THE IMPACT OF GAUGE THEORY

ON ELEMENTARY PARTICLE PHYSICS

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ABSTRACT :

Gauge theory has acquired a central role in our understanding of elementary particles. We give an assessment of the achievements and prospects for future development.

La théorie de jauge a acquis un rôle central dans notre compréhension des particules élémentaires. Nous donnons un état des réalisations et des perspectives de développement futur.

Recent developments, both experimental and theoretical, add new arguments for singling out gauge theories in the unique tool for understanding the interactions of elementary particles. From a philosophical point of view, the overwhelming merit of gauge theories is that they lead to unique interaction schemes, approaching the ideal of a theory with a minimum of arbitrary (i.e. experimentally determined) parameters. The essential element for the wide acceptance of non-abelian gauge theories was given by the relatively recent proof of their renormalizability, which opened the possibility that they can give models of elementary particle interactions which are not only aesthetically satisfactory, but also mathematically meaningful. Renormalization theory remains in fact the main tool for giving mathematical sense to realistic (i.e. four dimensional) models.

An exciting consequence of the advent of gauge theories is the unification of interactions which were previously considered as independent. We have already a unification of weak and e.m. interactions, and the process can continue. At each new level of unification we reduce the number of independent couplings, and we approach the ideal goal of a theory with no arbitrary parameters. At present, we think in terms of three types of interactions, each associated with a gauge group : i) Strong interaction, arising from the colour gauge symmetry $SU(3)_c$.

ii) Weak and electromagnetic interactions, arising from a gauge group, G, which contains at least $SU(2) \otimes U(1)$.

iii) Gravitational interactions (which I will not discuss here).

According to the more widely accepted scheme, strong interactions and weak-electromagnetic ones are independent of each other, i.e. they arise from "gauging" two symmetry groups, $SU(3)_c$ and G, which commute among themselves. In simple terms, gluon carries neither electric charge nor weak isospin. The opposite view, which can accomodate integrally charged quarks, is also being actively explored.

The unification of i) and ii) in a single gauge group is an attractive possibility, and a few interesting schemes have been proposed. Gauge theories lead to an interpretation of bosonic dynamical variables as variables which are related to local symmetry properties. Fermion fields are added on, much in the same way as "matter fields" are added in Einstein's theory of gravitation. This situation could be drastically changed by the emergence of supersymmetries, which involve transformations of boson into fermions and viceversa. Supersymmetry has not yet had an impact on our understanding of experimental data, but spectacular developments are well possible in the near future.

For weak interactions the advent of gauge theories has meant the passage from a phenomenological model - useful only at lowest order in the Fermi coupling constant - to a theory where any process can be computed to any desirable order. The list of physical effects which can now be computed in finite terms contains three main headings :

i) Second order weak processes, such as $K^{\circ} \rightarrow \mu^{+}\mu^{-}$, and the $K_L - K_S$ mass difference.

ii) Weak corrections to e.m. effects, such as the (g - 2) of the muon.

iii) E.m. (radiative) corrections to weak processes.

We need not emphasize the importance of these achievements : as an example, radiative corrections to beta decay play an essential role in the verification of the relation between the muon coupling constant, G and the beta decay vector coupling constant, G_V :

$$\frac{G - G_V}{G} = 1 - \cos\theta \approx 2.5\ \%$$

A second feature of gauge theories is asymptotic freedom. This has proved essential for the success of QCD. Renormalizability in fact guarantees the existence of a perturbative series, with finite coefficients, for any physical quantity, A :

$$A = \sum a_n \alpha^n$$

on the contrary, renormalizability does <u>not</u> guarantee that the above series can be the basis of an effective approximation scheme, one where a specified accuracy can be reached with a computation of manageable proportions. This was a serious problem with the old theories of strong interactions, such as that based on the π- N Yukawa coupling.

The asymptotic freedom of QCD means that effective perturbative calculations can now be carried on for physical processes involving short distance, or high q^2, interactions. This possibility has an important fallout for weak and electromagnetic interactions of hadrons. Deep inelastic processes give an important example which has been extensively discussed during the meeting. Another important instance of this new possibility is given by explicit calculations of non leptonic weak processes, especially those involving the decay of charmed particles, and particles containing new types of heavy quarks (see Maiani's talk).

<u>QCD - a unique theory of hadrons</u>

Quantum chromodynamics has emerged as the unique theory of hadrons.

This unicity follows from the requirement of saturation of quark-quark forces in the singlet $q\bar{q}$ and qqq states, as well as from the requirement of approximate scaling in deep inelastic phenomena.

QCD is an asymptotically free theory : the effective fine structure constant α_s decreases at short distances, (i.e. at large Q^2), according to

$$\alpha_s (Q^2) = \left(\frac{33 - 2F}{12\pi}\right)^{-1} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-1} \qquad \text{for } Q^2 >> \Lambda^2$$

where F is the number of quark flavours.

This expression is valid for large Q^2 , i.e. $Q^2 >> \Lambda^2$, i.e. for values of Q^2 where α_s is small. Λ^2 gives the mass scale in which α_s becomes very large, i.e. the scale where quark interactions become strong. We note that Λ is the only parameter in this expression. Since Λ has the dimension of mass, we can always eliminate it by choosing Λ as the unit of mass, i.e. by choosing units in which $\Lambda = 1$. In such units QCD becomes a theory without arbitrary parameters !

The value of Λ can be determined by studying the violation to Bjorken scaling in deep inelastic scattering. The preferred value is now $\Lambda \approx 0.5$ GeV. This means that for Q = 3 GeV we have $\alpha_s \approx 0.4$, a smallish value which allows meaningful perturbative calculations. The situation is even better since first order corrections are typically proportional to α_s/π, rather than to α_s itself. The operational definition of a Q^2 dependent coupling constant, as well as the technology necessary for doing computations is a rather technical subject, as it involves the theory of renormalization and an extensive use of the renormalization group, and I will not discuss it here. Actual computations are not very different from similar computations in QED, and in many instances one finds that it is possible to adapt with little extra work results obtained a few decades ago.

The above expression of α_s is strictly valid only if quarks are massless. One can take roughly into account the effect of the quark masses by taking for F the number of quark flavours with mass <u>less</u> than Q^2. We would then put F = 4 in the range $2 < Q^2 < 25$ GeV^2, which is relevant for most of the present work.

Asymptotic freedom implies that there is a large body of physical phenomena which can be computed, essentially by perturbative methods, with a controllable accuracy. These phenomena yield meaningful tests of the theory. To list a few :

1) Predictions for the total hadronic cross sections in e^+e^-.

2) Predictions on the scaling violation in deep inelastic

phenomena.

3) Spectroscopy of bound states of heavy quarks.

4) Weak decays of particles including heavy quarks.

Inroads are being made into different ways of testing QCD, through the study of elementary gluon processes, the counterpart of QED processes such as e^+e^- scattering, $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow e^+e^-\gamma$, etc. The doctrine behind these tests is that whenever an elementary process, such as

$$q + q \rightarrow q + q + \text{gluon}$$

takes place at high energy and large momentum transfer, each of the emitted quarks and gluons gives rise to a jet of hadrons carrying the energy and momentum of the originating quark or gluon. One can thus measure the cross section for an elementary process by measuring the cross section of the corresponding multijet event.

This area of physics is now at the beginning, but promises to become one of the active areas of research in machines such as PETRA, PEP, or the $P\bar{P}$ collider at CERN.

We thus have, in the upper reaches of the Q^2 spectrum, a rich area of collaboration of theory and experiment for the testing of QCD. The great challenge for theoreticians lies now at the other end of the spectrum : understanding quark confinement, and, more in general, developping the calculational techniques needed to apply QCD to low and intermediate energy phenomena, i.e. to the main body of classical hadron physics.

In this field we are far from a satisfactory situation and there are no results that would be presented in a meeting devoted to new experimental results and to the interaction of theory and experiment. The progress is nevertheless quite impressive. We have learned many unsuspected facts on the behaviour of classical gauge theory, in particular on the existence of exact localized solutions of the classical equations of motion, called the instantons. The existence of these solutions is now revolutionizing our views on the nature of quantized gauge theories at large distances, and these developments might lead to a convincing demonstration that QCD leads to colour confinement.

A consequence of the existence of instantons which is highly relevant to the comparison of theory and experiment is the solution of the η puzzle. It was thought that QCD led to the prediction of the existence of four very light pseudoscalars. Three of them were identified with the pion. The fourth had the quantum numbers of the η, which is however not light at all. It has been recently shown by 'T Hooft that the puzzle is not there : a subtle consequence of the existence of instantons is that QCD predicts the existence of only three, not four, light pseudoscalars. In conclusion QCD already offers specific predictions in a large area of high energy physics, and we hope that continued effort will enlarge this area ; we have good hopes to achieve a number of important qualitative results, such as the proof of colour confinement.

Weak and electromagnetic interactions

In this field theoretical physics has scored two undeniable successes : the prediction of charm, the prediction of neutral currents.

Where we proceed from the present SU(2) ⊗ U(1) model ? We have no overwhelming indications on how to develop the model, and wether we should. The problem we are facing has been clearly stated by Bjorken : gauge theories of weak interactions are flexible while QCD is essentially unique. A possible way of reducing this flexibility comes from the idea of a super unification which derives weak, e.m. and strong interactions from the gauging of a single group. The requirement of unification does not lead to a unique solution, and different weak-electromagnetic theories could be unified with QCD. The present SU(2) x U(1) model is compatible with unification without further extensions, for instance in an overall SU(5) symmetry (Georgi and Glashow).

In this situation the strongest incitements to modify the present model come from new experimental results, often from rumours. Many new models are born of experimental rumours, and often die with them. There have been two new developments which suggest an enlargement of the standard four quarks-four lepton scheme, one very firm, consisting in the discovery of τ and of the Υ resonance, the other being the persistent, although still not conclusive, lack of parity violation in atomic physics.

Recent results, presented here, indicate that τ decays into its own light neutrino, ν_τ, to which it couples in a V - A way with essentially full strength.

The very useful limit on the τ lifetime given by Pluto is very close to excluding the possibility that τ decays through ν_e, ν_u mixing. It seems that we have found the third replica of the e - νe doublet, and that we should abandon theoretical ideas of using τ in more exotic structures. The discovery of new quark doublet was then not only expected, but required in the SU(2) ⊗ U(1) scheme : the γ resonance was quickly accepted as the first manifestation of the new quark doublet and tentatively classified as a $b\bar{b}$ state.

The third lepton and quark doublets, however, are not mere replicas, in that they open new possibilities, namely that of giving a natural explanation of superweak CP violating forces which can now be explained through complex mixing between d, s, and b quarks. If neutrinos are not exactly massless a similar mixing would lead to CP violating neutrino oscillations - an exotic possibility, but worth looking into.

In conclusion, we have excellent results, but we still lack a theory of weak interactions which forces itself on us because of its unique elegance and adherence to experimental facts. In this condition theoreticians will be largely led by the new experimental developments. And these are sure to come since the instrumental premises are there, both with machines now operating or being built, like PETRA and PEP, and with projects such as the $p\bar{p}$ colliders, and ISABELLE, and the future projects on large e^+e^- machines which are now taking shape.