy differs from nuclear spectroscopy in that the typical interval of spacing is more like 100 MeV than one MeV or less. But the similarities of the level structure to that of the other nuclei are quite remarkable. We even think that we are now identifying rotational series for these particles as was done for the more complex nuclei. The nucleon may turn out to be a spinning cigar, as are so many nuclei. We describe rotational series by means of Regge trajectories, and the mathematical developments in this discussion are of considerable interest.

We are seeking, of course, a real dynamical theory that will describe the whole system of strongly interacting particles, and we hope that the studies of the simpler nuclei, the mesons, baryons, and antibaryons, will bring us closer to this fundamental law than would the study of more complex nuclei. What form the dynamical theory will take is not absolutely clear at the present time. There are two leading candidates. One is a theory based on a number of basic fields. (It is not easy to do a great deal with that hypothesis at the present time, but it may have a future.) The other candidate, which seems to be making considerable progress, is the bootstrap hypothesis, according to which there is no fundamental entity among the strongly interacting particles. These particles would compose one another by virtue of the forces that arise from exchanging one another. Whether either of these approaches or some other will emerge as the basic theory in the next few years is the exciting question. In the meantime we have discovered algebraic principles and approximate conservation laws, which help a great deal in leading us to an understanding of what the correct theory can be like. These principles predict the existence of families of related strongly interacting particles, charge multiplets and charge supermultiplets, as well as mass splitting rules within these families. They also give us selection and intensity rules governing the production of the particles and their quick decays induced by strong interactions.

Let us list the relevant conservation laws, exact and approximate, other than the familiar conservation laws of charge and of energy and momentum. For the strongly interacting particles we have first the exact nongeometrical quantum number A, the baryon number, which is the number of baryons minus the number of antibaryons, or atomic mass number. As to geometrical quantum numbers, the relativistic quantum mechanics itself tells us that the laws should be invariant under the operation *CPT* which changes particles into antiparticles and left into right and reverses the sign of time in microscopic reactions. But also, it appears from experiment and analysis thereof that the world is exactly symmetrical under *CP* and *T* separately; this expresses invariance with respect to the exchange of left and right on the one hand and time reversal on the other hand. *CP*, of course, is the modern version of parity after the revolution that upset the older idea of invariance under just interchanging left and right without interchanging particle and antiparticle at the same time.

Now we come to the approximate symmetries or conservation principles for the strongly interacting particles. All these symmetries can, in the present view, be regarded as nongeometrical (not directly related to ordinary space-time). One of these is *C*, which takes particle into antiparticle; its conservation is violated by the weak interaction. For the strong and electromagnetic forces, conservation of *C*, together with conservation of *CP*, gives us conservation of *P*, the old-fashioned parity.

Then there is the set of additive quantities. We start with the conservation of the z-component of isotopic spin and the strangeness. We notice that electric charge is a linear combination of these two, and is, $I_z + Y/2 = Q$, which is, of course, conserved. That I_z and Y are conserved separately is a property of the strong and electromagnetic interactions, but not the weak interaction. Next we come to two operators that are symmetries of the strong interaction, but broken by electromagnetism. These are the two remaining components, I_+ and I_-, of the isotopic spin, responsible for the familiar charge independence of nuclear forces. Recently we have found additional symmetries that are still more approximate, but nevertheless useful, namely four operators which we can call F_4, F_5, F_6, and F_7 in a certain rotation. These are conserved by part only, of the strong interaction and violated by another part; nevertheless they apparently play an important role. In the same notation the three components of isotopic spin are called F_1, F_2, F_3, and the quantity Y (related to strangeness) is proportional to F_8. These operators $F_1 \ldots F_8$ are the symmetries of the "eight-fold way".

I think that an important role must also be assigned to eight more quantities, which, unlike these F's, are pseudoscalars. We can call the new quantities F_1^5, $F_2^5 \ldots F_8^5$. These symmetries are broken even worse than the first eight, but I think they are worth considering anyway. All these algebraic structures and approximate conservation laws are still subject to investigation, and the experimental study of the spectroscopy of the strongly interacting particles interacts fruitfully with the theoretical study of the approximate symmetries.

Now, apart from the strongly interacting particles and the carriers of the force, like the photon and graviton, we have the famous and mysterious leptons: the electron, that peculiar thing called the muon which we have never really digested, and a neutrino for each of them, ν_e and ν_μ. There are perhaps other leptons still undiscovered; if so they are not very "lept". The leptons don't experience the strong forces. They suffer—as far as we know—only from gravitation, electromagnetism, and the weak forces. There is an astonishing and completely mysterious parallel between the electron and the muon (with a mass 200 times as great). The mass seems to be the only distinguishing feature between them. The electron and muon neutrinos (which both seem to have rest mass zero) have, as far as we know, no distinction whatsoever except that one of them goes with the electron and the other goes with the muon. I will anticipate by saying that a fairly complete description of what we know about the weak interactions at the present time involves an interaction of the following form: a four-vector and four-pseudovector operator J_μ times its Hermitian conjugate. This interaction in itself is very reminiscent of the effective electromagnetic interaction (after elimination of virtual photons) which is the interaction of the electromagnetic current with itself. Now this J_μ, the so-called weak current, has leptonic terms and also has strongly interacting particle terms. We have an explicit rule for the leptonic part because in the weak interaction of leptons alone there is not the disturbing effect of strong interactions to complicate the situation. The rule says simply that the neutrino interacts when it is spinning to the left; the negative electron interacts when it is spinning to the left; and the same for the negative muon and its neutrino. For the neutrinos, which appear to have exactly zero rest mass as far as we can tell, the lefthandedness condition is very effective. Weak and electromagnetic processes will never produce the neutrinos, except when they are spinning to the left

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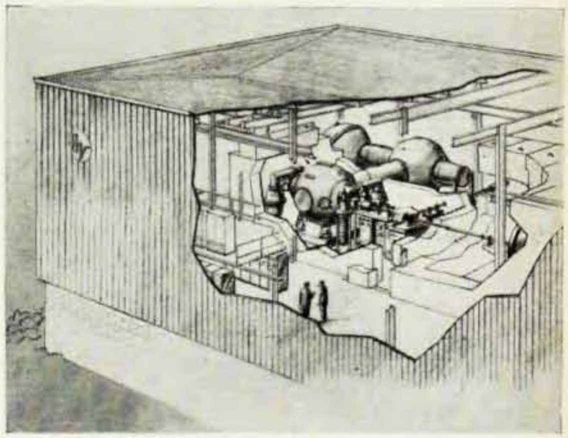

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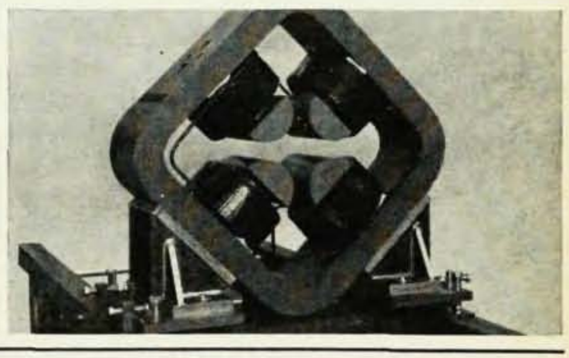

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(and the antineutrinos correspondingly when they are spinning to the right). That raises the interesting philosophical point of whether there are right-handed neutrinos which don't interact through weak or electromagnetic interactions. They would have to be made in pairs by gravity, and that is something that we are not likely to check experimentally for quite a while—although one must not underestimate the ingenuity of experimental physicists.

In the effective interaction $J_\mu^+ J_\mu$, there is of course a term electron-neutrino—electron-neutrino, which is present theoretically and which is now being sought experimentally through neutrino-electron scattering. It will be exciting to see whether the existence of the term is confirmed. In the same way, in ordinary nuclear physics there must be, according to the $J_\mu^+ J_\mu$ law, a weak interaction term essentially of the form neutron-proton—neutron-proton. In other words, there should be a nuclear force due to the weak interactions—a parity-violating nuclear force present to an amplitude of one part in a million or so. And that also is being experimentally sought, and perhaps has even been found.

Now what about the structure of the part of the weak current J_μ that has to do with strongly interacting particles? It seems that it has a very simple description in terms of the approximate symmetry operators for the strongly interacting particles that we mentioned before. The electromagnetic charge Q, as we saw, is a linear combination of I_z and Y; in other words, it is a linear combination of what I have called F_3 and F_8. In the same way the weak charge (that charge for which the weak current is the current) appears also to be a simple linear combination of such symmetry operators, namely F's and F^5's. The conservation of these quantities is only approximate, but the algebraic properties, i.e., their commutation relations, seem to be exact. That is a very interesting circumstance which we have not fully digested. Moreover, the algebraic structure of the weak charge (the commutation relation of the weak charge with its Hermitian conjugate) seems to be the same for leptons and baryons, and the strengths, the coefficients outside, are also equal. Here we have the famous principle of universality of strength and form of the weak interaction. So we actually know quite a bit about the current J_μ, and the form $J_\mu^+ J_\mu$ seems to work pretty well. The following comments are in order, however.

First, it would be very nice if there were particles going across between the current and itself, in the way the photon goes across between the electromagnetic current and itself. Such a particle for the weak interaction, a so-called intermediate boson, charged plus or minus, would be massive, and no one has any idea of the mass, which could be anything above a billion volts. A search for it is actively under way now at CERN and Brookhaven, and perhaps it will be found. If it is not found at these energies, we must pursue it to still higher energies. Of course, we can set no limit at the present time on how high this energy could be. The particle may elude us altogether, and we will then have to assign to it a very high or infinite mass, but we hope not; it would be much nicer to see it.

Another comment is that there is one important heuristic rule, the so-called non-leptonic $|\Delta \mathbf{I}| = \frac{1}{2}$ rule, which has not found a simple explanation in the $J_\mu^+ J_\mu$ picture. It may be that we will have to complicate the theory in order to accommodate the rule; that would be a pity. Theorists are examining various ways of messing up the theory, but they are also trying to derive the rule without complicating the theory.

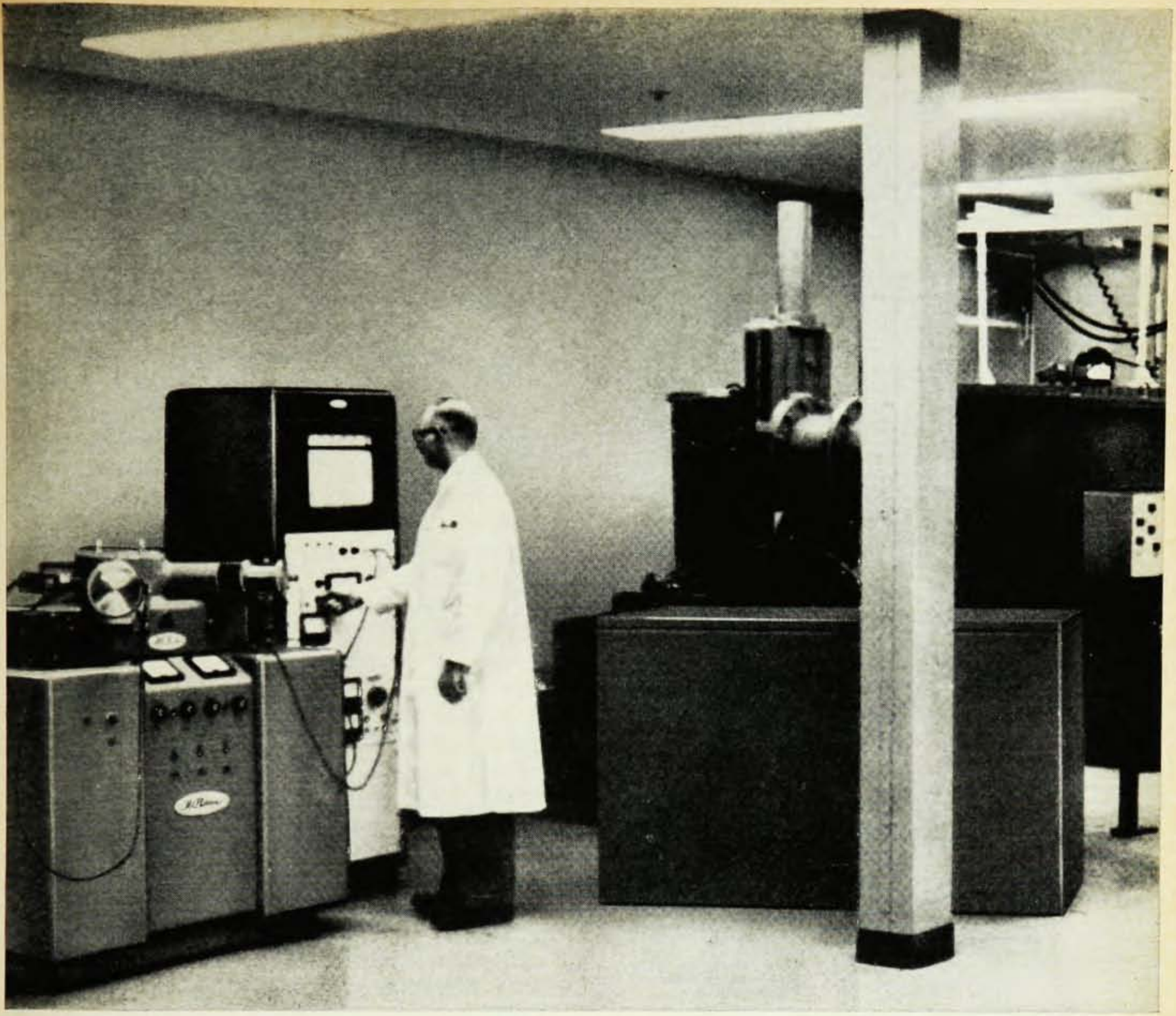
My last remark is that if you write down in detail the field theory, the detailed dynamical description, of a current J_μ interacting with J_μ^+ through an intermediate boson, the resulting equations are not yet in a perfectly divergence-free condition. Maybe they will be soon; or maybe we will have to invent a slightly different kind of theory.

With those qualifications, I think we can say that we have made good progress in our understanding of the weak interactions.

Now, we want certainly to extend the experimental investigation of both strong and weak forces to higher energies. We want to do so for many reasons. There is first of all the fairly obvious reason that we want to study things like the form factors in the matrix elements of the weak current and the electromagnetic current at higher and higher energies to get an idea what they are like at smaller and smaller distances. What are the shapes of the particles for electromagnetism and for weak currents?

Second, we need higher energies for further investigations of the spectrum of excited levels, which seems to go up extremely high. (It looks as if the sequence of nuclear excitations in baryons, for example, includes as many distinguishable levels as in some more complicated nuclei.)

Still more important is the possibility of discovering new conserved quantum numbers, which would have the value zero for all the particles we know about at the present time. (Take strange-



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Technical Sales and Service Offices: LaCanada, California • Livonia, Michigan • Tokyo, Japan • Tel Aviv, Israel • London, England ness for example; 15 years ago nobody had ever seen a strange particle, so nobody knew that this quantum number could be different from zero.)

The X or W particle, the intermediate boson for weak interactions, may require a lot of energy for its creation.

There is the fascinating prospect, which is pointed up by a number of theoretical considerations, of studying the individual scattering amplitudes in the limit of energies which are fairly large compared to the masses, i.e. compared to 1 BeV (particularly when the log of the energy over the mass of the particle is fairly large). At such energies there may be a simplicity in the amplitudes even for strong interactions. I remember Fermi always used to ask, "Where is the hydrogen atom of this problem?" Where, in what domain, will we find a simple system with a relatively simple law for its description, which will be the forerunner or the test of a real theory? That the "hydrogen atom" of the strong interactions lies in the domain of high energy seems fairly likely.

Finally, there is the really exciting prospect of total surprises, things completely outside our experience, which our present-day theoretical language is inadequate to describe. For the last few years, theoreticians have been doing pretty well. Fifteen years ago they were in miserable repute after spending ten years describing the muon by a theory of the pion. The experimental discovery of strange particles took them totally by surprise, just like the existence of the muon. I think another reversal of the positions of experimentalists and theorists is about due now. The strain has been accumulating for 15 years; the shock should come fairly soon.

From the theoretical viewpoint, even without surprises, we want to understand some things that are now completely mystifying. Why are there leptons, particularly this funny arrangement of leptons? Why are there strongly interacting particles? Why is there a particular set of conservation laws? Why are there these approximate symmetries, which seem to have exact algebraic properties, but which are not conserved very well? Why this weird parallel between the muon and the electron, with the huge mass ratio? Why are the coupling constants of various interactions what they are, in particular the famous 1/137? For these things we have no clue whatsoever now, and it is unthinkable to abandon the intellectual endeavor without ever getting a clue. Let's hope that some answers will come while we here can still appreciate them.