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PROGRESS REPORT FOR A RESEARCH PROGRAM
IN THEORETICAL HIGH-ENERGY PHYSICS

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ABSTRACT

Last year's research program dealt with a variety of topics including small- p_t hadronic phenomenology (dual topological unitarization, Pomeron-f identity hypothesis, t-channel approach to diffraction peak and hadron size, tunneling in Reggeon field theory); bound-state problems in quantum electrodynamics (positronium decay, hyperfine splitting of positronium and muonium); quantum field theory (graph counting, strong-coupling solutions for eikonal problems with SU(2) constraints, unitarity restriction and semi-classical solutions, quark confinement); unified gauge models of weak and electromagnetic interactions (Weinberg-Salam model, exclusion of effective $V_e V_N + A_e A_N$ neutral-current interaction, Cabibbo angle and quark mass ratios); bound-state mean field theory (structural equivalence of two-dimensional four-fermion and Yukawa-like models, renormalization of four-dimensional four-fermion models, Fermi theory of weak interactions as a Yang-Mills theory); acoustic detection of cosmic neutrinos; topics in gravitation and cosmology; as well as other studies involving the interactions of elementary particles.

Progress Report for a Research Program
in Theoretical High-Energy Physics

The Department of Physics of Brown University, with the support of the U. S. Department of Energy under Contract EY-76-C-3130.A002, has been carrying out a research program in Experimental and Theoretical High-Energy Physics since 1958. David Feldman, Professor of Physics, is the Principal Investigator of the Theoretical Program; Co-Principal Investigators are Herbert M. Fried, Gerald S. Guralnik, Kyungsik Kang, and Chung-I Tan. This report serves to summarize the progress which has been made during the present contract period (1 January 1978 - 31 December 1978) by the Theoretical Group (Task A).

The report is divided into three sections:

- I. Present Status of the Theoretical Group;
- II. Theoretical Papers Published During the Preceding Year and Papers in Press;
- III. Scientific Personnel Associated with the Theoretical Program.

I. Present Status of the Theoretical Group.

During the past year, the overall scope of the theoretical program remained essentially unchanged from that of previous years. Thus, the major effort continued to be devoted to theoretical studies in the physics of high-energy phenomena, the properties and interactions of elementary particles, and quantum field theory. Other problems of current interest such as applications of field-theoretic methods to the general theory of relativity were also considered.

In collaboration with Dr. G. P. Lepage, Professor Caswell has completed several calculations in bound-state QED. These include the $O(\alpha^2 E_F \ln \alpha^{-1})$ contributions to positronium decay and hyperfine splitting (hfs) and the $O[\alpha^2 E_F (m_e/m_\mu) \ln^2 (m_\mu/m_e)]$ contributions to hfs in muonium (Ref. 373).¹

1. References cited are listed in Section II of this report.

These are the most accurate theoretical calculations of bound states in QED at the present time and are essential for a meaningful comparison with experiment in these systems. Professor Caswell and Dr. Lepage have also calculated the $O[\alpha^2 E_F m_e m_\mu / (m_e + m_\mu)^{-2}]$ contributions to positronium and muonium hfs arising from all diagrams with infinite Coulomb exchanges, and have organized clearly the remaining $O(\alpha^6)$ bound-state calculations (Ref. 376). Finally, Professor Caswell, together with Professor C. M. Bender, has completed an investigation of graph-counting (in both finite and asymptotic order) in ψ^{2N} field theory (Ref. 369).

The research of Professor Fried during the past year consisted of several distinct investigations. These were concerned with (i) the strong-coupling solutions for eikonal problems with $SU(2)$ isotopic constraints; (ii) the use of unitarity as a restrictive condition on the set of possible semi-classical solutions to a functional formulation of elastic and inelastic asymptotic cross sections; (iii) a preliminary study into possible field-theory mechanisms of quark-antiquark confinement; and (iv) methods for the approximate representation of particle propagators G_c in the presence of external fields $A(x)$. Well-defined results have been obtained in the first,² second,³ and third (Ref. 367) studies, while very preliminary work is now under way in the fourth.

During the past year, Professor Guralnik and collaborators have made substantial progress in their development of bound-state mean field theory. They have applied this method to the massless, two-dimensional $(\bar{\psi}\psi)^2$ model (Refs. 364, 366) and have shown it to be renormalizable to all orders in the bound-state mean field expansion with a dependence on only one renormalized parameter. The Green's functions were shown to be structurally identical to an infinite class of theories with fundamental Yukawa-type couplings $\bar{\psi}\psi\phi$ and additional scalar self-interactions of the form $F(\phi)$ with ϕ a

2. H. M. Fried, Phys. Rev. D 16, 1916 (1977) (Report No. Brown-HET-352).

3. H. Moreno and H. M. Fried, Phys. Rev. D 12, 203 (1975) (Report No. COO-3130TA-320); Phys. Rev. D 17, 352 (1978) (Report No. Brown-HET-355).

fundamental boson field. For a particular choice of renormalized parameters of the Yukawa-type theories (which occurs as $Z_3^{\sigma} \rightarrow 0$), the renormalized Green's functions are numerically equal to those of the four-fermi model. The actual structure of $F(\sigma)$ does not matter, and hence, in this limit, the operators forming $F(\sigma)$ are irrelevant. Using Wilson's renormalization parametrization, Professor Guralnik and Dr. Tamvakis have shown that the equivalence of these models occurs at a nontrivial fixed point of the Yukawa-type models; hence, the irrelevance of the bare couplings of the operators in $F(\sigma)$ (and the scalar kinetic term) is a statement of universality. Professor Guralnik and Dr. Tamvakis have also applied the mean field expansion to the four-dimensional four-fermi interaction $(\bar{\psi}\psi)^2$ (Ref. 362). They found this model to be renormalizable; further, it is completely specified to any order by one renormalized mass and one renormalized coupling constant, with the induced bound-state mass and couplings completely fixed in terms of these two parameters. Again, this theory is fully equivalent to a Yukawa-like model with a particular choice of the renormalized parameters of the Yukawa model, and, as in the two-dimensional case, there is a class of irrelevant operators. These authors have also analyzed the Nambu-Jona-Lasinio model (Ref. 368) using not only the renormalization-group techniques needed in the $(\bar{\psi}\psi)^2$ model but also Ward identities. They showed that this model is renormalizable and completely specified by only two parameters, and demonstrated equivalence to a σ model for an appropriate choice of renormalized σ -model parameters. In collaboration with Drs. F. Cooper and N. J. Snyderman, Professor Guralnik has examined a prototypical weak-interaction model of the form $(\bar{\psi}_Y \gamma_5 \tau_i \psi)^2$ and have concluded that it is renormalizable, has at most two free parameters, and has induced vertices identical to those of Yang-Mills theory with elementary gauge fields at low energy (Ref. 361). All of these calculations indicate that bound-state mean field theory is an important technique which, when applied to some previously unrenormalizable theories, leads to renormalizable theories which might be of great physical interest because of the dynamical

fixing of parameters which are free in more conventional theories.⁴

Unified gauge theories of weak and electromagnetic interactions have attracted considerable attention in recent years on the part of theorists and experimenters alike. Although the original Weinberg-Salam model has been remarkably successful in accounting for most observed phenomena involving the weak interactions, gauge theory itself does not fix the gauge group and fermion representations uniquely. In fact, new experiments have often suggested the need for extending the flavor gauge group and representations. One such example is the series of experiments carried out by the Seattle and Oxford groups to test parity violation in atomic bismuth due to the weak interactions. In view of the negative results of these experiments, models have been invented in which the effective neutral-current interaction is of the form $V_e V_N + A_e A_N$. In collaboration with Dr. J. E. Kim, Professor Kang has examined the possibility of deriving such neutral-current interactions in a natural fashion⁵ when the right-handed fermions are all assigned to singlet representations (Ref. 365). Since this is not possible in the case of the minimal gauge group $SU(2) \times U(1)$, these authors chose the gauge group $SU(2) \times U(1) \times U(1)'$ for which there are two massive neutral bosons. However, the constraints coming from the requirement of no triangle anomalies in the theory essentially exclude the possibility of neutral-current interactions of leptons and hadrons of the form $V_e V_N + A_e A_N$, thus suggesting that parity violation in the electron-hadron interaction is inevitable; indeed, the recent results for the scattering of polarized electrons by deuterons show that parity is violated in neutral lepton-hadron interactions. Renormalizable gauge theory has the distinct virtue that physical quantities, including particle masses and mixing angles, are in principle calculable as a consequence of spontaneous symmetry breaking.

4. We note that Dr. Tanvakis' contributions to this program are described, in part, in his doctoral dissertation entitled, "Induced Boson Self-Couplings in Four-Fermion and Yukawa Theories."

5. For a discussion of the naturalness conditions, see K. Kang and J. E. Kim, Phys. Lett. 64B, 93 (1976) (Report No. COO-3130TA-330) and S. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977).

However, there are in practice a number of problems that are left unsolved, such as the fermion mass ratios and weak mixing angles. Recently, Weinberg⁶ has suggested that the Cabibbo angle and the mass ratios of the light to the heavy quarks, such as m_d/m_s and m_u/m_c , might be related to each other in the sense that the light quarks get their masses from some perturbative effects in lowest order of gauge theory. Professor Kang, together with Mr. Rothman, has studied the precise conditions that need to be satisfied by the Higgs representations and also by the unitary transformations between the weak-interaction eigenstates and the physical states of the quarks in the left-right symmetry gauge model (Ref. 371). The conditions which they found differ from those of earlier authors and give a physically acceptable Cabibbo angle. Finally, Professor Kang has reviewed the current status of gauge models with respect to neutral-current phenomena for the Seoul Symposium on Elementary Particle Physics.

Professor Tan's research efforts during the past year have, for the most part, been concerned with investigations of both the perturbative and the nonperturbative aspects of multiparticle hadronic interactions at high energies. A simple and esthetically pleasing picture emerging from the QCD-motivated perturbative topological expansion⁷ is the P(Pomeron)-f identity hypothesis for diffraction scattering (Ref. 370). Together with Drs. D. M. Tow and J. Tran Thanh Van, Professor Tan has tested this hypothesis with two-body data at moderate energies, and has concluded that it cannot be ruled out at the present time on experimental grounds (Ref. 360). Recently, Pennington, Schrempf and Schrempf have argued on theoretical grounds that there is a "crisis" for the P-f identity hypothesis because it violates a certain dispersion relation; however, Professor Tan and Dr. J. W. Dash have explained why one should not expect this dispersion relation to hold either with or without the P-f identity hypothesis, so that the "identity crisis" is avoided (Ref. 374). In collaboration with Drs. U. Sukhatme and J. Tran Thanh Van, Professor Tan has developed a consistent approach for understanding the concept of hadron size and the magnitude of

6. S. Weinberg, *A Festschrift for I. I. Rabi*, L. Motz, Editor (New York Academy of Sciences, New York, 1977), in press.

7. G. Veneziano, Nucl. Phys. B74, 365 (1974); G. F. Chew and C. Rosenzweig, Phys. Reports 41C, 263 (1978).

the diffraction peak from a t-channel viewpoint (Ref. 375); the elastic amplitude is determined as the shadow of multiparticle production in the framework of dual topological unitarization⁷ while incorporating pion exchanges. Their result resolves a long-standing puzzle⁸ over the role of the pion mass played in high-energy hadron reactions. At higher energies where a perturbative approach fails, nonperturbative features of Gribov's Reggeon field theory (RFT) become relevant. In order to resolve ambiguities of RFT in the supercritical region, Professor Fan has examined in Ref. 359 a nonperturbative path-integral formulation of $D=0$ RFT (the physical transverse dimension corresponds to $D=2$). By breaking the classical permutation symmetry, he has shown that tunneling for $D=0$ when the bare Pomeron intercept is greater than unity cannot be due solely to classical instanton configurations. The analysis suggests that the $D \neq 0$ supercritical RFT has an instanton as the unique vacuum.

Professor Westervelt has extended his theory of thermo-acoustic arrays⁹ so that it now applies to the sound generated by hadron showers (Ref. 363).¹⁰ Professor Westervelt is scheduled to deliver an invited paper at the Nineteenth Meeting of The Acoustical Society of America which will be devoted entirely to project DUMAND; Professor Westervelt is a member of a Fermilab collaboration engaged in research exploring the feasibility of project DUMAND.

Professor Feldman has been continuing his study of the implications of supergravity for the long-range properties of classical gravitational theory, taking into account the possible effects of many-body interactions. He has also been looking into quantum field-theoretic models in the presence of a background (Robertson-Walker) metric.

8. H. Abarbanel, G. F. Chew, M. L. Goldberger, and L. Saunders, Phys. Rev. Lett. 25, 1735 (1970).

9. P. J. Westervelt and R. S. Larson, J. Acoust. Soc. Am. 54, 121 (1973).

10. This work has been reported in an invited paper presented at the VIIIth International Symposium on Nonlinear Acoustics held in Paris, France (3-6 July 1978); a preliminary report was given at the Neutrino 78 Conference, Purdue University (28 April-2 May 1978).

II. Theoretical Papers Published During the Preceding Year and Papers in Press.

- HET-359 C.-I Tan, "Quantum Stability in Reggeon Field Theory: Tunneling at $D = 0$," Phys. Rev. D (in press).
- HET-360 C.-I Tan, D. M. Tow, and J. Tran Thanh Van, "Test of Pomeron-f Identity Hypothesis," Phys. Lett. 74B, 115 (1978).
- HET-361 F. Cooper, G. Guralnik, and N. Snyderman, "Is the Fermi Theory of Weak Interactions a Yang-Mills Theory in Disguise?" Phys. Rev. Lett. 40, 1620 (1978).
- HET-362 K. K. Tamvakis and G. S. Guralnik, "Renormalization of Four-Fermion Theories in a Mean Field Expansion," Phys. Rev. D (in press).
- HET-363 P. J. Westervelt, "Nonlinear Sound Generation by Hadron Showers,"
TA-341 Journal de Physique (in press).
(Rev)
- HET-364 D. Campbell, F. Cooper, G. S. Guralnik, and N. Snyderman, "The Relationship Between the Two Dimensional $\psi\bar{\psi}\psi\bar{\psi}$ Model and Yukawa Like Models," Phys. Rev. D (in press).
- HET-365 K. Kang and J. E. Kim, "Difficulty of $V(e) \cdot V(q) + A(e) \cdot A(q)$ Neutral Currents in $SU(2) \times U(1) \times U(1)$ Theory," Phys. Rev. D (in press).
- HET-366 K. Tamvakis and G. S. Guralnik, "Irrelevant Operators and Equivalent Field Theories," Nucl. Phys. B (in press).
- HET-367 H. M. Fried, "Eikonal Speculations on Infrared Confinement," Phys. Rev. D (submitted).
- HET-368 G. S. Guralnik and K. K. Tamvakis, "Renormalization of the Nambu Jona-Lasinio Model in a Mean Field Expansion," Nucl. Phys. B (in press).
- HET-369 C. M. Bender and W. E. Caswell, "Asymptotic Graph Counting Techniques in $\psi^2 N$ Field Theory," J. Math. Phys. (in press).
- HET-370 C.-I Tan, "Dual Topological Unitarization--Phenomenological Aspect,"
TA-342 presented at the *Marseille Conference on Hadron Physics at High Energies, Marseille, France, June 1978*.
- HET-371 K. Kang and A. C. Rothman, "Calculability of the Cabibbo Angle in Gauge Theories," Phys. Rev. D (submitted).

- HET-372 H. M. Fried, "Unitary Restrictions on Semi-Classical Approximations
TA-343 to Certain Functional Integrals," presented at the *Marseille
Conference on Mathematical Problems in Feynman Path Integrals*,
Marseille, France, May 1978.
- HET-373 W. E. Caswell and G. P. Lepage, "A New Theoretical Prediction of
the Ground State Hyperfine Splitting in Muonium," *Phys. Rev.
Lett.* (submitted).
- HET-374 J. W. Dash and C.-I Tan, "The P-f: Resolution of the 'Identity
Crisis'," *Phys. Lett.* (submitted).
- HET-375 U. Sukhatme, C.-I Tan, and J. Tran Thanh Van, "Elastic Peak and
Hadron Size from a t-Channel Viewpoint," *Z. Phys. C* (submitted).
- HET-376 W. E. Caswell and G. P. Lepage, "Reduction of the Bethe-Salpeter
Equation to an Equivalent Schroedinger Equation, with Applications,"
Phys. Rev. A (in press).

III. Scientific Personnel Associated with the Theoretical Program.

1 January 1978 - 31 December 1978

D. Feldman - Professor
H. M. Fried - Professor
G. S. Guralnik - Professor
K. Kang - Professor
P. J. Westervelt - Professor
F. Guérin¹ - Visiting Professor
C.-I Tan - Associate Professor
W. E. Caswell - Assistant Professor (Research)
K. K. Tanvakis - Graduate Research Assistant,² Research Associate³
D. A. Fitzpatrick - Graduate Research Assistant
J. P. Kowall - Graduate Research Assistant
J. F. McCabe⁴ - Graduate Research Assistant
M. C. Ogilvie - Graduate Research Assistant
A. C. Rothman - Graduate Research Assistant

1. From 1 September 1978.

2. Until 31 March 1978.

3. From 1 April 1978 to 30 June 1978.

4. From 1 June 1978.