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PERSONAL IMPRESSIONS OF RECENT TRENDS IN PARTICLE PHYSICS

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ABSTRACT

Some remarks about the present situation in high-energy physics, in particular regarding the problems connected with the low momentum end of QCD, the vacuum in QCD and the problem of the origin of masses.

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PERSONAL IMPRESSIONS OF RECENT TRENDS IN PARTICLE PHYSICS

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There are three discoveries made in the last ten years that have deeply influenced our understanding of particle physics.

1) Deep inelastic scattering experiments with electrons and neutrinos as proof for the actual existence of quarks within hadrons.
2) The discovery of two more quark flavours and one more heavy electron.
3) The increasing significance of Yang-Mills field theories.

The first group of discoveries put the quarks definitely on the map. It showed that small ($< 10^{-16}$ cm) charged units indeed exist within the hadrons, with spin ½ and with not too strong interactions at large momentum transfers.

The discoveries of more flavours (c and b quarks) and of the τ electron were to some extent gratifying and to some extent disquieting. The existence of the c quark was a confirmation of theoretical predictions by Bjorken, Glashow and collaborators, but the discovery of the b quark opened up the possibility of an unending series of flavours with increasing masses. Certainly, five is not infinity, and six flavours have indeed been proposed in order to explain the violation of CP conservation; but what if there is a seventh flavour? Does the beginning proliferation of flavours indicate an internal structure of the quark, a new spectroscopy, a higher rung of the quantum ladder? Does the third electron (the τ particle) indicate an extended spectrum of electrons coming from some internal structure? Two remarks have to be made here: one is this: A new spectrum of internal excitations would require the appearance of states with $J > \frac{1}{2}$. Only the discovery of a particle with $J = 3/2, 5/2$, etc. would be a clear indication of a new spectroscopy. Second: We know from deep-inelastic scattering that the size of the quark is less than several 10^{-16} cm. Hence, true excitations of an internal dynamics should be expected at energies $> 1/R$ which is > 20 GeV, much higher than the masses of the new quarks and electrons. Thus, if the newly discovered particles are part of a spectrum of an internal structure, they can only be the fine structure of the ground state.

It is worth recalling that Nature in the whole Universe consists only of the u and d quark, the ordinary electron and neutrino. There is not enough energy available to excite the higher flavours. Possible exceptions are neutron stars and the earliest stages of the Universe. The question arises what is the rôle of those other short-lived particles. Why are they here? As Rabi has asked "Who ordered them?"

It may be significant, however, that for each quark pair of charge 2/3 and 1/3, there is one electron: the ordinary electron goes with the u-d pair, the muon with the c-s pair and the τ with a t-b pair, of which the t is not yet discovered. Does this indicate something or is it accidental?

We now come to the Yang-Mills theories. The present views of weak and strong interactions make use of non-Abelian field theories. In a non-Abelian field theory the field itself is a carrier of charge.

The charge is not bound to the fermions that are the sources of the field. The field itself is a source. Therefore, there are direct interactions between the field quanta, such as gluons or intermediate bosons.

Let us first discuss QCD. Here the field quanta (gluons) remain massless. The fact that the charge (colour) is exchanged between the quarks and the gluon field is the basic reason for asymptotic freedom. The effective charge is not tied to the quark but spread over the adjacent field. Thus high momentum transfers (small distances) "see" only part of the charge. In addition we believe (no proof yet; see below) that, at large distances, the interaction between quarks becomes infinite so that they cannot exist as free particles. These circumstances lead to the concept of a "running coupling constant", depending on the amount of momentum transfer Q^2. It goes to zero for high Q^2 and to infinity for low Q^2. We are considering here the effective coupling constant g, not g_0, that appears in the original Lagrangian. The latter one is fixed; the running coupling constant g is the result of taking into account gluon-quark and gluon-gluon interactions plus applying the renormalization methods.

If, for the moment, we consider only u and d quarks which, probably, have no or negligible mass, we face a theory without any length entering the equations, since the coupling constant g_0 is dimensionless. Still a length appears in the following way: there must necessarily be a momentum transfer Q_1 for which the effective coupling g is of order unity. This value Q_1 determines a mass Q_1 and a length Q_1^{-1}. For higher Q, one can use perturbation approach, for lower Q one cannot. Since the coupling becomes quite large for $Q < Q_1$, the corresponding bound states (hadrons) are of the size Q_1^{-1} and the hadron masses are $\sim Q_1$. Obviously Q_1 must be of the order of a good fraction of one GeV. In other words, we have to choose g_0 such that $g(Q^2 \sim 1 \text{ GeV}) \sim 1$. (Actually, this is a somewhat simplified description of the situation since the non-renormalized coupling constant goes to zero. But it illustrates the logical connections.)

In QED the situation is quite different. There, the effective coupling constant increases with Q^2 because, at high Q, the vacuum polarization ceases to shield the electric charge. What we understand by "charge e" is the fully shielded charge at large distances. That value is finite for $Q = 0$ and equal to $(137)^{\frac{1}{2}}$ but it increases as $\log (Q/m)$ for high Q.

Let me say a few words on how one can, perhaps, describe the situation*) in QCD for small Q. All this is tentative since we do not have a reasonable theoretical approach for the strong coupling situation at $Q < Q_1$. Let us look at the vacuum in QED and in QCD. In the first case it is full of field fluctuations and virtual pairs. The photons and pairs "present" in the vacuum are virtual because their energy is positive. We call such a vacuum a "simple" vacuum. Let us be sure that the energy ε of an electron positron pair always is positive. For the sake of simplicity, we neglect the masses. Then the energy consists of two parts, a kinetic term $\sim r^{-1}$, where r is the distance between partners, and an attractive energy $-(e^2/r)$. Clearly $\varepsilon \sim r^{-1} (1 - e^2)$ will always be positive, since e^2_{eff} is small and increases only logarithmically with $Q \sim r^{-1}$. In QCD things are different. The energy ε of a quark pair or of a gluon pair can become negative if $Q \sim r^{-1} < Q_1$; then $g^2 > 1$ and $\varepsilon \sim r^{-1}(1 - g^2)$ becomes negative! The true vacuum, therefore, should consist of real (not virtual) gluon and quark pairs or "balls" of a size $\sim Q_1^{-1}$. The very big ones, $r >> Q^{-1}$, seem to

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*) The following ideas were suggested to me by S. Coleman and K. Johnson. I take the responsibility for the formulation.

have very large negative energy, but their phase space is very small; hence we expect a finite average size of those balls and a finite negative energy density of the true vacuum. The true vacuum is liquid-like, with gluon- and quark-balls of size Q_1^{-1} forming and transforming.

Now we make a daring hypothesis. The true vacuum expels all gluo-electric field lines in a similar way as a superconductor expels magnetic field lines. Then, an assembly of real quarks (sources of gluo-electric field lines) would have to form a bubble around it in the true vacuum. In that bubble the true vacuum cannot exist (because of the presence of gluo-electric fields) and the bubble will be filled with a "simple" vacuum. After all, in a small region (smaller than Q_1^{-1}) the effective coupling constant is smaller than unity and, therefore, it does not pay to form real gluon or quark pairs ($\varepsilon \doteq r^{-1}(1 - g^2) > 0$). Quarks can only exist within a simple vacuum and are caught in the bubble. The energy density of the simple vacuum is zero; it is higher than the true vacuum. Thus, the forming of a bubble in the true vacuum costs energy proportional to the bubble volume. All this is identical with the assumptions of the bag model. If it is true, we have a QCD argument in support of the bag model.

T.D. Lee has presented a way that perhaps makes plausible the expulsion of gluo-electric fields from the true vacuum. It goes as follows: A change of the effective coupling constant can also be expressed by a changing dielectric constant $\kappa(Q^2)$. Let us assume arbitrarily that $\kappa(Q_1^2) = 1$, and call g_1 the coupling constant for $Q = Q_1$ (it is per definition equal or near unity). Then $g^2(Q^2) = g_1^2/\kappa(Q^2)$. Therefore at large distances ($Q^2 \rightarrow 0$), κ must go to zero, in order to describe the fact (it may be a fact - we are not sure) that $g^2(Q^2)$ goes to infinity. So, the true vacuum at large ought to behave as a medium with a gluo-dielectric constant going to zero. In ordinary media made of atoms, the dielectric constant is always

$\kappa < 1$; that means effective charges are smaller than true charges. This is because the little dipoles in the medium turn their negative ends to the (positive) true charge, thus shielding it. When $\kappa < 1$, it is as if the little dipoles would turn their positive ends towards the true charge, thus antishielding (increasing) its effectiveness. (Of course, real dipoles would not do that; there must be another yet unclear mechanism. But we know, after all, that gluonic charges indeed are antishielded at distances $> Q_1^{-1}$). Now, the electric energy density is $\vec{D}\cdot\vec{E} = \vec{D}^2/\kappa$. It becomes infinite for $\kappa \to 0$, since $\vec{D}$ is fixed by the charges. Thus electric fields will not penetrate into this medium, because it costs infinite energy.

The discussion so far applies only to QCD with u and d quarks. The appearance of quarks with non-negligible masses, such as the other quarks, represents a great difficulty for QCD because it contains no mechanism to provide masses to the quarks. Only the masses of the non-strange or non-charmed hadrons (that part which does not come from the intrinsic quark masses) are understandable. They are derived from the kinetic energies of the quarks, confined to a volume of the size Q_1^{-1}, and from contributions of the spin-spin interactions between quarks that are caused by the gluo-magnetic field. They raise the masses when the spins are parallel and lower them for antiparallel spin.

In QED there may be some hope that the strong effective coupling at high Q gives rise to structures that may explain the masses of the diverse electrons. This hope does not exist in QCD because of asymptotic freedom. The masses of the higher flavours must be produced by another mechanism, such as a coupling to a Higgs-type field.

This brings me to the other Yang-Mills field theory: the Weinberg-Salam*) theory of electro-weak interactions. I have less

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*) Most references to a theory by names are intrinsically unfair, except in the case of Einstein. There are many more people than those two who have contributed to it. Perhaps one should call it Q.WE.D. By now, the name W-S has become established.

to say about this theory, not because I think less of it, but because it triumphs and shortcomings are well known and less controversial. The triumphs consist of a successful unification of weak and electromagnetic forces. This is seen most clearly in the fact that the neutral current effects of the weak interaction are different in character from the charged current effects: they are not purely (V-A) couplings, that is, they do not have maximal parity violations. It comes from the most astonishing, but experimentally well-established, fact that nature chooses to mix the neutral part of the weak interactions (the I_3 component of an isotopic triplet of intermediate bosons) with the electromagnetic interactions. The mixing angle is the famous Weinberg angle. This shows clearly that there are four "components" of weak-electric field: W^+, W^-, Z^0 and γ, the latter two being the two orthogonal mixtures between W^3 and an isotopic scalar representing the "Ur-electromagnetism" (U(1) group) before mixing. What I call "shortcomings" is the necessity of introducing a new field, the Higgs field, which is responsible for the masses of the participating fermions and bosons, and for the above-mentioned mixing. It is necessary to provide masses by a coupling with a field whose vacuum expectation value does not vanish; with finite masses ab initio, the theory would not be renormalizable. The Higgs coupling contains as many arbitrary coupling constants as there are masses. This is a rather awkward way to "explain" the existence of masses and their magnitudes. It is possible, of course, that those Higgs particles really exist. Then the Higgs coupling _is_ Nature's way to make masses. I believe that Nature should be more inventive, but experiments may prove me wrong.

Experiments have verified a great deal of the predictions of the W-S theory, in particular, in respect to the detailed properties of the neutral current events. The deservedly famous SLAC experiment about the parity non-conserving scattering of electrons by nucleons is an outstanding example. The fact that the Weinberg angle comes out to be the same in all experiments, certainly is a strong support of the theory. However, we still have no experimental evidence for the existence of intermediate bosons, to say nothing of Higgs bosons. In a few years, facilities will be available with enough energy to produce them. Woe to the theory if they do not show up!

We have indicated before that a Yang-Mills type of field theory leads to asymptotic freedom and infinite binding at low momentum transfer. This is the case (most probably) with QCD. In the W-S theory of electro-weak interactions it is not so. Things do not blow up at low Q^2 because the particles get masses from the Higgs field. Thus the "true" vacuum does not form. (In the electromagnetic part, the bosons are still massless, but they do not carry charge.) At high momentum transfer, it is again the Higgs coupling (being not of the Yang-Mills type) which prevents asymptotic freedom.

Although the last decade has given us many more insights into the world of particles, some of the great questions are still open. We do not even know whether QCD makes sense at low momentum transfer. There is the question of the origin of the masses of the higher quarks, the question of the nature of quark flavours and of heavy electrons (is there a limit or is there an internal structure?), the question of the unification of electro-weak and strong forces, and the question of the uniqueness of the electric charge e, all of which are still completely unexplained. The fractional charges of the quarks make the last problem even more mysterious.

There are, of course, a number of tentative efforts to get at some of the unsolved questions. The studies of supersymmetries and of grand unification schemes are examples. So far, these studies have not yet yielded solid results. The uncertainty of the number of flavours and heavy electrons makes it hard to invent supersymmetries that contain the right number. The present grand unification schemes are forced to make simplistic assumptions such as that no essentially new phenomena will be found up to the incredibly high energies where supposedly the three interactions merge. Past experience shows that this is not very probable.

Nobody can predict, however, what the experiments will tell us and what new ideas will emerge. There is a Danish proverb: Predicting is difficult, especially if it concerns the future. One thing, however, seems to be sure: Ten years from now, the picture will be very different and much richer, perhaps even more profound.