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NEW TRENDS IN PARTICLE PHYSICS

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(Talk delivered at the meeting of the Société Française de Physique in Poitiers on July 1, 1977.)

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The last decade has brought many new discoveries and ideas into Particle physics. Indeed some participating scientists are a little over-optimistic today when they state that the most important problems are about to be solved, just as some of them were too pessimistic ten years ago when it seemed to them that Particle physics was at a stand-still.

What has happened during the last ten years? Most of it had to do with an accumulating evidence that hadrons are composite entities made up of partons or quarks, whatever name you may choose. Since new physics nearly always starts with experiments, let me first quote a few of the relevant ones made in the last decade.

NEW EXPERIMENTS, STRONG INTERACTIONS. I start with the so-called M.I.T.-SLAC experiment carried out under the leadership of Jerome Friedman, H. Kendall and R. Taylor. In some ways, it is the analogue of the Rutherford experiment of 1911 in which it was shown that the electric charge in the atom is concentrated within a small volume by observing large scattering angles when atoms were bombarded by energetic α-particles. In the M.I.T.-SLAC experiments energetic electrons were scattered by protons and relatively large scattering angles were observed, a fact which again points to the concentration of the protonic charge within small units, much smaller than the dimensions of the charge distribution within the proton. Here we have something like a direct experimental evidence for the presence of charge subunits, the quarks. The existence of these subunits was already strongly suspected when experiments revealed a rich spectrum of different hadron states with quantum numbers and other properties pointing towards a definite internal structure. It was M. Gell-Mann and G. Zweig who interpreted the lowest states of the spectrum as consequence of a three-quark structure in the case of the baryons and a quark-antiquark structure in the case of the mesons. Both the analysis of hadron spectroscopy and the results of the M.I.T.-SLAC experiment indicated the following properties of the quarks: they are particles with spin $\frac{1}{2}$, and possess fractional charges, $\frac{2}{3}$ and $-\frac{1}{3}$ of the protonic charge. In order to explain the presently known hadron states, one must assume four different kinds of quarks, named by the letters u, d, s, c, whose charges, isotopic spins, strangeness and "charm" are listed in Table 1.

Table 1. Quark Properties

Only mass differences between quarks are reasonably well defined. The mass m_o of the u- and d-quark is not defined and may even be zero.

Name	u	d	s	c
Charge	+2/3	-1/3	-1/3	+2/3
Spin	1/2	1/2	1/2	1/2
Isospin	1/2	1/2	0	0
Strangeness	0	0	-1	0
Charm	0	0	0	1
Mass (MeV)	m_o	m_o	$m_o + 150$	$m_o + 1300$

The existence of the charmed quark was most spectacularly supported by the discovery of the J/ψ meson and its derivative quantum states, all of which seem to be quantum states of a system of charmed quark-antiquark pairs. Recently also charmed mesons and baryons were observed, which consist of one charmed quark together with u- or d-quarks.

The most curious fact is that quarks have never been observed as isolated free particles, although the scattering experiments indicate that they are not very strongly bound within the hadrons. Whenever a quark acquires a large momentum in a collision, it leaves the nucleon only in form of a meson (quark-antiquark pair), the antiquark together with another quark being produced somehow in the collision process.

Here I would like to mention an experiment which is not as well known as it deserves to be. It was performed at SLAC by J. F. Martin and L. Osborne, (Phys. Rev. Letters 38, 1193 (1977)). They scattered very fast electrons at protons and neutrons and measured the charge distribution of the fast mesons emitted in the forward direction. These mesons most probably contain the quark which was hit by the electrons. Thus the charge distribution of the escaping mesons will reflect the charge distribution of the quarks that were hit by the electron. The cross-section to be hit by an electron is proportional to the square of the charge. Now, the proton is supposed to consist of three quarks with charges $\frac{2}{3}$, $\frac{2}{3}$, $-\frac{1}{3}$; we therefore expect a ratio of 8:1 of positive versus negative quarks hit. The acquisition of an antiquark when forming a meson would sometimes produce a neutral meson but would not change the charge ratio. However, additional mesons are produced in the collision which would reduce the ratio 8:1; indeed the observed ratio was 5:1. This positive surplus for protons as targets is perhaps not so surprising. Even if the quarks had integer charges 1 or 0, the positive proton necessarily would contain more positive entities, although the observed large ratio would be difficult to explain. The interesting result was the one obtained when neutrons were the targets. Then also a positive surplus of about 1.5:1 was observed. If the neutron consisted of unit or zero charges, the number of positive and negative units would have to be equal. With the fractional charges of $-\frac{1}{3}$, $-\frac{1}{3}$, $+\frac{2}{3}$, one expects a ratio 2:1, reduced by the background mesons, and that is just what was observed.

There were many more experiments done in the last decade that gave evidence for the existence of quarks. Recently the investigation of meson jets leaving the collision point with relatively large transverse momentum threw some light on the interaction of quarks during the collision. From those experiments and many others one can draw the conclusion that the interaction between quarks is "soft". By this term we understand an interaction which is weaker for high momentum transfer (smaller distances) than it is for low momentum transfer (large distances). The transition occurs at about 0.2 GeV, or at distances of 1 fermi. For smaller distances the interaction between quarks is relatively weak, although somewhat stronger (maybe ten times) than electromagnetic interactions; for larger distances the interaction tends towards infinity, since it still seems impossible to separate quarks.

It is surprising that the best evidence of the large distance interaction between quarks is available from the newly discovered charmed quarks. The spectrum of the newly discovered J/ψ mesons can be very well interpreted by assuming an attractive potential between the charmed quark and its antiparticle, proportional to the distance r:$V=\kappa r$, with $\kappa = 0.18\ (\mathrm{GeV})^2$ when r is measured in units of $\frac{\hbar c}{1\mathrm{GeV}}$ and V in GeV. This is an interaction that increases with distance.

NEW EXPERIMENTS, WEAK INTERACTIONS. Among the important experimental discoveries of the last decade that are not or only indirectly connected with the quark hypothesis, we quote the discovery of neutral currents in weak interactions. This experiment was performed for the first time at CERN and has changed considerably our view of the weak interactions. Before this discovery it was generally assumed that in weak interaction processes a transfer of charge from one particle to another must necessarily take place. The discovery of weak interaction processes without charge transfer (neutral currents) has changed our view of the nature of weak interactions, and makes it more plausible that there exists a relation between weak and electromagnetic interactions, since the latter ones never exhibit that charge transfer. Weak interactions without charge transfer are extremely difficult to observe since the resulting transitions also are effected by much stronger electromagnetic effects. To isolate them, one must use the unique particle that is subject only to weak interactions and no others: the neutrino. Therefore the discovery of weak interactions without charge transfer had to wait until intense neutrino beams were available.

Another important recent discovery was that of a third electron, the heavy lepton τ. The existence of the muon, the second electron, already was and remains a great mystery; now we face a third much heavier particle of similar nature. It remains to be seen whether it also, like the muon, exhibits exactly the same properties as the electron apart from the mass. It also remains to be seen whether it is accompanied by a third massless neutrino.

NEW THEORETICAL IDEAS. So far we have enumerated a number of important experiments which have extended the scope of particle physics in the past decade. Our list is far from complete, but it is obvious, even from this restricted list, that the subnuclear realm of natural phenomena turned out to be much richer than one was led to believe. I now turn to the theoretical developments of the last decade.

I begin with the admirable and daring conclusion by S. Glashow and J. Bjorken and by S. Glashow, Iliopoulos and Maiani about the existence of a fourth type of quark. It was based upon a minimum of evidence -- the surprising absence of strangeness changing neutral currents. They started from the well-known fact formulated by N. Cabibbo more than a decade ago, that the weak interaction "recognizes" the then known three quark-types u,d,s only in the two linear combinations u,d' = (cos θ·d + sin θ·s), where θ is the Cabibbo angle. They concluded that the second orthogonal linear combination s' = (-sin θ·d + cos θ·u) must also play a role and predicted the existence of a fourth quark c, which forms a pair c,s' with the other linear combination s' which plays a parallel role to the pair ud' in the weak interaction. The interactions of these two pairs leads very naturally to the ordinary weak interaction phenomena with neutral and charged currents, but excludes neutral currents with $\Delta S=1$. It was one of these impressive coincidences of ingenious insight and luck which happen sometimes in theoretical physics when, a few years after Glashow's, Iliopoulos' and Maiani's prediction, the fourth quark was indeed brought into evidence by the discovery of the J/ψ particle by Ting and Richter.

The second important theoretical development was the attempt by S. Weinberg and A. Salam of a unification of weak and electromagnetic interactions. It is an attempt to continue Maxwell's great synthesis of electric and magnetic phenomena, albeit so far with less complete success. There is a certain similarity between weak and electromagnetic interactions insofar as it is possible to describe the former by assuming that there exists a vector field which mediates the weak interactions. However, the quanta of this field would have to be rather massive in order to explain the very short range of these interactions. They also must be able to carry charge since charge is exchanged in some manifestations. These quanta -- the so-called intermediate bosons -- have not been observed so far, but the large mass (deduced from the range of the interaction) would prohibit their production as free quanta with presently available instruments. Now Weinberg and Salam constructed a theory in which light quanta and intermediate bosons are different components of one and the same field. The differences in mass come from the interaction with a new kind of field -- the so-called "Higgs field". Indeed it is possible to construct such a theory in which the two interactions are mediated by one fundamental interaction constant -- the electric charge. The weakness of the weak interactions compared to the electric ones is only a "low energy" phenomenon. If the interaction energies would be large compared to the masses of the intermediate bosons (about 100 GeV), the electromagnetic and weak interaction phenomena would merge and become indistinguishable.

It is interesting to note that such unification requires the existence of neutral intermediate bosons besides the charged ones. At the time this conclusion was reached by Weinberg and Salam, the neutral weak currents were not yet discovered. The subsequent discovery greatly increased the expectation that this theory is a step towards a deeper understanding of these interactions. The decisive experimental support of these ideas, however, would be the actual discovery of the intermediate boson and the experimental test of the expected interference effects between electromagnetic and weak phenomena. Either of the two discoveries requires energies of the order of 100 GeV in the center of mass.

The beauty of such a unified theory lies in the fact that the theory of weak interactions would then exhibit at high energy the same elegant simplicity as electrodynamics, which, in principle, allows to calculate the phenomena in all approximations (renormalization). Without the merger with electrodynamics, the weak interaction theory remains non-renormalizable, that is, the theory is unable to describe what happens at high momentum transfer in real or virtual states. On the other hand, a new field, the Higgs field, has to be introduced with special arbitrary coupling constants, determining the masses of the intermediate bosons and also of the interacting fermions, such as electrons, muons and quarks.

One of the most important theoretical problems is the description of strong interactions. Since the discovery of the quarks as constituents of the hadrons the problem is reduced to the question of forces between quarks. These forces seem to be rather independent of the quark type. Therefore one would like to connect the forces with a property which is common to all quarks. Here the so-called "color" lends itself easily as the source of the field which transmits quark-quark forces. What is "color"? The significance of color as a new degree of freedom of the quarks comes from an apparent violation of the Pauli principle, when three quarks form a baryon. For example, we find in the double charged Δ-state, three u-quarks with parallel spin in the same quantum state. In all well investigated baryon states the three quarks form a state which is symmetric instead of antisymmetric in respect to quark exchanges. On the other hand, quarks, as spin-$\frac{1}{2}$ particles, ought to fulfil the Pauli-principle, and form an antisymmetric state. This has led to the introduction of a new tri-valued degree of freedom for the quark, a kind of tri-valued spin, called "color". A quark can be found in any of three states called, say, red, blue, and yellow. The reference to color is appropriate because any color can be thought of consisting of a specific linear combination of three fundamental colors. Furthermore the sum of the three fundamental colors results in "white"; in the same sense, the sum of the three color states of the quarks, if appropriately added, give zero color, just as two spinors can be added to give zero spin. Indeed, the combination of three colored quarks resulting in a state of no color ("white") is antisymmetric in the three quark (a so-called singlet state). This is in analogy with the fact that the state of two spinors of opposite direction giving zero total spin is also an antisymmetric singlet state.

Thus by ascribing three color degrees of freedom to the quarks and, furthermore, by postulating that all known hadron states must be color singlets, we have rescued the Pauli-principle. In addition, we have provided a good reason why we find only 3 quarks or quark-antiquark pairs in hadrons: the colorless singlet state can only be constructed with three colors, or with one color and its complementary color (the antiparticle obviously carries a complementary color). There are other less direct reasons for the introduction of the color degree of freedom, such as the observed probability of quark-pair production by electron-positron annihilation. This probability is proportional to the number of quark-types and would be abnormally high if the quarks did not come in three different color states.

As it was mentioned before, the color of quarks is regarded as a possible source of the field which mediates the forces between the quarks. Indeed, a theory of this type has been proposed by a number of theorists. It is called quantum-chromo-dynamics. It is an analogue of quantum-electrodynamics; the color plays the role of the charge -- it is a tri-valued charge, not two-valued (plus or minus) as the electric charge. The field quantum corresponding to the photon is called the gluon; it also represents a mass-less vector field with "electric" and "magnetic" components. There is one difference, however: Whereas the electromagnetic field does not carry charge, the gluon field is supposed to carry color, the equivalent of charge in that theory. It means that with any emission or absorption of a gluon a unit of color is exchanged between the quark and the gluon. Theories of this type, where the field carries charge, are called "non-abelian" field theories (gravity has similar properties: the field carries energy, the source of the field). It can be shown that non-abelian field theories differ in one characteristic way from "abelian" ones like electrodynamics. In the latter ones the effective charge increases with increasing momentum transfer beyond its "normal" value for small momentum transfer. Since a momentum q is related to a distance x by $q\cdot x \sim h$, it also means that the charge acts stronger at small distances. In a non-abelian theory the situation is turned around: The effective charge is reduced at high momentum transfer or small distance. This effect is called "a - symptotic freedom" and can perhaps be visualized by taking into account the fact that "charge" is spread into the field around a source. Then close encounters are subject to a smaller force, not unlike the fact that gravity decreases towards the center of the earth. This effect is supposed to explain that, inspite of the strong interaction between quarks, they behave like almost free particles when electrons interact with them inside a hadron where the distances are short.

Moreover, non-abelian field theories behave differently at large distances too. In electrodynamics the interaction at large distance is transmitted by quanta of low frequency; the effect is weak and falls off like r^{-1}. In a non-abelian theory, the field interacts with itself and it is not clear yet what the large distance behavior would be like. At present it was not yet possible to find a consistent solution at large distances. There is hope that the interaction will not fall off like r^{-1}, but increase with distance, so that such a theory might be able to explain the confinement of quarks, the impossibility of separating a quark from a hadron. Indeed, it is possible that quantum-chromo-dynamics would yield the potential $V(r)=\kappa r$ for large distances (larger than 10^{-13}cm) which is the one that gives the right spectrum of the J/ψ-mesons. So far, however, this was not yet demonstrated.

The theory should also be able to explain that the presently known hadrons are those quark combinations whose total color is zero (color-singlets). Zero-color may be a necessary condition for a bound system or, at least, non-zero total color should require very high energies so that the corresponding states are not yet observed. None of these conditions have yet been shown to follow from quantum-chromo-dynamics. However, if this theory would indeed give a field potential between two quarks which increases with increasing separation, it would also be true that a hadron with a total color different from zero would have a gluon field of very high (perhaps even infinite) energy. The two effects are connected.

It is by no means sure that the quark interaction really is based upon quantum chromo-dynamics, that it is mediated by massless vector fields whose sources are the colors of quarks. So far this field theory had very little basis in facts. Certain features of this theory fit well with the general properties of quark interactions that emerge from the observations, such as the "softness" of that interaction, (weak at small distance, strong and confining at large distances). It is not clear yet whether these few qualitative features are enough to believe that we are on the right track. In particular, recent studies by Feynman and Fields of the jet structure of mesons, produced at large angles in hadron collisions, point towards quark-quark interactions which are difficult to explain by means of quantum-chromo-dynamics. The elementary scattering cross-section between two quarks should be proportional to the 4th power of the momentum transfer, just like the Rutherford scattering, but the experimental evidence does not bear this out, if one can correctly deduce the direction and momentum of the scattered quarks from the large angle jets.

The rather doubtful conclusions drawn from quantum-chromo-dynamics, especially in respect to the long range confinement of quarks have led to more phenomenological approaches to the problem of quark-interaction. One of the most successful approaches is known under the name of M.I.T.-bag theory. It developed under the leadership of K. Johnson and R. Jaffe. One introduces the confinement as a given fact by postulating that the quarks can exist only within a certain spatial region called "the bag". The quark current accross the surface of the bag is postulated to be zero. A hadron is described by a bag filled with three quarks or with a quark-antiquark pair. The simplest relativistic formulation of this program ascribes a special energy to the bag proportional to its volume. In other words, the bag acts like a bubble in an uncompressible liquid, the gas pressure which stabilizes an ordinary bubble against the pressure in the liquid, is replaced by the quantum pressure of the quarks within the bag. This picture reproduces an amazing number of facts associated with the behavior of hadrons, if one ascribes a zero-mass to the u- and d-quark and a finite mass to the s- and c-quark (about 300 and 1300 MeV respectively).

The bag model also introduces a short range interaction between the quarks, very much along the lines suggested by quantum-chromo-dynamics. The corresponding field-quanta, the gluons, are also supposed to be confined to the bag. The latter assumption allows only three (or a multiple of three) quarks or a quark-antiquark pair to exist within the bag: because of the confinement of gluons, there is no gluo-electric field outside the bag; therefore according to Gauss' law the total "charge" of the quark-content in the bag must be zero. Since color is the gluonic charge, this means that the quarks must form a "colorless" combination, which is only possible with three quarks or with quark-antiquark pairs. The interaction does more than that: It introduces, for example, a spin-spin interaction which, in complete analogy with the electromagnetic spin-spin interaction in s-states; it is repulsive for parallel spin and attractive for opposite spin (we are dealing with oppositely charged quarks). Thus we can explain why the pion is lower than the ρ-meson, and why the nucleon is lower than the Δ-particle. (These particles differ only in the spin-direction of the quarks.) One can determine the coupling strength from these splits and it turns out that it is appreciable. The number which corresponds to $e^2/\hbar c = \frac{1}{137}$ is near $\frac{1}{2}$ here. Thus, the gluon-quark coupling is quite appreciable at those momenta which correspond to the lowest hadron states.

It is of particular interest that the confined gluon-field gives rise to a quark-quark interaction at large distances, which results in a potential of the form $V(r) = \kappa \cdot r$, when the mass of the quark is so large that we face non-relativistic conditions, as we do in the J/ψ-system. The constant κ depends on the quark-gluon coupling constant, and it is surprising and gratifying that the coupling constant determined from the level splits at the lower hadron states gives rise to exactly the value of $\kappa = 0.18\ (\mathrm{MeV})^{-2}$ which reproduces the J/ψ spectrum. In addition, the same constant is also connected with the slope of the Regge trajectories; most of the energy E and angular momentum J of baryons with large J comes from the contributions of the gluonic field, which produces the potential $V = \kappa \cdot r$. Then one can derive the simple equation $J = 2\pi\kappa E^2$ for the rotational states of hadrons. Indeed, the experimental slope $J/E^2 \sim 1(\mathrm{GeV})^{-2}$!

UNSOLVED PROBLEMS. In spite of these impressive successes, the bag-model of hadrons still is rather incomplete. So far it is not possible to quantitatively describe any process in which the number of bags changes, such as the production of mesons by hadron collisions or by electromagnetic processes.

In a field like particle physics where progress towards a deeper understanding of the phenomena is rather slow, one is frequently over-impressed by the partial success of a few new ideas and one does not realize how very far we still are from any thorough understanding of the subnuclear realm of phenomena which occur when matter is subject to very large energy exchanges. We are still facing a large list of unsolved problems including some of the most important properties of the particles which make up the atomic nucleus. There exists no theory telling us the reasons why the masses of the hadrons have the observed values. In the Weinberg-Salam theory the particle masses are caused by arbitrary coupling constants with an arbitrary scalar field -- the Higgs field -- the existence of which has never been experimentally confirmed. In other words, the hadron masses are introduced into the theory "by hand" without any intrinsic explanation. But the fact that the nucleon is almost 2000 times heavier than the electron is a most fundamental relation on which the chemistry of terrestrial matter depends. In the last instance all chemical structure and the possibility of life is based upon this mass ratio and we have no real theoretical understanding of it except that it must somehow be connected with the strong interactions.

We introduce arbitrary coupling constants into the theory, such as the electric charge, the gluon-quark coupling, the Higgs-couplings and we have no idea why these couplings have the observed values. Since the discovery of the electron, energy and accuracy of our instruments of observation was increased by a factor of about 10^{12}; still, we did not come nearer to an understanding why $e^2/\hbar c = 1/137$.

One of the most important phenomena among nuclear particles is the existence of a nuclear force between neutrons and protons. It is the force which keeps the nuclei together and therefore represents the most basic phenomenon for the understanding of the structure and evolution of matter. We don't know much about its origin. We are as ignorant about the nature of that force, as the chemists were about the chemical force in the 19th century when the internal structure of atoms was yet unknown. Certainly it must have something to do with the exchange of mesons between nucleons but we are not able yet to present a theory of that force in terms of the internal structure of the nucleons, in a similar way as we are able to derive the chemical force as a consequence of the quantum structure of the atom according to Heitler and London.

Many of the concepts which we use today when we describe the phenomena are hypothetical and beset with internal contradictions. We speak of quarks but are unable to isolate them. Is it consistent to introduce a particle that cannot exist as an independent entity? We introduce new kinds of fields such as the gluon-field or the Higgs-field without much observational basis. We describe the weak interactions as mediated by the so-called intermediate bosons which have not yet been observed because their hypothetical mass is high. What if they do not show up when the energies necessary to produce them are available?

Finally, we speak of the quarks and the leptons as elementary particles. As time passes, more and more quark types and lepton types are discovered. Is there an end to it or will we face again a series of excited quantum states, indicating that quarks and leptons are composite systems of superquarks or infra-leptons? Only further experimentation will answer some of these questions.

Perhaps it is fitting to end this survey with a prophetic statement of Isaac Newton which he made 250 years ago in his Optics, which encourages us to continue our quest:

> "Now the smallest particles of matter cohere by the strongest attractions, and compose bigger particles of weaker virtue; and many of these may cohere and compose bigger particles whose virtue is still weaker, and so for diverse successions, until the progression ends in the biggest particles or which the operations in chemistry, and the colors of natural bodies depend, and which by cohering compose bodies of a sensible magnitude.
>
> There are therefore agents in nature able to make the particles of bodies to stick together by very strong attractions. And it is the business of experimental philosophy to find them out."