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Report Number C00-2232B-195

MASTER

Report of Technical Progress under
the Current DOE Contract, EY-76-C-02-2232.* 000B

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The following is a review of work done under the present contract. It covers the period February 1, 1979 to approximately February 1, 1980.

Footnote numbers refer to the report numbers of papers completed, see pages 10 and 11.

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(I) Mathematical Physics and Formal Results

(a) In a quantum field theory one has a significant amount of freedom in defining the coupling parameter to be used. This freedom can be turned to an advantage and lead to a potentially useful handle reminiscent of an invariance property. One specifically interesting definition is given by the 't Hooft transformation. This transformation is a change of variables of the renormalized coupling constant to a new coupling parameter such that the resulting Gell-Mann-Low function is a low order polynomial with coefficients independent of renormalization scheme. Explicit expressions for this transformation were obtained for $(\phi^4)_d$, $d=2,3,4$, field theories, quantum electrodynamics, and quantum chromodynamics. The mathematical properties of the transformation were given in detail and in several cases these transformations were shown to be valid up to the first non-trivial zero of the Gell-Mann-Low function.¹⁷⁷

II Gauge Theories

Gauge field theories are the main candidates for understanding most of the phenomena of particle physics. The theory of strong interactions is Quantum Chromodynamics (QCD). Quantum Flavordynamics (QFD) is the unified gauge theoretic description of weak and electromagnetic interactions. More recently there have been attempts at a grand unification leading to gauge theories that give a unified description of all three forces, strong, weak, and electromagnetic. Work along all of the above three lines was carried out in our group during the past year.

It is generally accepted that gauge theories must exhibit dynamical symmetry breaking in order to correctly describe hadronic physics. Much research was focused on various aspects of dynamical symmetry breaking in the above three areas.

(a) Some general features of a dynamically broken gauge theory such as: the possibility of a parameterless field theory, finite mass renormalization, a solution to the strong CP puzzle, were discussed.¹⁸⁰

(b) The role of dynamical chiral symmetry breaking in QCD is relatively well understood. Using exact integral representations, the magnitude of the pion decay constant was estimated in QCD. In addition, the asymptotic behavior of the pion form factor and the electromagnetic self energy of a quark were estimated.¹⁸² The absolute magnitude of the light quark masses based on QCD dynamics and phenomenology were obtained and compared with previous estimates.¹⁹⁴

A more specific focus of activity in the area of dynamical symmetry breaking is the search for a mechanism of symmetry breakdown which will replace the Higgs mechanism of spontaneous symmetry breaking, via elementary spin-0 fields. This mechanism is already a not so attractive feature

of QFD and its use becomes less attractive in grand unified theories. The following three sections describe work related to this important question of alternatives to the standard Higgs picture.

(c) In the simplest dynamical mechanism introduced by Weinberg and others, the required Goldstone bosons are bound states of a new species of quarks whose superstrong gauge interactions (generated by a new hypercolor degree of freedom) spontaneously break the weak-interaction group. The production, and decay characteristics of composite pseudo Goldstone bosons which are likely to be present in schemes that make use of hypercolor were analyzed to be close to, yet actually distinguishable from, those of the elementary Higgs bosons of the Weinberg-Salam model.¹⁸⁹

(d) An alternative to the Weinberg hypercolor idea was proposed. It was suggested that exotic quarks belonging to 6, 8, 10 or higher representations of QCD may exist. If so, chiral symmetry breaking via exotic quark-antiquark condensation may occur at very large mass scales $\approx 10^3$ GeV. Goldstone bosons resulting from this symmetry breaking could couple to weak currents thus becoming longitudinal components of the $W^\pm$ and Z^0 . In this way the local gauge invariance of the Weinberg-Salam model would be dynamically broken down to U(1), and the $W^\pm$, Z^0 would obtain masses satisfying $M_w = M_z \cos \theta_w$. Elementary Higgs scalars would be unnecessary.¹⁹³

(e) New results, extending earlier work on dynamical alternative to the Higgs mechanism were obtained.¹⁸⁶ This paper also showed how CP violation might arise in a dynamically broken gauge theory. The possibility of dynamical symmetry breaking in the Weinberg-Salam model was also examined.¹⁸⁸ Using a dynamical mechanism all the mass parameters of the original SU(2) X U(1) model were calculated in terms of the mixing angle.

The physical implication is that fermions with ultraviolet masses of the same order as the weak boson masses have to exist if dynamical symmetry breaking is to occur.

Other results on gauge theories were:

(f) New leptons (τ) and new quarks (related to T) raise the question whether the introduction of more fermion doublets in $SU(2) \times U(1)$ is the only way to cope with the situation. It is found that there exist new alternatives for extending the standard four quark model. An example is an $SU(3) \times U(1)$ gauge theory which is described in detail.¹⁷⁴

(g) An important puzzle in particle physics is the "generation question": Why are there "generations", sets of fermions that have seemingly the very same properties except for their masses? Present experiments indicate that there are at least three generations, but there could be more. One point of view regarding this problem is that there is a fixed number of generations, equivalent at some fundamental level, and that this equivalence is broken spontaneously to yield the observed mass spectra. This approach was carried out for three generations (in the framework of the Weinberg-Salam model), the equivalence being described mathematically by a discrete group. The simplest group is found and some consequences of the model are studied: all mixing angles (Cabbibo angles) are calculable, CP violation enters in order to explain the observed mass spectrum of quarks, branching ratios for decays of the b-quark are fixed (up to corrections due to strong interactions), and the mass of the t-quark is about 15 GeV.¹⁷⁵

(h) A gauge model which unifies the n-quark, n-lepton, and n-Higgs boson generations by means of the symmetry group S_n was proposed. Restricting the theory to have real Higgs boson vacuum expectation values, it was

found that only a limited class of vacua existed in this model, all with some residual permutation symmetry in the vacuum. By insisting on no degenerate fermions, it was found that $n \leq 5$.¹⁸⁵

(i) A review of quantum chromodynamics for the general (but scientifically oriented) public was written and published in "Nature".¹⁷⁹

(j) The role of $\sin^2 \theta_W$ (θ_W = weak mixing angle) in the Weinberg-Salam model was examined. The effects of radiative corrections on this quantity were described. Improved predictions for M_W and M_Z were obtained which test the W-S model at the one loop level. A formula for the predicted value of $\sin^2 \theta_W$ in almost any grand unified gauge theory was derived.

From this formula it was found that the predicted lifetime of the proton in such theories is about $\tau_p \approx 10^{30} - 10^{31}$ yrs, several orders of magnitude smaller than previous estimates and very close to the present experimental bound.. This finding provided added motivation for proposed experiments designed to measure τ_p up to $\approx 10^{33}$ yrs.^{173,192}

III Phenomenology

(A) Weak Interactions

(a) The feasibility of observing the W^+ boson in the decay $Z^0 \rightarrow W^+$ anything was examined. This possibility is of interest because Z^0 factories capable of producing $\approx 10^4$ Z^0 's per day are being planned. It was found however in a calculation that the branching ratio into such decay modes was extremely small $\approx 10^{-7}$ - 10^{-8} ; so such an experimental observation would be very difficult.¹⁸⁷

(b) Properties of the intermediate vector boson W^+ and Z^0 were investigated. Lowest order and radiatively corrected decay rates were calculated. QCD effects were evaluated and their effect on a determination of the number of neutrino species via a measurement of the Z^0 's total width was illustrated. Deviations from $e-\mu-\tau$ universality in decay rates were examined. Properties of hadronic jets produced by W^+ and Z^0 decays were analyzed.¹⁹⁰

(c) A systematic analysis of non-leptonic two-body decays of D mesons was carried out. It is hoped that the dynamics which explains various features of K-decays (e.g. $\Delta I=1/2$ rule) will also explain the detailed features of D decays. This theoretical analysis is being tested experimentally.¹⁹¹

(B) Strong Interactions

(a) A modified definition of a hadronic jet was presented. This definition has theoretical and experimental advantages over the Sterman-Weinberg definition. This jet criterion provides additional tests of QCD at high energies. The differences between quark and gluon initiated hadronic jets were also described, and a discussion of the exponentiation of infrared effects and implied physical effects was given.¹⁸³

(b) In perturbative QCD calculations at non-asymptotic energies one needs a reliable estimate of the running coupling constant $\alpha_s(q^2)$. To obtain this a better estimate of the Gell-Mann-Low function is required than that given by perturbation theory alone. Borel type methods were used to give an approximation to the GML function reliable for $g^2/4\pi \approx 1.5$. The running coupling constant $\alpha_s(q^2)$ was then estimated for $\alpha_s(q^2) \lesssim 1.5$.^{176,178}

The analytic continuation of $\alpha_s(q^2)$ from space-like to time-like regions was also studied. It was shown that such an analytic continuation can be made and allows simultaneous tests of QCD both in neutrino scattering experiments and e^+e^- annihilation. In particular, a detailed study of R , the e^+e^- total annihilation cross section, was carried out in this formalism.¹⁸¹

(IV) History of Physics

(a) A comprehensive history of Einstein's contributions to quantum theory was written. It deals with the period 1905-1955 and treats Einstein's work on the theory of radiation, specific heats, fluctuations and quantum statistics. It also includes a detailed explanation of Einstein's critical attitudes toward quantum mechanics. ¹⁸⁴

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