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The following is a review of work done under the present contract. It covers the period February 1, 1980 to approximately February 1, 1981. 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) The Green's functions of a quantum field theory are known to have a singularity at the origin in the coupling constant plane which leads to the divergence of perturbation series. Analytic properties in coupling constant in the neighborhood of the origin are important for establishing summability methods and other non-perturbative approximations. It was demonstrated that the renormalization group places strong limitations on analytic continuation in coupling in theories like QCD. For all definitions of coupling constants any analytic continuation in the coupling parameter is shown to be limited to a horn shaped domain with zero opening angle. This extends an earlier result of 't Hooft's first obtained for one specific and non-standard definition of the coupling constant to all definitions in QCD including the standard ones.²¹⁴

(b) Calculations of the properties of the nonlinear sigma models were carried out in the lattice Hamiltonian approach. In this method the spatial directions are discretized while time remains a continuous variable. This paper extends previous calculations for the models in one spatial dimension having Ising, $O(2)$, $O(3)$, and $O(4)$ internal symmetry to models in arbitrary spatial dimension, d , having Ising and general $O(n)$ symmetry, for any n . For $d \geq 2$, these models all have a standard second-order phase transition with characteristic critical exponents. The strong coupling series for the mass gap was calculated as was the critical exponent, ν , for these models. This gives a non-trivial check on the rate of convergence of the strong-coupling expansions since one can compare the results of this work with highly accurate calculations on other models having the same d and n which, by the universality principle, must have the same critical exponents.²⁰⁹

(c) A Borel resummation procedure is used to check the accuracy of a recent calculation (by lattice techniques) of the behavior of the renormalized vs. bare coupling constant in three dimensional $g\phi^4$ field theory. The lattice calculation is found to be reasonably accurate.²⁰⁰

(d) The behavior of the Borel-resummed renormalization group functions for $g(\vec{\phi}^2)^2$ in 3 dimensions under transformations between different definitions of the renormalized coupling parameter was studied. This leads to a significant improvement in the accuracy of the Borel calculations for the critical exponents of the n-vector model. The results are consistent with the assumption that the renormalization group functions are analytic in a circle in the complex g-plane with a cut along the negative real axis starting at the origin.²⁰⁴

(II.) Gauge Theories

(a) In order to make further progress on the theory of strong interactions one needs more information about the nonperturbative properties of QCD and Yang-Mills theories. It has long been understood that symmetries of a theory often give valuable information about the solution even when the solution is not known exactly.

The search for a new continuous symmetry in Yang-Mills field theory was described.²⁰² A functional formulation of SU(2) gauge theory was introduced whose fundamental variable is the path dependent field $\psi = P \exp \oint A \cdot d\xi$, the variable in which the symmetry appears most naturally. A path dependent Lagrangian and functionally conserved Noether currents corresponding to translations, rotations, and scale transformations on the path were derived. In an analogous system, the 2-dimensional chiral model, the infinitesimal transformations associated with an infinite set of nonlocal currents and the corresponding Lie group were derived.²⁰¹ Using the qualitative features of these transformations, one finds that the extra sought for symmetry in the nonabelian theory is a path dependent gauge invariance. It is argued that the same Lie group is represented by the gauge theory.²⁰⁸ It was also proved that the extra symmetry exists in three dimensional Euclidean Yang Mills theory.²¹³

(b) Earlier work (mentioned in our previous progress report), on the signature of hypercolor-based schemes for dynamical symmetry breaking, was continued and extended. The implications of dynamical theories, at both high and low energies, were reviewed at length in a report prepared for Orbis Scientiae (1980)¹⁹⁶; discussed in detail was the question of experimental distinguishability

of dynamical theories and the canonical theory with elementary spin-0 fields. This last question has been recently re-examined²¹² in the context of e^+e^- annihilation experiments, and some model-independent results have been noted and underlined. A report on the subject was prepared for the XXth International Conference on High Energy Physics, held at Madison, Wisconsin, July 17-23, 1980.²¹¹

(c) Within the framework of a model for the QCD vacuum, a collision theory argument was used to assess the magnitudes of dynamical near-Goldstone modes.¹⁹⁸ The values so estimated for f_π and f_K were in fair (perhaps fortuitous) agreement with observation. A report on this calculation was prepared for the Wisconsin Conference.²¹⁰

(d) In a report prepared for Orbis Scientiae 1980, the theoretical aspects of proton decay were reviewed. A new renormalization group prescription was introduced which simplified the analysis of grand unified gauge theories. Based on these new calculations, it was found that the Georgi-Glashow SU(5) model predicts a proton lifetime of about 10^{31} yr. This value is within easy reach of ongoing experiments.¹⁹⁵

(e) The quest for a simple supersymmetric regularization scheme for supersymmetric gauge field theories is an important problem. A point splitting regularization scheme was proposed as a candidate for an explicitly supersymmetric regularization method. A supersymmetric and gauge invariant point-split supercurrent operator was constructed and the superconformal anomaly

was computed. It was demonstrated that one can use both dimensional regularization and point-splitting regularization to regularize supersymmetric gauge theory.¹⁹⁷

(f) An old problem in quantum field theory has been the vacuum energy problem. According to all conventional theories the vacuum ought to have an immense energy density which if actually present leads the general theory of relativity to imply that the universe is only 100 meters in diameter. Using supersymmetry and the concept of spontaneous symmetry breaking a new symmetry was found which implies the cancellation of the vacuum energy and the cosmological term such that, effectively, there are no observable consequences of the vacuum energy. This viewpoint has consequences for the early universe which are currently being explored.¹⁹⁹

(g) It is shown that in the Glashow-Weinberg-Salam model in which the Higgs bosons have weak isospin I and weak hypercharge Y , the condition $M_Z \cos \theta = M_W$, can be satisfied by infinitely many different sets of (I, Y) through the solution of the Pell equation $(2I+1)^2 - 3Y^2 = 1$. More precisely for the n th pair (I_n, Y_n) one has $(2I_n+1) - \sqrt{3} Y_n = (2 - \sqrt{3})^n$, where n is any positive integer.²¹⁶

(g) Weinberg and Susskind have observed that in the theory of electroweak interactions dynamically broken by an extra strong interaction (hypercolor), the relation $M_Z \cos \theta = M_W$ follows naturally if the $SU(2) \otimes U(1)$ quantum numbers of the hyperfermions are the same as those of ordinary fermions. This is because

the dynamical Higgs bosons composed of hyperfermions are weak doublets.

It is shown that in the dynamically broken theory, $M_Z \cos \theta = M_W$ is a consequence of the maximum parity violating nature of the hyperfermion representation in a model with $U(1) \otimes SU(2) \otimes SU_{\text{hyp.c.}}(N)$.²¹⁹

(i) A technique is proposed for calculating $\bar{\theta}$ in theories with soft CP violation. The method is based on ordinary covariant perturbation theory. (This paper appeared as a Harvard University preprint^{*}).

^{*}Howard Georgi, Theodore Tomaras, and A. Pais, "Strong CP Violation Without Instantons" Harvard University preprint HUTP-80/A046, 1980.

(III.) Phenomenology

So far the experimental observation of CP violation has been confined to K meson decays. The observation of the violation of this symmetry in other systems would be of great help in understanding its origin. Three papers on this aspect of CP violation were completed.

(a) The pattern of CP violation in the b-quark sector was studied. General techniques to expose new CP-violating effects in the cascade decays of B mesons were introduced. In the Kobayashi-Maskawa model, the CP asymmetries so obtained range from 2-20% for plausible values of the model parameters. Effects of this size should be observable in upcoming experiments. The CP asymmetries generated by these techniques are of order $\sin \delta$, where δ is the KM phase angle, and thus represent the maximum effects obtainable in this model.^{203,205}

(b) An alternative to the above approach for CP violation is to introduce many Higgs bosons such that CP is violated spontaneously. In order to avoid a large K_L - K_S mass difference natural flavor conservation must be introduced. The CP violation parameter for K decay, ϵ'/ϵ , was computed starting with a general Lagrangian which has spontaneous CP violation, natural flavor conservation, and QCD interactions. The result is in conflict with experimental measurement. This implies that if the KM phase angle is such that $\sin \delta = 0$, there is no simple model to explain CP violation in K-decay.²¹⁷

(c) An internal report for the CESR experimentalists was written concerning their measurement of K-meson multiplicity in B meson decays. The measurement has relevance for deducing the branching ratio for the b quark, $\Gamma(b \rightarrow u + \bar{u} + d) / \Gamma(b \rightarrow c + \bar{u} + d)$.²¹⁸

(d) The entire $O(\alpha)$ weak and electromagnetic corrections to neutrino neutral current cross-sections were calculated for the Weinberg-Salam $SU(2)_L \otimes U(1)$ model. These corrections are important because they allow a precise determination of the Weinberg angle, $\sin^2 \theta_W$, from experiment. In turn, once a precise value of $\sin^2 \theta_W$ is obtained, it can be used to test grand unified theories or as an input to predict the proton lifetime.²⁰⁶

(e) In a review, theoretical and experimental consequences of neutrino masses were discussed. The influence of neutrino masses on the tritium beta-decay spectrum and neutrino oscillations were explained. The effect of neutrino mass on "big-bang" cosmology and astrophysics was described. Exotic phenomena such as neutrino decay and the possibility of a neutrino magnetic moment were also reviewed.²⁰⁷

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