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

MASTER

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ABSTRACT

Last year's research has dealt with a wide range of topics in High-Energy Theoretical Physics. Important new results have been found in the fields of large-N expansions in quantum field theories via an effective Hamiltonian technique, and by the method of classical field equations supplemented by quantum boundary conditions; finite lattice QCD at $N_c = \infty$; neutrino oscillations and natural flavor conservation in gauge theory; the vanishing of the renormalized effective potential in ϕ_4^4 theory; a new method for treating singular differential equations; and an infrared cluster expansion in quantum field theory. In addition, substantial progress has been made in the analyses of lattice gauge theories; studies of factorization properties of mass and infrared singularities in QCD; non-hermitian quantum problems in the context of Gribov field theories; symmetry breaking via contracted groups; the calculation of Cabibbo-type angles and grand unification theories; and strong-coupling methods in gauge and nongauge field theories, using a systematic, lattice-formulated, perturbation theory, and by the extrac-tion of relevant infrared structure.

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 DE-AC02-76ER03130.A005, has been carrying out a research program in Experimental and Theoretical High-Energy Physics since 1958. David Feldman, Herbert M. Fried (Person-in-Charge), Gerald S. Guralnik, Antal Jevicki, Kyungsik Kang, and Chung-I Tan are principal investigators. This report serves to summarize the progress which has been made during the present contract period (1 January 1980 - 31 December 1980) by the Theoretical Group (Task A).

The report is divided into four sections:

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

I. Present Status of the Theoretical Group.

The high-energy theory program at Brown has received a new impetus with the arrival of Drs. S. Libby and J. Shigemitsu, specializing in infrared singularities of QCD and lattice gauge theories, respectively. In addition, Dr. Y. Goldschmidt, supported principally by the Physics Department's special funds for the year, has greatly strengthened our position in the area of quantum field theory.

Professor A. Jevicki has continued his ground-breaking work on the effective Hamiltonian formulation of the large- N expansion in various quantum field theories, while other members of the staff have obtained new results in the fields of Euclidean, large N_c expansions in QCD, Reggeon quantum mechanics, neutrino oscillations, natural flavor conserva-

tion in gauge theories, in the treatment of singular differential equations, renormalization theory of strong-coupling formalisms, and in the infrared structure of gauge field theories.

This activity has not gone unnoticed by the physics community. During the past year we have been host to many short-term visitors engaged in research on these topics; and we have received an extraordinary number of requests for such research visits, of both short- and long-term duration, for next year.

II. Individual Research Contributions.

During the past year, Professor Feldman and Mr. Crombie have been concerned with the general subject of "contracted" classical field theories. Such theories, in which the Goldstone-Higgs phenomena are realized as a consequence of a group contraction, offer an alternative to the standard approach to the spontaneous symmetry breakdown of internal symmetries. In the standard formulation, one considers a Lagrangian invariant under an internal symmetry group G and a vacuum which carries only the invariance of a subgroup H of G . In the contracted theories, this symmetry reduction is achieved by contracting from G to a new group G' where G' is a semi-direct product of some Abelian group with the residual symmetry group $\overline{H}$. These two types of theories lead to apparent and true symmetry breakdown, respectively, corresponding to the radical change in the group-theoretic structure of the field theory when subjected to the contraction process. It remains to be verified that the contraction of classical theories can be carried through consistently for all Lie groups and representations of interest. Once this point has been settled, the intention is to quantize the theories and check for their renormalizability. Mr. Crombie and Professor Feldman have also begun a study to see whether fermion fields can play the role of gauge fields. Two approaches are envisaged. In the first, an attempt is being made to generate self-consistent gauge invariant equations by an iteration process. The second approach will be based on the theory of connections.

The research of Professor Fried this year has concentrated on some half-dozen topics, of which half have been brought to completion. These include (1) a study (HET-407) of the strong-coupling structure of ϕ^4 theory by means of an analysis which extracts and sums all infrared structure from all relevant Feynman graphs. This is a non-lattice continuum approach to the calculation of a renormalization group β -function, in the strong-coupling limit, and produces a result quite similar to those found in strong-coupling lattice approximations to various theories. (2) A new, IR cluster expansion for ϕ^4 -field theory has been developed (HET-413) in association with J. Kowall. Of the various infrared expansions extant, this one is special in that it reduces the computation of any Green's function to a specification of a cluster-like expansion, similar to that found in statistical mechanics. This work was an outgrowth of the Ph.D. thesis (A New Semiclassical Approach in Charged Scalar QED) completed and submitted by J. Kowall, in May of 1980. A condensed version of this thesis (HET-406) was accepted for publication by Phys. Rev. D. (3) A brief observation was made (HET-412) concerning a possible method of estimating scattering amplitudes in eikonal approximation by the use of observed multiplicity distributions.

In collaboration with Dr. Kowall, Professor Fried is continuing work on (4) the strong-coupling/infrared structure of QED, using a method suggested by the success of the ϕ^4 program, but tailored to the special requirements of a gauge theory. Thus, gauge invariance is manifest at all stages of the calculation of the one-charged-particle closed-loop Feynman graph on which is superimposed all possible virtual soft-photon exchanges. The program of calculating a renormalization group β -function in this infrared approximation has been reduced to the estimation of the eigen value structure of a random, hermitian, antisymmetric matrix; and the answer as to whether or not a phase-transition exists for QED in the strong-coupling limit should be available very shortly. (5) Studies have continued, in collaboration with Professor H. Moreno of Mexico City, on the extraction

of an effective quark-antiquark potential from the (fictitious) scattering amplitude of a pair of such particles in eikonal approximation in QCD. The method envisages the evaluation of a particularly unpleasant functional integral by a stationary phase approximation, which requires the solution to the problem of a Yang-Mills field produced by an almost-classical color-charge current. The latter is defined by the motion of the scattering quark and antiquark, in an approximation which treats quark color degrees of freedom more rigorously than as simple point sources. Trivial (Coulombic) solutions have been found; and a search is continuing for non-trivial solutions displaying a full non-Abelian structure.

Finally, work has continued on (6) the search for a solution to the three-body Coulomb problem via eikonal methods. Scattering and various rearrangement collisions involving two-body bound states can be described using this new application of eikonal techniques, but the three-body bound-state problem continues to prove elusive. A major effort will be made again on this subject by Professor Fried and his collaborators (B. McKellar of Melbourne and R. Vinh Mau of Orsay) when they visit Brown in February 1981.

Dr. Goldschmidt's research work last year was performed in France, at the C.E.N. de Saclay, of the French Atomic Energy Commission. The work resulted in three publications. The first, "1/N Expansion in Two-Dimensional Lattice Gauge Theory",¹ showed how to calculate systematic corrections to planar diagrams using the method of orthogonal polynomials. The second, "Conservation Laws in Some Two-Dimensional Models",² consisted of a proof that the chiral models $SU(N) \times SU(N)$ and $O(N) \times O(N)$ have certain local laws which survive quantization. This indicates that the S matrix of these models must factorize. The third, "Large q Expansions for q-State Gauge-Matter Potts Models in Lagrangian Form",³ showed that within the framework of the Lagrangian approach there exists a systematic way to calculate the interesting gauge-matter phase diagram and to obtain an excellent agreement with Monte Carlo calculations.

¹J. of Math. Phys. 21, 1842 (1980).

²With E. Witten, Phys. Letters 91B, 392 (1980).

³With P. Ginsparg and J. B. Zuber, Nucl. Phys. B. (to be published).

Professor Guérin has studied the strong-coupling expansion in the Lagrangian formulation of a fermion field theory. In such an expansion, originally suggested by Professor Guralnik and collaborators, the interaction term is treated exactly and the kinetic term is treated perturbatively. The technique has been applied to the N-species Gross-Neveu model in the large-N limit where a simple exact solution exists: spontaneous breaking of discrete chiral symmetry occurs, and the fermion acquires a mass through its self-interaction. In collaboration with Dr. Kenway, the expansions of this model have been formulated for the fermion propagator; discrete chiral symmetry is broken at zeroth order and the resulting expansion in inverse powers of g^2N simplifies considerably in the limit of large N. In this limit the strong-coupling expansion may be summed to all orders and compared to the exact result. Extrapolation techniques, such as Padé approximants, are not needed. For the fermion propagator different regularization schemes may be adopted and three of these have been compared (HET-421). A continuum momentum cut-off is easier to work with and automatically avoids spurious fermionic states which afflict the naive lattice formulation. Using this cut-off previously known exact results have been recovered. For Wilson's regularization of the propagator, a mass counter-term is needed to cancel the contribution to the self-energy from its chiral-symmetry breaking term.

Professor Guralnik and collaborators (primarily Carl Bender of Washington University, and Fred Cooper and David Sharp of Los Alamos) have continued to make significant progress in their strong-coupling scheme for path integrals (HET-383). This scheme produces graphical rules for strong-coupling perturbation theory which are in many respects dual to the usual Feynman weak-coupling rules. The expansion performed is essentially in the kinetic energy terms of the theory rather than the interaction terms. Further emphasizing the dual property, the order of a graph in this strong-coupling expansion is determined by the number of internal lines rather than the number of vertices. Furthermore, the number of lines coming from each vertex is not fixed as is the case in weak-coupling expansions. At inter-

mediate stages of a calculation the strong-coupling diagrams are evaluated on a lattice and then at the conclusion of the calculation a collection of graphs are extrapolated back to the space-time continuum using Padé-like methods. It turns out that any single diagram of the strong-coupling expansion is relatively simple to evaluate since nothing more than algebra is required. This is in clear distinction to the weak-coupling case where higher order graphs require that increasingly difficult integrations be performed. The price paid for this apparent simplification of the strong-coupling expansion is that, in order to examine momentum dependence of a theory, it is necessary to go to high orders; and as a result many graphs must be dealt with and the algebra becomes too complex to do by hand. In order to handle the problem of generating and algebraically evaluating many graphs it is essential to use the Macsyma program on the MC computer at MIT. This program was developed by the Mathlab Group of the MIT Laboratory for Computer Science. Some of the analysis is also done using conventional programming languages on other computers. This year's work has resulted in a very comprehensive understanding of the strong-coupling parameterization and renormalization of theories with interaction of the form $g\phi^4$. In particular, the strong-coupling expansion of the renormalized effective potential of $g\phi^4$ quantum field theory has been extensively studied in d dimensional space-time (HET-415, 422, 434, 435, 436). The most striking result of this work is that one finds, as the dimensionality of space-time approaches the physical value of four, that the renormalized strong-coupling effective potential vanishes. This indicates that $g\phi^4$ is a free^{4,5} field theory in four dimensions, as has been suggested by other calculations. Results for the parameters of the effective potential are calculated by Professor Guralnik and collaborators as continuous functions of space-time. In zero and one space-time dimensions they have been able to perform exact analytic calculations of these parameters, which confirm the accuracy of numerical, strong-coupling perturbative methods. These results are particularly exciting as they tend to lend credence to the speculation made by

⁴J. Kogut and K. G. Wilson, Phys. Reports C12, 75, 1974.

⁵G. A. Baker and J. M. Kincaid, Phys. Rev. Letts. 42, 1431 (1979).

many theoreticians that the world is described only by asymptotically free theories. We see that ϕ^4 has voluntarily declared itself unusable.

As an exciting spin-off of their strong-coupling functional techniques, Professor Guralnik and his collaborators have also discovered a new method for treating singular, ordinary differential equations. This technique has been applied to a number of boundary layer problems (including the kink equation which is of direct interest to particle theorists) with very good results (HET-416).

Under Professor Guralnik's supervision Michael Ogilvie and Desmond Fitzpatrick have finished the requirements for the Ph.D. degree from Brown. Mr. Fitzpatrick did an extensive study of higher order mean field ($1/N$) techniques applied to lower dimensional field theories and obtained excellent agreement with exact results in the cases where they are known. This work is being prepared for publication. Mr. Ogilvie and Professor Guralnik studied the connection of Kosterlitz-Thouless vortices and $O(3)$ instantons (HET-427), and demonstrated the crucial role of the instanton gas in the Kosterlitz-Thouless phase transition. Other results of this work are being prepared for publication.

Mr. McCabe, Professor Guralnik, and Dr. Cooper have studied the application of mean field techniques to obtain numerical predictions from four fermion theories in four dimensions, and will continue this work into next year.

During the past year Professor Jevicki has developed, in collaboration with B. Sakita, H. Levine, and N. Pananicolaou, a new nonperturbative approach to Quantum Chromodynamics. Originally, it was suggested by G.'t Hooft in 1974 that for $N = \infty$, $SU(N)$ Yang-Mills gauge theories simplify and reduce to planar diagrams, which then provide an appealing phenomenological picture of hadron physics. The basic problem is how to solve QCD in the $N \rightarrow \infty$ limit. A direct summation of Feynman diagrams does not seem possible, and a more powerful, semiclassical approach to this problem has been developed by Professor Jevicki and his collaborators. The first stage of this

method was formulated⁶ in collaboration with B. Sakita (City College of New York) and it consists in summarizing the large-N graphs in terms of an effective Hamiltonian. The usefulness of the effective Hamiltonian formulation lies in the fact that now the $N \rightarrow \infty$ limit becomes particularly simple: it is determined by classical stationary points of the effective Hamiltonian. In HET-397 a general formalism for deriving large-N effective Hamiltonians was developed through the quantum collective field method. This represents a procedure for reformulating a given quantum Hamiltonian in terms of a general (over-complete) set of invariant variables. In Yang-Mills theory these are given by space-like Wilson loops and consequently the problem of summing planar diagrams was reduced to a nonlinear loop-space equation. Continuing the collaboration with B. Sakita, Professor Jevicki has applied this formalism to some simple lattice gauge theories (HET-414) and they have succeeded in obtaining exact results for the large-N behavior. The full Yang-Mills problem is however much more complex (essentially due to the non-trivial nature of the loop space); a direct solution of the loop-space equations does not seem feasible and some additional new techniques are needed. This led to the second line of development where the basic idea is to consider the relevance of original field equations to the large-N limit. In a series of papers (HET's 402, 414, 419) done in collaboration with H. Levine (Harvard University) and N. Papanicolaou (Berkeley) Professor Jevicki has established that there is a direct connection between the original classical equations and the effective, large-N equations. Basically, what they show is that the effective Hamiltonians can be understood as the original classical Hamiltonian with special, non-trivial boundary conditions. Consequently, certain real-time classical solutions can be used to determine directly the sum of large-N diagrams. This represents an important simplification of the large-N problem.

The present status of the above described semiclassical approach to large-N QCD was described in a review paper (HET-429). This summarizes the invited talks that Professor Jevicki has given this summer at the XXth Inter-

⁶A. Jevicki and B. Sakita, "The Quantum Collective Field Method and Its Application to the Planar Limit", Nucl. Phys. B (1980).

national Conference on High Energy Physics at Madison, Wisconsin and the Santa Barbara Meeting on Lattice Gauge Theories, 28 July - 3 August 1980.

During the preceding year, Professor Kang has studied three distinct topics: electroweak gauge theories with the constraint of natural flavor conservation, neutrino oscillations, and grand unification theories.

The two most powerful theoretical constraints on gauge theories, aside from renormalizability, are calculability of the Cabibbo-like mixing angles, and natural flavor conservation (NFC) in gauge-boson and Higgs-mediated neutral currents. The first problem arises from the observation that the eigenstates of the theory are not the mass eigenstates and there may be a non-trivial fermion mass matrix predicted by the gauge theories. Therefore it would be necessary to incorporate the non-trivial mass matrix in gauge theories so that calculability of the Cabibbo-type mixing angles can be naturally guaranteed, i.e., all mixing angles are functions of quark mass ratios only as, for example, in the familiar relation $\tan^2 \theta_c = m_d/m_s$. The constraint of NFC was promoted to a general theoretical condition for $SU(2) \times U(1)$ theories by a number of authors⁷ from the observed absence of strangeness-changing neutral currents. Professor Kang, in collaboration with Arthur C. Rothman, considered the general problem of applying NFC to an arbitrary local gauge broken down to a $U(1)$ subgroup (HET-425). There are two compelling reasons to consider NFC in this context. First, it is possible that $SU(2) \times U(1)$ may not be the ultimate operative gauge group of the electroweak interactions, as there exists the competing left-right symmetric model and the possibility of non-zero mass neutrinos. Secondly, generalizing the conditions for NFC was found necessary to discuss broader questions concerning calculability of mixing angles from the general class of electroweak gauge theories satisfying NFC (HET-409). The conclusion reached (HET-425) is that the facts of NFC for a general $U(1)$ -unbroken gauge theory require that all fermions of a given charge and helicity trans-

⁷K. Kang and J. E. Kim, Phys. Lett. 64B, 93 (1976) (COO-3130 TA-330); S. L. Glashow and S. Weinberg, Phys. Rev. D15, 1958 (1977); E. A. Paschos, Phys. Rev. D15, 1966 (1977).

form identically under the gauge group. Further, Professor Kang and Mr. Rothman proved a number of theorems (HET-409) relating NFC and calculability, for general gauge models of the electroweak interactions with an unbroken $U(1)$ symmetry. Here NFC is treated in the context of many Higgs fields, for recent works⁸ dealing with the calculations of flavor mixing angles from the mass terms in the effective Lagrangian call for a much richer Higgs content. The concept of non-triviality is theoremized so that all naturally flavor conserving gauge models may lead to non-trivial mixing angles.

The possibility of neutrino oscillations has its origin in that the weak interaction eigenstates are not necessarily the mass eigenstates, as in the discovery of $K^0 - \bar{K}^0$ oscillations. Professor Kang, in collaboration with Dr. J. E. Kim and others of Seoul National University (HET-430), studied the neutrino oscillations under the following set of rules: (1) the standard $SU_L(2) \times U(1)$ model with 45 chiral fields and Higgs doublets is operative under 100 GeV; (2) any nonrenormalizable effective Lagrangian which is $SU_L(2) \times U(1)$ invariant is suppressed by a natural mass scale M_N . They found that the neutrino oscillation parameters of order 1 eV or less suggest M_N of the order $10^8 \sim 10^9$ GeV. An $SU(7)$ grand unified gauge model is explicitly worked out in this context.

In two invited-conference talks (HET-423 and HET-433), Professor Kang has reviewed the motivations and successes of the minimal grand unification model, the Georgi-Glashow $SU(5)$ model.⁹ Also included are the shortcomings of the $SU(5)$ model and other improved grand unified models.

Professor Kang is the author of a review article (HET-431) on the path integral method of quantization of non-Abelian gauge fields, with applications to Quantum Chromodynamics; this was written at the request of the editorial committee for the Festschrift honoring Professor Chang Yul Chi of Seoul National University on his 60th birthday. Finally, Mr. Rothman

⁸See, for example, A. C. Rothman and K. Kang, Phys. Rev. Letts. 43, 1548 (1979) (HET-393), in which additional references can be found.

⁹H. Georgi and S. C. Glashow, Phys. Rev. Letts. 32, 438 (1974).

completed his Ph.D. under Professor Kang's supervision with the thesis entitled, "Calculability, Natural Flavor Conservation, and a Left-Right Symmetric Gauge Model of the Weak and Electromagnetic Interactions".

Dr. Kenway has studied aspects of two-dimensional quantum field theories which are of interest to both elementary particle and condensed matter physicists. One aim has been to devise a scheme for calculating the hadron spectrum of quantum chromodynamics (QCD). The four-dimensional theory is so difficult that related two-dimensional models are often used as testing grounds. Another aim has been to study the effect of random impurities on transport phenomena and topological order in real two-dimensional systems. These problems share some formal similarities. In collaboration with Professor Guérin, Dr. Kenway investigated the formulation of an expansion in the fermion propagator for the N-species Gross-Neveu model in the large-N limit. Different regularization schemes were adopted and compared, as described above in the research of Professor Guérin (HET-421).

The zero temperature electrical conductivity of a disordered solid is poorly understood. Some theoretical work indicates that extended states which produce metallic conductivity only exist in more than two dimensions, although this seems to be contradicted by numerical work. Wegner and Schäfer showed that the behavior of an electron in a random potential is described by a matrix non-linear σ -model defined on the non-compact space $O(M,M)/O(M) \times O(M)$ in the limit $M \rightarrow \infty$. This non-compact symmetry represents the essential physics of the problem. In collaboration with A. Houghton, A. Jevicki, and A. M. M. Pruisken, Dr. Kenway studied this model using a $2 + \epsilon$ expansion, (HET-420) calculating the β -function to one-loop order for general σ -models whose fields take values on an Einstein space. It may be found that all states are localized in two dimensions. Above two dimensions, for weak disorder, there are mobility edges, but these merge above a critical amount of disorder and all states become localized.

During the past year, Professor Libby has investigated a two-dimensional model of his own invention that couples fundamental representation fermions

to the $SU(N)$ or $O(N)$ sigma models. It is interesting for a number of reasons: the presence of instantons, renormalizability, asymptotic freedom, a large- N limit (in the $SU(N)$ case given by sums of planar diagrams) and particularly because it has an infinite set of classically conserved charges. In quantum mechanics, these conservation laws have both conformal and chiral anomalies. Professor Libby is presently investigating whether any of the conservation laws survive quantization, and if so, the possibility of an exact solution for the S -matrix exists.

Professor Libby has also studied spectral constraints on theories where, as 't Hooft has proposed, some spin $1/2$ particle bound states may realize an underlying chiral symmetry in the Wigner mode. He has continued an investigation of the factorization properties of high-energy scattering cross sections, and the attending issues of mass and infrared divergences.

During the last year Professor Shigemitsu, in collaboration with J. Kogut and R. Pearson, calculated the β -function for $SU(3)$ lattice gauge theory through sixth order in a strong-coupling expansion. Their results indicate that it is possible to renormalize the lattice theory by keeping the string tension fixed and go from the strong-coupling into the weak-coupling region, where ordinary perturbation theory should take over. This provides supporting evidence for the claim that both confinement and asymptotic freedom characterize the continuum limit of lattice QCD. These calculations also enabled them to extract the ratio between the A -parameter of perturbative QCD and the string tension. In the same work an estimate for the roughening temperature was obtained by calculating the width of the electric flux tube and seeing whether this quantity diverges. The roughening transition was found to occur well within the weak-coupling region. Similar studies were carried out for the $Z(N)$ and $P(N)$ lattice gauge theories¹⁰ and for the $SU(N)$ gauge theories for general N .¹¹

¹⁰With J. Kogut, R. Pearson, and D. K. Sinclair, to appear in Phys. Rev. D.

¹¹With J. Kogut, Phys. Rev. Lett. 45, 410 (1980).

Professor Tan's research effort during the past year includes the investigation of the structure of finite lattice QCD at $N_c = \infty$ and the application of approximation and numerical analysis to the study of Gribov field theory. Although the $1/N_c$ expansion to QCD is generally acknowledged to be a sensible approximation scheme, progress toward calculating the first $N_c = \infty$ term has been confined to severely truncated models. Nonetheless, these warm-up exercises are beginning to provide both the arsenal of $1/N$ techniques and insight into the special properties of $N_c = \infty$ QCD. Together with Drs. R. Brower and P. Rossi, a class of finite lattice chiral models has been studied (HET-410). These periodic chiral chains are indeed equivalent to gauge theories on the surface of three-dimensional polyhedra. The one-link Schwinger-Dyson equation which gives the square of the transfer matrix is solved for all N_c . From the large N_c solution, the chiral chain problems with periods $L = 2, 3, 4$ and infinity are solved exactly on the weak-coupling side of the Gross-Witten cross-over singularity, which is shown to be located at $\beta_c = 1/4, 1/3, \pi/8$ and $1/2$, respectively. This cross-over singularity comes about due primarily to the large fluctuation in the infinite group volume at $N_c = \infty$ while the spatial correlations remain short-range; the above result thus provides a persuasive illustration as to why the cross-over phenomenon should persist for QCD₄ at $N_c = \infty$.

Together with Drs. B. C. Harms and S. T. Jones, a new method for solving (non-Hermitian) quantum problems has been employed to analyze Reggeon quantum mechanics with both cubic and quartic interactions (HET-417, 424). The spectrum is found to be more complicated than previously assumed and the phenomenon of "ground state oscillation" was discovered, which suggests the existence of multiple phases at higher dimensions. In addition, the asymptotic behavior of soft hadronic collisions was studied (HET-408) in the framework of Gribov's field theory for interacting pomerons. An analog model of Ising-spin on a lattice with an anti-hermitian three-spin interaction was constructed, and the existence of a desired non-trivial fixed point was demonstrated utilizing a Migdal approximation.

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

- HET-406 J. Kowall, "A Semiclassical Calculation of the Photon Propagator in Two-Dimensional Scalar QED", *Physical Review D*, (in press).
- HET-407 H. M. Fried, "A Different Method in Quantum Field Theory: Strong Coupling and the Infrared Structure of ϕ^4 Theory", *Nuclear Physics B* 169 (1980) 329.
- HET-408 C-I. Tan, "Migdal Approximations in the Gribov Field Theory on a Lattice". (Conference paper presented in China in January 1980).
TA-348
- HET-409 A. Rothman and K. Kang, "Generalized Mixing Angles in Gauge Theories with Natural Flavor Conservation", submitted to *Annals of Physics*.
- HET-410 R. Brower, P. Rossi, and C-I. Tan, "Chiral Claims for Lattice QCD at $N_c = \infty$ ", submitted to *Physical Review D*.
- HET-411 U. Mohanty, "Is Bose Einstein Condensation a Clustering Transition in Configuration Space?", submitted to *Physical Review Letters*.
- HET-412 H. M. Fried, "Estimate of Eikonal Scattering Amplitudes via Multiplicity Distribution", submitted to *Physical Review D*.
- HET-413 J. Kowall and H. M. Fried, "A Cluster Expansion and Field Theory", submitted to *J. Math. Physics*.
- HET-414 A. Jevicki and B. Sakita, "Large N Limit of the One-Plaquette Kogut-Susskind Hamiltonian", *Physical Review D* 22, (1980) 467.
- HET-415 C. Bender, F. Cooper, G. S. Guralnik, and D. Sharp, "Renormalizing the Strong-Coupling Expansion for Quantum Field Theory: Present Status", *Proceedings of ORBIS Scientiae* (to be published).
- HET-416 C. M. Bender, F. Cooper, and G. S. Guralnik, "A Novel Approach to the Solution of Boundary Layer Problems", *Advances in Applied Mathematics* 1, (1980) 22.
- HET-417 B. C. Harms, S. T. Jones, and C-I. Tan, "Complex Energy Spectra in Reggeon Quantum Mechanics with Quartic Interactions", *Nuclear Physics* (in press).

- HET-418 A. Jevicki and H. Levine, "Semiclassical Approach to Planar Diagrams", Physical Review Letters 44, (1980) 1443.
- HET-419 A. Jevicki and H. Levine, "Large N Classical Equations and Their Quantum Significance", Annals of Physics (in press).
- HET-420 A. Houghton, A. Jevicki, R. Kenway, and A. M. M. Pruisken, "Noncompact σ -Models and the Existence of a Mobility Edge in Disordered Electronic Systems near Two Dimensions", Physical Review Letters 45 (1980) 394.
- HET-421 F. Guérin and R. D. Kenway, "A Strong-Coupling Expansion for Fermion Field Theories and the Large-N Limit of the Gross-Neveu Model", submitted to Nuclear Physics.
- HET-422 C. M. Bender, F. Cooper, G. S. Guralnik, H. Moreno, R. Roskies, and D. H. Sharp, "Effective Potential for a Renormalized d-Dimensional $g\phi^4$ Field Theory in the $g \rightarrow \infty$ Limit", Physical Review Letters 45, (1980) 501.
- HET-423 K. Kang, "Introduction to Grand Unification Theories" (invited talk presented at the XVth Rencontre de Moriond, Les Arcs, Savoie, France, 9 - 21 March 1980.
TA-349
- HET-424 B. C. Harms, S. T. Jones, and C-I. Tan, "New Structure in the Energy Spectrum of Reggeon Quantum Mechanics with Quartic Couplings", Physics Letters 91B (1980) 291.
- HET-425 A. C. Rothman and K. Kang, "Natural Flavor Conservation", Physical Review D (in press).
- HET-426 M. Ogilvie, "Spin Waves, Vortices, Fermions, and Duality in the Ising and Baxter Models", submitted to Physical Review D.
- HET-427 M. C. Ogilvie and G. S. Guralnik, "Instantons and Vortices in Two-Dimensional Field Theories", submitted to Physics Letters.
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Effective Potential", submitted to Physical Review.

IV. Scientific Personnel Associated with the Theoretical Program
1 January 1980 - 31 December 1980

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H. M. Fried - Professor
G. S. Guralnik - Professor
K. Kang - Professor
F. Guérin¹ - Visiting Professor
C-I. Tan - Professor²
A. Jevicki - Assistant Professor
S. Libby³ - Assistant Professor of Research
J. Shigemitsu³ - Assistant Professor of Research
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³From 1 September 1980