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The title of my talk today is really a little misleading, with the implication that I will tell about some details of particular problems that now concern particle physicists. Actually, I intend to discuss the basic nature and philosophy of particle physics, and to show how particle physicists think and what they are trying to do, with a few current problems outlined as illustrations.

The real revolution in our thinking about particles occurred about forty years ago, with the coming of quantum mechanics and its offspring, the quantum field theory. It took many years for the implications of these theories to sink into the consciousness of physicists, but now they are part of the essential philosophical background of those who work with particles. Previous to these theories, there was a clear separation between our description of particles (or of material bodies in general) and of the forces that act on them. The motion of a particle, or body, was described by giving its position at every instant of time; the particle was said to be at a given place at a given time, with this place changing as time went on. In contrast to this, forces were described by fields, like the well known gravitational, electric, and magnetic fields. A field is distributed throughout space, rather than being located at a definite point, and requires a different type of mathematical description.

The quantum mechanics tells us that the position and momentum of a particle can no longer be specified exactly; this fact is familiar in the form of the "uncertainty principle". The position of a particle at a given time must be described by a distribution in space; thus the description of the particle acquires field-like properties. On the other hand, the quantum field theory tells us that the electromagnetic field, which embraces both the electric and magnetic fields, can be described in terms of particles. These particles are the light quanta whose existence was already recognized at the time, and which are now known as photons. Thus there is a double duality; particles can be described by fields, and fields of force (at least the electromagnetic field) can be described by particles. The equal validity of two apparently very different descriptions of the same thing has been called "complementarity" by Niels Bohr, and has led to volumes of philosophical discussion, but physicists take comfort in the fact that predictions of experimentally observable phenomena are independent of one's philosophical point of view.

Quantum Electrodynamics

The quantum theory of the electromagnetic field in its modern form is the most precisely verified theory in all of physics. It is usually referred to by the abbreviation Q. E. D., for quantum electrodynamics, and these initials seem appropriate for a theory whose experimental proof of correctness seems to be so good. Let me add, however, that many experimenters are extending the tests to higher energies, hoping to find a breakdown somewhere; this is one of the "current problems of particle physics".

Because so many of the concepts involved are common to all of particle physics, it is profitable to look more closely at Q. E. D. This theory involves three kinds of particles: electrons, positrons, and photons. The electron and positron are the negative and positive varieties of the same entity; we say that one is the antiparticle of the other. It does not matter which is called which; this is a matter of convention, and in our world, where the negative variety is common, the other would be called the anti-particle. Here we encounter for the first time the idea of anti-particles, now a general concept in particle physics. There is only one kind of photon; it can be said to be its own anti-particle.

One tends to think of the electrons and positrons as being real particles, with an obvious physical existence, while the photons are thought of as the carriers of the electromagnetic field. This is a natural prejudice, based on some facts that I shall describe shortly, but I would like to point out that one could, without violating logic, say that the electrons and positrons are the carriers of the forces that act between photons. It is true that these forces are so small that their experimental detection would be extremely difficult, but this does not constrain one from talking in that way. It is better to say that all the particles involved are mutually interrelated by a set of equations which describe all possible interactions among them, a concept which one would like to be able to extend to a wider class of particles.

Another important concept illustrated by Q. E. D. is that particles can be created and destroyed. Photons can be created whenever there is energy available; when one turns on an electric light, photons stream out, and when these strike a dark surface, they are absorbed and destroyed. Electrons, on the other hand, cannot be made so casually; even when there is enough energy available to make one electron, that is, enough energy to be equivalent to the mass of one electron, the process does not take place. But when the energy equivalent to two electrons is available, an electron-positron pair is created. What causes the restriction to pairs? The answer is, conservation laws. We can start this discussion by stating the conservation laws of mechanics, which are familiar to most of us. Energy, including the energy equivalent to mass, is conserved. That is, the total amount does not change in any process that occurs. Similarly, linear momentum and angular momentum are conserved. In the case of pair production, two additional conservation laws come into play. One is familiar, the conservation of electric charge. When a positive and a negative particle appear together, the net charge of the whole system does not change. The other is less familiar, but is just as important. It is called "the conservation of lepton number", and would require the formation of electrons in pairs even if the electron were a neutral particle. More will be said about this later. One's feeling about the greater reality attached to electrons compared to photons is based primarily on the more stringent requirements on their creation and destruction.

I would like to say one more thing about Q.E.D. before I go on. Its basic formulation is not too complex, at least to a theoretical physicist, but it contains within itself the seeds of mathematical disaster. Suppose we consider a single electron. It is surrounded by an electric field, which is described by an indefinite number of photons. These in turn can generate an indefinite number of electron-positron pairs. It does not matter whether there is enough energy for these to emerge as actual particles; the so-called virtual pairs, capable of emerging when called on, must be included in the equations, just as sharks below the surface of the water affect the actions of people in a small boat. Thus what started as a one-body problem has become a problem involving an indefinite number of bodies; mathematically this leads to an infinite set of equations containing an infinite set of variables. In the case of Q.E.D., disaster is evaded by a fortunate circumstance. This circumstance is the fact that the coupling constant, a quantity expressing the strength of the interaction between the electrons and the photons, is a rather small number. As a consequence of the smallness of this number, the successive stages of the infinite process rapidly diminish in importance, and the mathematical problem simplifies to one that, although it still requires a great amount of ingenuity and labor, can be solved to a high degree of precision.

The Four Interactions

We have so far spoken of one type of interaction, or force, and one set of particles. If that were all, we could say that we have a very good theory, but on the other hand, we wouldn't have much of a universe. The real world contains particles and interactions of much greater complexity. There are four recognized types of interactions. The first is gravitation, which is so weak in its effects on individual particles that it is generally ignored in particle physics. The second is the electromagnetic interaction, which has already been discussed at some length. It acts between all particles with electric or magnetic properties, which includes almost all known particles. It is described by a very good theory, which may even be exactly correct, but as I mentioned before, one of the current experimental problems is to look for possible deviations from the predictions of the theory at very high energies. The carrier of this force field is the photon, which is unique among known particles in that all of its properties, including its very existence, are predicted by the theory. Other quantities, such as the mass of the electron and the magnitude of the unit of electric charge, appear in the theory as arbitrary parameters whose value must be determined by experiment. One would hope, in a complete theory, that these would be predicted also. The search for such more complete theories is one of the basic tasks of particle physicists.

The gravitational and electromagnetic interactions are well known and are important in obvious phenomena of daily experience;

the remaining two appear only in particle physics and are not so familiar. They have been given the rather unimaginative names of "the weak interaction" and "the strong interaction", since they are weaker and stronger respectively than the electromagnetic interaction. As we shall see, they also differ in other ways.

The Weak Interaction

The weak interaction is responsible for the phenomenon of beta-decay, in which a radioactive nucleus ejects an electron and a neutrino. The weakness of the interaction is shown by the slowness of the process. Many other types of decay caused by this interaction are now known. It acts on practically all known particles, and is described by what may be called a reasonably good theory. One thing that is lacking is that the carrier of the weak force has not been found. The postulated carrier has been given a name, the W particle, and the search for this particle in the laboratory is one of the current problems of particle physics.

Actually, the designation W would apply to a family of related particles; one kind would not be enough, because the weak interaction is more complex than the electromagnetic interaction, for which a single kind of carrier is sufficient. If the W does exist, it will have a quite large mass, several times that of a proton, and will therefore require a rather high energy to produce in the laboratory. You may wonder how such a heavy particle can be involved in processes like the beta-decay of the neutron, where the total mass involved is less than the mass of the force carrier. The answer is implied in a statement I made earlier, that particles can exert an influence even when they are in virtual states, which are states with total energy less than that corresponding to their mass. The process of production or materialization of particles can be thought of as a transition from a virtual state to a free state. It is only when they are set free by the application of sufficient energy that particles make their existence evident in a direct way.

Leptons

I would now like to introduce a family of particles which feel only the weak interactions, plus of course the electromagnetic. These are called leptons, from a Greek word meaning "thin" or "small". The family consists of the electron and positron, the positive and negative muon, and two kinds of neutrinos plus their corresponding anti-neutrinos. The electron is a well-known particle and an essential constituent of matter. Why the muon exists is a real mystery. It acts just like a heavy electron, except that it is unstable, decaying into an electron, a neutrino of one kind, and an anti-neutrino of the other kind, but this is not a fundamental difference; it is simply heavy enough that there are lighter things it can decay into. The electron, being the lightest charged particle, has no place to go under the restriction of charge conservation. I remember once being asked by Professor Rabi, "Consider the muon. Who ever ordered that?" That was ~~a number~~ of years ago, and it is still a good question. The neutrinos have almost no properties at all. They have no mass and no electric charge, and no magnetic properties; they are the only particles which respond only to the weak interaction, but in this they play a very prominent role.

I mentioned earlier the quantity called the "lepton number", and this is a good place to discuss it further. The lepton number attached to an electron is equal to one, and that attached to a positron is equal to minus one. Thus, when an electron-positron pair is created, the conservation of total lepton number is satisfied. What about beta-decay, where a single electron is created? In this case, an anti-neutrino is created at the same time, and the anti-neutrino has a lepton number of minus one, again satisfying the conservation law. The neutrino also performs the function of allowing the conservation of angular momentum in beta-decay. The muon has its own separate lepton number, and its own set of neutrino and anti-neutrino. This seems like an unnecessary complication, but it is the way the world is made. Physicists generally try to find simplicity in nature, and a situation like this is both a frustration and a challenge. As you will soon hear, there are in particle physics still greater challenges to the physicist.

The Strong Interaction; Hadrons

These challenges appear in connection with the strong interaction, whose best known manifestation is the nuclear force that holds together neutrons and protons to form the nuclei of atoms. This interaction is responsible for what is commonly meant by atomic energy, referring to the large scale release of energy in a nuclear reactor or a bomb. The particles on which it acts contain most of the mass and most of the energy of the material world. It is in a sense the most important of the interactions, and it is by far the most complex.

The particles that respond to the strong interaction bear the generic appelation "hadrons", from a Greek word meaning "thick" or "bulky". I am sorry to have to use so many special terms, but you can take some comfort in the fact that I shall not introduce all of the words that have been coined to represent special categories of particles. The hadrons can be divided into two broad classes, baryons and mesons, from words meaning "heavy" and "medium" respectively. The former have, in the sense that I used before, the most real existence. They obey a conservation law, "the conservation of baryon number", which works in the same way as the conservation of lepton number among the leptons, except that one set of such numbers suffices for the baryons. All baryons have baryon number equal to plus one, and all anti-baryons have the number minus one. They can be created and destroyed in baryon-antibaryon pairs, like proton plus antiproton or proton plus anti-neutron; also, baryons with the same number can change from one to the other, like the change from neutron to proton or from anti-neutron to antiproton. This is a very important law; without it there would be nothing to prevent protons and neutrons from decaying into lighter particles, leaving a world composed of nothing but electrons, neutrinos and photons.

The total number of kinds of baryons known, including the anti-baryons, is over 100. This number changes continually, as new members of the class are discovered in the laboratory. Among all these, only two are stable as free particles, the proton and the anti-proton, which happen to be the lightest ones, and have no place to decay to with conservation of their baryon number. The neutron is commonly thought of as a stable particle, because it occurs in nature as a constituent of atomic nuclei, but this is because it is stabilized by the nuclear binding energy. A free neutron decays with a half life of about a quarter hour, turning into a proton, which conserves baryon number, an electron, which conserves electric charge, and an anti-neutrino, which conserves lepton number. This decay is promoted only by the weak interaction, which is why it takes so long; it is exactly like the beta-decay of radioactive nuclei.

The other class of hadrons, the mesons, are often thought of as the carriers of the strong interaction; they are sometimes called the "nuclear glue". They are not constrained by a conservation law like that for baryons and leptons, and can be made or destroyed in any numbers, subject of course to other conservation laws, including the conservation of energy. The difference between mesons and baryons can be stated in a simple and compact form by saying that mesons are hadrons having a baryon number equal to zero. Then the lack of constraint on the creation and destruction of mesons follows from the fact that all zeros are equal. The total number of kinds of mesons known, including the anti-mesons, is over 60, and all of these are unstable. They are seen as free particles only in flight, between the place where they are created in a high-energy collision and the place where they decay or interact with some other particle.

Some Theoretical Ideas

What do we do in the face of this preposterous proliferation of particles? Surely all of the hadrons are not fundamental; no thoughtful physicist believes that. Are some more fundamental than others? There is no reason to think so; the greater familiarity of the proton and neutron can be attributed to their relative stability, due to their position at the bottom of the mass range, which can hardly be considered a fundamental distinction. There are two ways of thinking about this situation that are current now. One way starts with the idea that there does exist a set of truly fundamental particles, out of which the observed particles are made. If such a set should exist, it would consist of three particles. Professor Gell-Mann has suggested a name for these; he calls them "quarks", a made-up word originally used by James Joyce in an entirely different connection. These "quarks" would have rather unusual properties which would make them easy to identify if they are ever turned loose as free particles. I hardly need to say that physicists are now looking very hard for particles with these unusual properties, or to add that they have not as yet been found.

The other current form of thought is that all of the hadrons conspire together to generate one another. Since this theory gives all members of the family equal billing, it is often referred to as "nuclear democracy". Professor Chew calls it the "bootstrap theory", for obvious reasons.

A natural question at this point would be: How well does the quantum field theory work for the baryon-meson system? It did extremely well for the electron-photon system. But if you recall what

I said earlier, you will realize that there is a very great difficulty here. The success of the quantum field theory in the electromagnetic case depends on the smallness of the electromagnetic coupling constant. For strong interactions, the coupling constant is large, and the infinite sequences of virtual particles and simultaneous equations mentioned earlier appear in full force. The theory becomes a mathematician's nightmare; even if it is correct, no one knows how to find accurate solutions for the equations. Therefore, a rather different approach is commonly used, called the S-matrix theory.

In the S-matrix theory, one considers only the initial and final states of a reaction between particles, without trying to specify what happens during the actual event. The S-matrix itself is a set of mathematical functions that describe the relation between any given initial state and all possible final states. At first glance there seems to be no physical content in such a theory; one can make up functions to describe any possible relation. The physical content is introduced by requiring that the S-matrix must satisfy certain conditions known as "unitarity" and "analyticity". With these conditions it becomes very useful in dealing with the reactions and transformations of particles. Theorists are still arguing about whether the S-matrix theory is equivalent to, or is derivable from, the quantum field theory.

Hadron Spectroscopy; Symmetry Principles

I would now like to return to the 160-plus known hadrons. There is no reason to believe that this is a complete set, in fact just the opposite is true. Further experimental work continues to turn up new members, and most physicists now suspect that the number can be extended indefinitely. The situation can be compared with those presented by the species of living things, by the chemical elements, or by the lines of an optical spectrum. In each case, the first step toward understanding was classification. Species were classified into genera, orders, and so on long before there was any idea of organic evolution. Groups of related elements were recognized before the periodic table was proposed. The lines of optical spectra were grouped into series and multiplets before there was any understanding of the reason for such regularities.

In the last two of these examples, there finally came a comprehensive theory, the quantum mechanics, which accounts for all the observed phenomena. We are far from this stage in particle physics, but we do have a beginning in the form of a scheme of classification. Among the three examples given, the classification of hadrons most resembles that for spectral lines. The existence of multiplets, that is, of finite groups of closely related particles, is very clear. The evidence for series, that is, of open-ended related sequences, is less pronounced, but it seems very probable that series do exist. These resemblances are by way of analogy only, and the theory of optical spectra cannot be applied to the hadrons. But there is a clear indication of an underlying system which physicists hope to understand some time as they do the spectra today.

Spectral lines are classified according to quantum numbers, and it is natural to seek a similar scheme for the hadrons. Quantum numbers are closely related to conservation laws, which in turn are closely related to symmetry principles. When a physicist speaks of a symmetry principle, he means something more general than the common concept of symmetry, as embodied, for example, in the statement that a snow crystal is a symmetrical object. He refers to any case in which a physical law is invariant to a transformation of coordinates. This is most easily understood by some examples. The laws of motion are not changed when the coordinate system in which they are expressed is shifted by an arbitrary amount in any direction. This invariance leads to the principle of conservation of linear momentum. Similarly, the invariance to an arbitrary rotation of the coordinate system leads to the conservation of angular momentum. The conservation of energy follows from the invariance to a shift along the time axis. We can say, if we like, that the conservation of energy is a consequence of the fact that the laws of motion look the same whether the equations are written in terms of standard time or daylight saving time. Thus all of the familiar conservation laws of mechanics follow from symmetry principles.

In the theory of optical spectra, the most important quantum numbers are those associated with the angular momentum, but there is also introduced another concept that is not familiar in classical mechanics. This is the concept of parity, which arises from a transformation like a reflection in a mirror, which turns a right-handed system into a left-handed system and vice versa. The corresponding conserved quantity is called the parity, and is important in the classification of spectral lines. Until a few years ago, it was thought that the parity was conserved in all processes, but as a result of some brilliant theoretical and experimental work it was discovered that this is not so; the weak interaction does not conserve parity. We have an example here of an approximate conservation law, which implies that the symmetry on which it is based is also only an approximation. An approximate conservation law does not prevent the change of the corresponding quantity, but hinders it, so that the change is seen only in rare processes, or in processes which are prevented from going any other way by stronger conservation laws.

Let us now return to the hadrons. As you may have guessed, quantum numbers corresponding to angular momentum and parity are important in their classification, but these are far from enough. Other quantum numbers and other symmetries are needed. Here we must depart entirely from familiar concepts. One of the other quantum numbers has already been mentioned, the baryon number, which is absolutely conserved. There are also the numbers that have been given the names of "hypercharge", "isotopic spin", and "Z-component of the isotopic spin", which are only approximately conserved. I have now enumerated the six most important conserved or approximately conserved quantities whose corresponding quantum members are used in the classification of the hadrons.

The experimental high energy physicists are working very busily in the field that I have been discussing, which may be called the "spectroscopy" of the hadrons. They are looking for new particles, and determining their quantum numbers. The search for particles is made by examining the products resulting from high energy collisions, using devices which make visible the tracks of these products, or arrays of counters to signal their presence. Many particles decay so rapidly that their tracks are too short to be seen; in these cases the existence of the particles is deduced from correlations among the particles into which they decay. Quantum numbers are deduced from the conditions under which a particle is made, and from the ways in which it decays, making use of the conservation laws and other generally accepted theoretical concepts.

Special Unitary Groups

Among the quantum numbers enumerated a moment ago, there are two, the angular momentum and the parity, which are related to rotations and reflections of a coordinate system in ordinary three-dimensional space. We may wonder whether a similar set of transformations in some more elaborate kind of space can generate all the quantum members belonging to the hadrons. It seems probable that this is so. Gell-Mann and Ne'eman have originated an approach to this problem which is now the basis of very intense theoretical investigations by many people. The kind of mathematics used is group theory, which was developed in the 19th century but which still gives the best way to deal with the symmetry properties of coordinate transformations. The groups used are called "special unitary groups", represented by the letters SU followed by a number. The group SU2, for example, is related to rotations in three-dimensional space, and can be used to find the properties of angular momentum, which, of course, are also obtainable by more elementary methods. I am sure that you are waiting for me to say "SU3", which has become a much-used expression in particle physics. I have now said it. The group called SU3 leads to what has been called the "eight-fold way" because it predicts that among the hadrons there should occur multiplets of eight kinds of particles, with a predicted relation among their quantum members and their masses.

Such multiplets do occur, and in fact it was the experimental observation of these regularities that led the theorists to examine the consequences of the group SU3, which was known to relate to sets of eight quantities. SU3 also gives sets of 10 and of still larger numbers, and the recent experimental confirmation of the existence of a well-defined multiplet of 10 hadrons gives a very strong feeling that there is some reality in the SU3 concept. Higher groups, like SU6 and SU12, are also being tried. These repeat some of the successes of SU3, and give additional predictions, but they have what may be a fatal defect. They seem to be inconsistent with the requirements of special relativity, which most physicists feel should be met by all theories. Whatever turns out to be correct finally, I am sure that something related to a special unitary group will play a part. I would also like to add that this kind of treatment is not in conflict with any of the types of theories that I mentioned earlier; it can join with any of them in a fruitful partnership. The same can be said for the treatment of series of related particles by a method proposed by Regge, which seems to be receiving experimental confirmation.

Time Reversal

Other current problems involve a searching inquiry into some of the most fundamental symmetries of nature. I shall speak about one of these, which is called "time reversal invariance". This principle states that all elementary processes can proceed equally well in either direction; mathematically, it is equivalent to saying that the equations of motion are invariant to a change of sign of the variable representing the time. It is not inconsistent with our common experience, which tells us that it is easier to scramble an egg than to unscramble it. The scrambling of an egg is not an elementary process, and even though each individual molecular encounter is reversible, the superposition of many encounters is governed by statistical considerations which lead toward the most probable state, that of maximum disorder. The commonly accepted laws of mechanics and of electromagnetism are invariant to time reversal, and physicists have had a strong prejudice that this should be true of all laws of nature. Now there is some evidence that this is not so, and again, as in the case of parity violation, the weak interaction seems to be the culprit.

The experimental search for time reversal is not done by running experiments backwards, but by studying processes whose detailed behavior is influenced by certain terms in the theoretical equations which must be equal to zero if the equations are to be invariant to time reversal. In the case that I am discussing, the process is the decay of a kind of meson, the long-lived variety of the neutral K-particle. The long life referred to is about a twenty millionth of a second; the short-lived variety lives only a ten billionth of a second. The decay normally goes in any one of several different ways, which I shall not enumerate, but which do not include the decay into two pions, the pion being another kind of meson. This mode of decay is supposed to be strictly forbidden by the requirement of time reversal invariance, but it has recently been found to occur. This mode is rare; it happens in only about 1/3 of one percent of the cases, and requires very careful experimentation to identify with confidence, but the result has been confirmed in several laboratories and is generally believed to be correct.

Theorists are now madly trying to find some other explanation for this effect than a failure of time reversal invariance; if they cannot, another of our long-cherished ideas is gone. This, and the failure of parity conservation, are two examples of the profound changes in the most basic laws of nature which have been brought about by particle physics. No one knows what other great surprises will come in the future.

Closing Remarks

You will notice throughout this narrative how experimenters and theorists work together very closely in particle physics, to their mutual benefit. Theorists often furnish ideas for experiments, some (but not all) of which are good, and help in the interpretation of the results, in addition to their basic task of trying to build a satisfactory framework into which all of our knowledge of particles will fit consistently, and which, one hopes, will predict correctly the results of future experiments. The material for this framework is at present fragmentary, and I do not believe that any responsible theorist would claim that much progress can be made without more experimental results. Without experiment, theory will grind to a halt, or will degenerate into sterile speculation.

This brings up another current problem, of a financial nature. I refer to the need for support of future high energy experimentation on an adequate scale. The field is, by its nature, an expensive* one. Large accelerators are needed to produce high energy particles, and elaborate experimental equipment to observe the effect that they produce. Often the most important conclusions follow from measurements on very rare events, so that large volumes of data must be obtained and processed. A particular need which has been the subject of a great deal of discussion in the last few years is for a new accelerator to give higher energy particles than are now available in the laboratory. This will be expensive, but the prospect of gaining further understanding of the complex and fascinating world of particles is an intense inducement. I believe that it would be a great mistake for the United States to abandon its leadership in a fundamental branch of science in which it is now pre-eminent.

Footnote

[*] In the question period following the presentation of this paper, an objection was made to the use of the word "expensive" in this connection, and some other much more costly Federal projects were mentioned. I believe that particle physics is important enough to stand on its own feet in justifying the support necessary to assure future progress, at a level which seems expensive to many people.