COO-3130TA-340
Brown-HET-358

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

David Feldman
Principal Investigator

Herbert M. Fried
Gerald S. Guralnik
Kyungsik Kang
Chung-I Tan
Co-Principal Investigators

Department of Physics
Brown University
Providence, Rhode Island

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed or represents that its use would not infringe privately owned rights.

EY-76-C-02-3130.A001 (Task A-Theoretical)

1 October 1977

EB
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

Last year's research program dealt with a variety of topics including hadron dynamics (Pomeron interaction in the eikonal approximation, estimates of all eikonal pionization graphs, study of the critical behavior in Reggeon field theory, status of Regge pole models in KN scattering); phenomenology of renormalizable gauge theory (tests of flavor mixing, dimuon events, SU(3) gauge model with unmixed quarks, lepton models, CP violation, neutrino magnetic moment); spectral sum rules (axial-vector masses, mixing angles); application of the self-consistent field approximation to relativistic quantum field theory; topics in gravitation and cosmology; as well as other studies involving elementary particle interactions.

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. Energy Research and Development Administration under Contract EY-76-C-3130.A001, 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 September 1976 - 31 December 1977) 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 Sixteen Months and Papers in Press;
- III. Scientific Personnel Associated with the Theoretical Program.

I. Present Status of the Theoretical Group.

During the past sixteen months, 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.

Professor Fried's research during the last year continued in several fields closely related to the use of the eikonal approximation in both phenomenological and field theory contexts, as well as in the subject of statistical mechanics.¹ While continuing the study of methods recently

1. H. M. Fried, Phys. Rev. A 14, 1208 (1976) (Report No. COO-3130TA-329).

devised to describe interacting Pomerons (Ref. 336),² new results have been obtained in the application of eikonal methods to field theory and potential theory problems containing isospin (Ref. 352), with the construction of an eikonal scattering amplitude directly from first principles in a strong-coupling limit. In addition, together with Dr. H. Moreno, a semi-classical estimate of the sum of *all* eikonal pionization graphs (tower graphs plus non-planar graphs) has been performed by Professor Fried under the restrictions of s-channel unitarity; the result (Ref. 355) justifies the Cheng-Wu supposition that total cross sections must increase as the square of the logarithm of available energy, while changing their prediction of an inelastic multiplicity that grows as a power of the energy to one which grows more reasonably as a logarithm of the energy. This technique, in which the interplay of unitarity with certain non-linear, semi-classical Euler equations is able to generate physically intuitive solutions in a reasonably straightforward manner, should be useful in other, related problems of high-energy physics and statistical mechanics.

The work of Professor Guralnik during the past year has led to considerable development in the application of self-consistent field approximations to relativistic quantum field theory. In collaboration with Dr. N. J. Snyderman, it was shown that most four-dimensional interactions involving four-Fermion interactions generate renormalizable interactions (Ref. 340). Instead of using the usual coupling constant expansion, a very natural expansion which treats bilinear products of Fermi operators on essentially the same footing as single Fermi operators was used. This expansion always results in bound states, generated by the bilinear operators, which can be used to effect renormalization. It follows that the statement that a theory is renormalizable or not depends in an essential way on the perturbation method used. The investigations of Professor Guralnik and Dr. Snyderman showed that these self-consistently expanded four-Fermi theories are completely equivalent to expansions of theories involving bilinear combinations of Fermions, coupled to one boson field, and cubic and quartic meson couplings

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

provided the bare parameters are chosen in a specified manner; to give predictive power to the self-consistent method, an intensive study has been made of the implications of these restrictions on the bare parameters with respect to the renormalized parameters of the theory. Together with Professor C. M. Bender and Dr. F. Cooper, Professor Guralnik has developed a functional integration method for performing self-consistent approximations to all orders (Ref. 341). This method, while equivalent to previous differential methods (Ref. 340),³ simplifies many aspects of the technique. In a study of the ϕ^4 interaction in the self-consistent approximation, it was found that the ϕ^4 interaction is completely equivalent to a similarly expanded cubic interaction $\phi^2\chi$, with χ an elementary field, if in the cubic interaction the renormalized mass of the ϕ and χ single-particle states are fixed, the bare coupling goes to infinity, and the χ wave function renormalization goes to zero; the renormalized coupling constant is then a calculable number and is the same as predicted in the ϕ^4 theory with the same masses. A similar study showed that the $(\bar{\psi}\gamma^\mu\psi)^2$ interaction generates quantum electrodynamics with α a predicted number if the Johnson, Baker, Willey calculation can be done. Professors Guralnik and Bender have developed and studied a Green's function truncation procedure which, with the aid of a computer, was used to examine the spectrum of the anharmonic oscillator. The results were compared with those obtained from the much more complicated variational calculations. In lowest order, the results for the low-lying poles are extremely good and within a few percent of the correct values; the next iteration produces higher poles whose locations are very close to the correct values and improves the accuracy of the lower poles by almost a factor of ten. The success of this method led Professor Guralnik to suggest that Mr. N. Tsamis examine the anharmonic oscillator in the simpler self-consistent field method.⁴ Using MIT's "MACSYMA" algebraic manipulation method, the first several poles have been examined in lowest order with good results. Mr. Fitzpatrick is extending these calculations to more poles and to higher orders.

3. F. Cooper, G. S. Guralnik, and S. Kasdan, Phys. Rev. D 14, 1607 (1976) (Report No. COO-3130TA-328).

4. N. Tsamis, " $(\lambda\phi^4)_1$ Quantum Field Theory in the Mean Field Path Integral Formulation," B. S. Thesis, Department of Physics, Brown University, June 1977.

The research efforts of Professor Kang have ranged over a number of currently interesting topics in particle physics, including tests of flavor-changing neutral-current weak interactions within the framework of the unified renormalizable gauge theory; the axial-vector mass relations and mixing angles from the spectral sum rules for the axial-vector currents and pseudoscalar fields; and the elastic and charge-exchange KN scattering at high energies. It has been reported previously⁵ by Professor Kang and Dr. Kim that flavor conservation can be embedded in the renormalizable gauge models of weak and electromagnetic interactions in a *natural* fashion, irrespective of the specific choices of the parameters in the theory. The naturalness conditions have more recently been rediscovered and refined by other authors.⁶ These conditions present a powerful guideline for building lepton and quark models of weak interactions. A five-quark gauge model which admits strangeness-conserving, charm- or fancy-changing neutral currents in a natural way was constructed and used to explain the observed rates of the opposite- as well as the equal-sign dimuons (Ref. 337). The general form of the neutral currents satisfying strangeness-flavor conservation in the general class of $SU(2) \times U(1)$ gauge models was tested against existing published data on elastic νp and $\bar{\nu} p$ scattering (Ref. 343) and deep-inelastic νN and $\bar{\nu} N$ scattering (Ref. 349); it was found that the existence of the right-handed charged currents and the mixing of flavors other than strangeness due to these currents are not ruled out by published experiments. In Ref. 348, Professor Kang and Dr. Kim exhibited several acceptable gauge models in the $SU(2) \times U(1)$ scheme which satisfy theoretical constraints (strangeness and μe flavor conservation and the absence of the axial-vector anomaly in triangle diagrams) as well as experimental constraints based on published data; particular attention was given to the modifications that would be required should any of the constraints be ruled out by future experiments. Finally, we note that Professor Kang, Dr. Kim, and Mr. R. Nabavi have proved that the naturalness conditions imposed on the strangeness flavor is valid up to the one-loop order, even if there is mixing of flavors among the u-type quarks (Ref. 350).

5. K. Kang and J. E. Kim, Phys. Lett. 64B, 93 (1976) (Report No. COO-3130TA-330).
6. S. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977).

Together with Dr. R. Vergara Caffarelli, Professor Kang has extended his previous study⁷ of spectral sum rules to the axial-vector currents and has obtained the mass relations and mixing angles of the axial-vector mesons (Ref. 342); although the status of the axial-vector multiplets is somewhat unclear, their results support quite strongly the existence of the $J^{PC} = 1^{++}$ multiplet around A_1 in which one has a canonical D-E mixing. Professor Kang, in collaboration with Drs. D. Joynson and B. Nicolescu, has extended his earlier study⁸ of high-energy hadron scattering to KN scattering so as to see whether the same new feature observed in the pion-nucleon charge-exchange scattering, which called for either unconventional high-energy terms or an unusual ρ trajectory near the forward direction, is also present in the more complicated KN system (Ref. 345). They found that the simple Regge-pole model is surprisingly good for KN scattering except for certain discrepancies near the forward direction. They have predicted polarizations of several classes of models at high energies which can be used to discriminate among the different models; in addition, they have suggested that KN charge-exchange scattering and η^0 production would be best for testing the possible existence of the unconventional effects near the forward region.

A neutrino, which is massless and electrically neutral, can nonetheless have electromagnetic properties due to its weak interactions with charged particles. In Ref. 333, Dr. Kim has calculated the neutrino magnetic moment under the assumption that the weak interactions are described by the $SU(2) \times U(1)$ model with right-handed doublets wherein a charged heavy lepton (L^-) is grouped in both the "V-A" and "V+A" sectors with neutrinos; the order of magnitude is within the upper bound obtained from $\bar{\nu}_\mu$ -e elastic scattering data. Dr. Kim has also obtained two general classes of lepton models in the $SU(2) \times U(1)$ scheme based on the two assumptions: (a) the natural absence of μ e-flavor-changing neutral currents, and (b) natural μ e universality (Ref. 346). One of these has both "V+A" and "V-A" decaying negatively charged heavy leptons,

-
7. K. Kang, Phys. Rev. 177, 2439 (1969) (Report No. NYO-2262TA-195); X. Y. Pham, P. Gauron, and K. Kang, Phys. Rev. D 14, 794 (1976) (Report No. COO-3130TA-326).
8. K. Kang and B. Nicolescu, Phys. Rev. D 11, 2461 (1975) (Report No. COO-3130TA-310).

vanishing $\mu \rightarrow e\gamma$ and $\mu \rightarrow ee\bar{e}$ rates, and Weinberg-Salam-type neutral currents for known leptons; the other, which is vectorlike, has "V-A" decaying (and probably V decaying) charged heavy leptons and nonvanishing $\mu \rightarrow ee\bar{e}$ decay rates at higher orders. Both of these models are consistent with the current neutrino-electron scattering data. Further application by Dr. Kim of the naturalness idea to the CP problem has constrained a host of gauge models (Ref. 351). For the natural suppression of CP at the order G_F , the necessary and sufficient condition is that the quarks of charge q and $(q-1)$ do not belong to the same isomultiplets for at least one chirality; for the natural suppression of CP at the order $G_F\alpha$, the number of quark multiplets is generally constrained. Finally, we note an attempt which has been made by Dr. Kim to search for a mechanism to build a weak and electromagnetic interaction model which starts with unmixed quark representations within the gauge group $SU(3)$ (Ref. 334); the conventional mixing of the quarks (e.g., d and s) is transferred to the mixing of the gauge bosons.

In collaboration with Dr. B. C. Harms, Professor Tan has concentrated his effort, for the most part, in developing nonperturbative approaches to the study of the critical behavior of Reggeon field theory (RFT). One of the central problems in the theory of high-energy hadron interactions has been the observation that all hadronic cross sections rise with increasing energies. One promising approach to the analysis of this phenomenon is to work within the framework of RFT in which the bare Pomeron is treated as a quasiparticle and is associated with quantum fields in one "time" and two transverse dimensions. Renormalization-group analyses suggest that the infrared behavior of RFT is analogous to a second-order phase transition of a many-body system, and, in particular, the critical point occurs at $\alpha_0 > 1$. (negative mass-squared). Difficulties arise since the original bare expansion is defined only for $\alpha_0 < 1$. Professor Tan and Dr. Harms have succeeded in developing a reformulation of RFT which not only allows a smooth continuation from $\alpha_0 < 1$ to $\alpha_0 > 1$, but also leads to an expansion capable of treating both regions on an equal footing. By working exclusively with a single field, they unambiguously formulate an analog model of RFT in terms of a classical spin on a rapidity-impact-parameter lattice (Ref. 344). Through

the use of an asymmetrical transfer matrix, they arrive at a kink-like ground-state configuration for the analog model. The key to their alternative formulation is a canonical transformation which results in the new Hamiltonian depending on the sign of $1-\alpha_0$ only through a potential of the Landau-Ginzburg type. By going on a lattice for the impact-parameter space only, they also arrive at a quantum lattice-spin model (Ref. 347). It is explicitly shown that the quantum spin model at $D = 0$ is equivalent to the classical lattice-spin model of Ref. 344.

Professor Westervelt has shown (Ref. 357) that a close connection exists between the process of gravitational radiation and the optical and radar tests of general relativity. The emission and subsequent absorption of a photon is accompanied by a gravitational wave whose energy content has been derived previously.^{9,10} If the photon originates on Earth and passes by the Sun on a path toward a planet, three related events caused by the gravitational wave occur: momentum is imparted to the Sun¹¹ in an amount exactly balancing the transverse momentum acquired by the photon as a consequence of its general relativistic deflection; the Sun is displaced¹² in the direction of the photon momentum a distance exactly compensating the time delay suffered by the photon; the Sun acquires an incremental kinetic energy exactly balanced by the photon Doppler shift. Professor Westervelt's work can be said to constitute an indirect experimental verification of the existence of gravitational radiation; no direct experimental verification exists as of this moment. In a related manner, it is of interest to realize that the gravitational wave functions derived by Professor Westervelt satisfy Einstein's field equations exactly, and they are hence valid for arbitrary amplitudes. This means that valid estimates of very high-energy events may be based on this theory. An example of where this technique may be used to advantage is in the discussion of gravitational radiation

-
9. P. J. Westervelt, JETP Lett. 4, 225 (1966) (Report No. NYO-2262-116).
 10. R. J. Adler, Phys. Rev. D 11, 2685 (1975).
 11. P. J. Westervelt, Acta Phys. Polon. 35, 203 (1969) (Report No. NYO-2262TA-178).
 12. P. J. Westervelt, *Relativity and Gravitation*, C. G. Kuper and A. Peres, Editors (Gordon and Breach Scientific Publishers, New York, 1971), p. 323 (Report No. NYO-2262TA-208).

from supernova explosions.¹³ Finally, we note that Professor Westervelt has completed a study of the coupling of gravitational waves to an oscillator constructed from two massive particles separated by a one-dimensional boson gas.

According to Mach's principle, the inertial masses of elementary particles are a manifestation of their interaction with the mass distribution of the universe. This point of view has led Professor Feldman to undertake a study of quantum field-theoretic models in the presence of a background (curved space-time) metric, with particular emphasis being placed on the question of the renormalizability of such models, the occurrence of spontaneous symmetry breaking, and the properties of gauge fields. Under Professor Feldman's direction, Mr. A. A. Brandes¹⁴ has carried out a synthesis of the theory of homogeneous spaces from a modern differential-geometric standpoint; this should serve as a prelude to the study of cosmological models within the framework of theories with supersymmetric symmetry.

13. R. J. Adler, Phys. Rev. D 12, 3007 (1975).

14. A. A. Brandes, "Homogeneous Spaces and Cosmological Models," B. S. Thesis, Department of Physics, Brown University, June 1977.

II. Theoretical Papers Published During the Preceding Sixteen Months and
Papers in Press.

- HET-333 J. E. Kim, "Neutrino Magnetic Moment," Phys. Rev. D 14, 3000 (1976).
- HET-334 J. E. Kim, "Vectorlike SU(3) Weak and Electromagnetic Interaction Theory with Unmixed Quark Representation," Internal Report (1976).
- HET-335 C. M. Bender, G. S. Guralnik, R. W. Keener, and K. Olaussen, "Numerical Study of Truncated Green's-Function Equations," Phys. Rev. D 14, 2590 (1976).
- HET-336 H. M. Fried, "Eikonal Field Theory Production of Interacting Pomerons," Phys. Rev. D 16, 457 (1977).
- HET-337 J. E. Kim and K. Kang, "Five-Quark Model with Flavour-Changing
TA-334 Neutral Current and Dimuon Events," Presented at the *XIth Rencontre de Moriond, Flaine, France, 28 February-12 March, 1976*.
- HET-338 P. J. Westervelt, "Non-Linear Interaction of a Spherical Wave with a Plane Wave," J. Acoust. Soc. Am. (in press).
- HET-339 P. J. Westervelt, "Absorption of Sound by Sound," J. Acoust. Soc. Am. (submitted).
- HET-340 N. J. Snyderman and G. S. Guralnik, "Dynamically Broken Gauge Model
TA-335 Without Fundamental Scalar Fields," *Quark Confinement and Field Theory*, D. Stump and D. Weingarten, Eds. (John Wiley and Sons, New York, 1977), p. 33.
- HET-341 C. M. Bender, F. Cooper, and G. S. Guralnik, "Path Integral Formulation of Mean-Field Perturbation Theory," Ann. Phys. (in press).
- HET-342 R. Vergara Caffarelli and K. Kang, "Axial Vector Mass Spectrum and Mixing Angles," Phys. Lett. 65B, 386 (1976).
- HET-343 K. Kang and J. E. Kim, "Test of Flavor-Changing Neutral Currents from Elastic Neutrino- and Antineutrino-Proton Scattering," Phys. Rev. D 16, 568 (1977).
- HET-344 B. C. Harms and C.-I Tan, "Non-Perturbative Formulation of Reggeon Field Theory on a Lattice," Phys. Lett. 67B, 435 (1977).
- HET-345 D. Joynson, K. Kang, and B. Nicolescu, "Status of the Regge-Pole Model for KN Scattering," Phys. Rev. D 15, 3296 (1977).
- HET-346 J. E. Kim, "General Lepton Structure with Naturalness Assumptions," Phys. Rev. D 16, 172 (1977).
- HET-347 B. C. Harms and C.-I Tan, "One-Component Formulation of Reggeon Field Theory," Phys. Rev. D (in press).

- HET-348 K. Kang and J. E. Kim, "Constraints in Quark and Lepton Models,"
Phys. Lett. 68B, 147 (1977).
- HET-349 K. Kang and J. E. Kim, "Flavor-Changing Neutral Currents in Elastic
TA-336 and Deep-Inelastic Neutrino-Scattering," Presented at the *XIIth
Rencontre de Moriond, Flaine, France, 6-18 March, 1977.*
- HET-350 K. Kang, J. E. Kim, and R. Nabavi, "Comment on the Glashow-Weinberg
Theorem," Phys. Rev. D 16, 911 (1977).
- HET-351 J. E. Kim, "Conditions for Natural Suppression of CP Violation,"
Phys. Rev. D (submitted).
- HET-352 H. M. Fried, "Strong-Coupling Solutions in an Isotopic Eikonal
Problem," Phys. Rev. D (in press).
- HET-353 B. K. Chung, "Multiplicity Distributions and Total Cross Section
at High Energies," Phys. Rev. D 16, 139 (1977).
- HET-354 H. M. Fried, "Two Topics in Eikonal Physics," Presented at the
TA-337 *Topical Seminar on Particles and Fields, Tübingen, West Germany,
June 1977.*
- HET-355 H. Moreno and H. M. Fried, "Inelastic Eikonal Phenomenology in a
Stationary-Phase Approximation: II," Phys. Rev. D (submitted).
- HET-356 H. M. Fried, "Summing All the Eikonal Graphs," Presented at the
TA-338 *Cargèse Summer Institute, Corsica, France, July 1977.*
- HET-357 P. J. Westervelt, "On the Close Connection Between Gravitational
TA-339 Radiation and the Optical and Radar Tests of General Relativity,"
*Proceedings of the Eighth International Conference on General
Relativity, Waterloo, Ontario, August 1977, p. 348.*

III. Scientific Personnel Associated with the Theoretical Program.

1 September 1976 - 31 December 1977

D. Feldman - Professor
H. M. Fried - Professor
G. S. Guralnik - Professor
K. Kang - Professor
P. J. Westervelt - Professor
C.-I Tan - Associate Professor
W. E. Caswell¹ - Assistant Professor (Research)
J. E. Kim² - Research Associate
D. A. Fitzpatrick - Graduate Research Assistant
J. P. Kowall³ - Graduate Research Assistant
M. C. Ogilvie - Graduate Research Assistant
A. C. Rothman - Graduate Research Assistant
K. K. Tamvakis - Graduate Research Assistant

1. From 1 September 1977.
2. Until 31 August 1977.
3. From 1 June 1977.