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

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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. Atomic Energy Commission under Contract AT(11-1)-3130 [formerly AT(30-1)-2262] has been carrying out a research program in Experimental and Theoretical High-Energy Physics since 1958. The Theoretical Program has been under the direction of David Feldman, Professor of Physics. This report serves to summarize the progress which has been made during the present contract year (1 September 1971 - 31 August 1972) 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 high-energy nuclear physics, elementary particle physics, 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 Cronin continued his efforts at constructing a multiparticle realization of the chiral group SU(2)×SU(2). The aim here has been to construct realizations where \( \chi_s^i |n> = \sum_m C_{nm}^i |m> \). Here, \( \chi_s^i \) is the axial charge generator of chiral SU(2)×SU(2), and \( n,m \) refer to the number of pions. Having found a set of the \( C_{nm}^i \), it is hoped...
that this will yield constraints on the allowed S-matrix elements for processes involving different numbers of pions.

The research of Professor Fried during the past year consisted mainly of work in the fields of high-energy eikonal approximations, and the analysis of high-multiplicity pion production within a hadronic bremsstrahlung model. An extension, involving summing over tower graphs, of known eikonal estimates which give total cross sections of the form \( \sigma_T \sim \ell n^2 s \) was completed (Ref. 262)\(^1\); the result shows that extraordinary cancellations neglected in previous estimates must take place, thereby destroying the basis for the previous \( \sigma_T \) result. Two distinct projects dealing with pion production, obtained by the bremsstrahlung of neutral vector mesons in proton-proton collisions, were concluded. In the first (Ref. 249), a prediction of charged-particle multiplicities was made, while the second (Ref. 261) discusses the various one-particle inclusive distributions of the model. A comparison of these predictions with large transverse-momentum experiments is awaited.

The relatively small mass of the pion taken within the framework of current algebra leads to many interesting theoretical results. Thus, if one considers the pion irreducible vertex with \( n \) external pion lines, \( \pi_n \left( p_1 \cdots p_n \right) \), and characterizes the low-energy limit by a parameter \( \xi \) (so that \( p_i + \xi p_i \) ), it has been shown\(^2\) that in the soft-pion (\( \xi \rightarrow 0 \)) and weak chiral-symmetry-breaking (\( M_\pi^2 + 0 \)) limits, \( \pi_n \) is of the form \( a \xi^2 + \beta M_\pi^2 + \text{higher-order terms} \). The validity of this expansion has been challenged by Li and Pagels\(^3\) who have argued that with \( \pi_n \) determined from \( L = L_0 + \lambda L' \) (where \( L_0 \) is realized by Goldstone bosons and \( L' \) breaks the symmetry with strength \( \lambda \) ), it

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1. References cited are listed in Section II of this report.
cannot be analytic in $M_\pi^2$ at the origin and indeed it may have terms of the form $aM_\pi^2 \ln M_\pi^2 + b(M_\pi^2)^2 \ln M_\pi^2$. Furthermore, Carruthers and Haymaker have indicated that the radius of convergence of the SU(3)×SU(3) perturbation limit is much smaller than the experimental value of the symmetry-breaking parameter. In view of these problems, Professor Guralnik, in collaboration with Professor B. W. Lee and Drs. H. S. Tsao and T. F. Wong, decided to study these phenomena in a linear SU(2)×SU(2) σ model (Ref. 250). This model has all the symmetry properties assumed by Li and Pagels; it can be solved exactly in $\lambda$ to any given number of loops, is renormalizable, and with simple symmetry-breaking terms gives PCAC. They have, for this model, evaluated the explicit low-energy form of the two-point functions, the $\pi\pi$ scattering amplitude, and the $\pi N$ scattering amplitude. In all the matrix elements they have studied, they have found that the nonanalytic corrections vanish faster than $\zeta^2$ or $M_\pi^2$. Thus, although the expression $\pi_\pi - \alpha \zeta^2 - \beta M_\pi^2$ has nonanalytic corrections, they are of the form $\zeta^4 \ln M_\pi^2$, $M_\pi^4 \ln M_\pi^2$, etc.; hence the usual phenomenological Lagrangian still gives the correct low-energy limit. In addition to the preceding work, Professor Guralnik has also been spending some time on models of the type Weinberg has proposed for the weak interactions, with particular emphasis on the renormalization and the problems caused by anomalies.

A major effort was devoted to the completion of the study of two-particle inclusive processes at high energies in terms of the dual-resonance model (an initial account of this work was reported last year5). This project, which was carried out by Professors Kang and Tan with the assistance of Messrs. Jen and Shen, was:

concerned with various questions, including the scaling properties, factorization, and correlation effects of the two-particle production cross sections (Refs. 247, 255, 256). While the distribution showed the expected scaling properties for all kinematic regions, it was found that the factorization of the inclusive distribution function is realized only upon a nontrivial treatment of the singularities and certain kinematic relations. Thus, Professors Kang, Tan and collaborators have speculated that the singularity structure of the dual-resonance model, which can be shown to have multi-Regge behavior, may be of a model-independent nature; based on this hypothesis, they have discussed the general properties of the Reggeon-Reggeon amplitude and deduced a finite-energy sum rule which can be used to estimate the triple-Reggeon as well as the two-Reggeon-particle couplings for diffraction scattering (Ref. 247). Correlation effects among the transverse momenta, relative azimuthal angle, and the relative rapidity were presented in Ref. 255 for future experimental analysis.

In collaboration with Dr. M. Lacombe and Professor R. Vinh Mau, Professor Kang has carried out a complete K-matrix unitarization of the Veneziano pion-pion amplitude (Ref. 253). By incorporating the correct behavior of the partial waves at the left-hand branch point, the s and p waves were constructed so as to satisfy the rigorous crossing conditions of the integral forms and the inequality relations; the results are in good agreement with recent experiments. With Mr. Jen, Professor Kang has considered a two-channel generalization of the K-matrix unitarization so as to include the KK channel; in particular, it has proved possible from this study to remove the up-down ambiguity of the isoscalar s-wave pion-pion phase shift above the p mass and to explain the S* particle which has been seen in some experiments around 1 GeV. Professor Kang, together with Mr. Shen, has re-examined the single-particle distribution previously reported so as to apply to the realistic situation of present accelerator

energies; the correlation between the transverse and longitudinal momenta, the average multiplicity, and the structure of the distribution function have been investigated. Finally, under Professor Kang's direction, Mrs. Lucey has completed her doctoral thesis entitled, "Gravity Problems and Particle Physics."

There are two rather contradictory approaches, each with its own successes, to explain and predict the results of a variety of experiments involving the interactions of hadrons. On the one hand, it is suggested that at high energies hadrons may be regarded as constructed out of more fundamental particles (partons) whose interactions with each other may in the first approximation be neglected. On the other hand, it is proposed that the dynamics of resonance excitation and formation is the primary feature of the data. Dr. Silver has attempted to reconcile these two viewpoints in terms of a propagator model for composite hadrons. A particular goal is to determine whether conjectured non-perturbative abstractions such as the light-cone algebra can be valid in the presence of interactions. Another is to make predictions for the new generation of colliding-beam and high-energy accelerators. Dr. Silver is at present trying to solve a number of theoretical problems, such as the establishment of current algebra sum rules, which stand in the way of a satisfactory statement of the model.

Professor Tan has been concerned with the investigation of the properties of multiparticle hadronic interactions at high energies through use of both model studies and general considerations. In the dual-resonance model, explicit two-particle inclusive spectra were derived in collaboration with Professor Kang and Messrs. Jen and Shen (see also the discussion on page 3); here, the important theoretical input is analyticity. The multiperipheral model, on the other hand, emphasizes direct channel unitarity. With Mr. Mak, Professor Tan has obtained specific characteristics of the single-
and the two-particle inclusive cross sections as consequences of
multiperipheralism (Ref. 257). More fundamentally, the foundation
of multiperipheralism was elucidated from the point of view of
inclusive sum rules, which are recognized as equivalent to the
requirement of unitarity (Ref. 254). A considerable kinematic
simplification for these sum rules was obtained by recognizing
that they can be diagonalized through the technique of multi-
dimensional Laplace transforms. This, in turn, has paved the way
for the exciting development of an "inclusive bootstrap" program
(Ref. 259).

Mr. J. R. Clynch has extended Professor Westervelt's work on
the scattering of electromagnetic waves by static gravitational
fields so as to apply to stationary fields, using the linearized
form of the Kerr metric. With this metric, there appears in the
generalized wave equation for the vector potential a term which is
dependent on the relative direction of the angular momentum of the
object and the polarization of the electromagnetic field, which
polarization-dependent term corresponds to those that appear in the
equation of motion of a particle with spin one. The field equation
for the vector potential was then treated in the long wavelength
limit as a scattering problem, and the angular pattern of the
scattered radiation was determined. Mr. P. J. Turner, directed by
Professor Westervelt, has completed his studies of the equations of
gerodesic deviation. This work confirms the conjecture that
passive receptors for gravitational waves are in principle not
workable.

NYO-2262TA-222).
Interactions with Simple Systems," B. S. Thesis, Department of
Physics, Brown University, June 1971.
10. P. J. Westervelt, JETP Lett. 4, 225 (1966) (Report No. NYO-
2262-116).
Under Professor Feldman's direction, Mr. Chung has completed his doctoral thesis, "Partial Wave Structure of the Dual ππ Scattering Amplitude." This work involved a study of the asymptotic behavior in the complex s (energy-squared variable) plane, as well as the cut structure, of the various I-spin partial waves. The coefficients associated with the threshold behavior of all partial waves were shown to be calculable in a straightforward way and, by way of example, the scattering lengths for the s, p, d, and f waves were determined. Integral and differential representations were introduced to obtain constraints which eliminate the negative partial-wave resonance widths for the parent and the first three daughter trajectories. This work is currently being written up for publication. Professor Feldman and Mr. Chung have also spent some time on the problem of the unitarization of dual-resonance amplitudes by making use of the generalized optical theorem and dispersion-theoretic techniques.
II. Theoretical Papers Published During the Preceding Year and Papers in Press.


III. Scientific Personnel Associated with the Theoretical Program.

1 September 1971 - 31 August 1972

D. Feldman - Professor
L. N. Cooper - Professor
H. M. Fried - Professor
P. J. Westervelt - Professor
G. S. Guralnik - Associate Professor
K. Kang - Associate Professor
J. A. Cronin\(^1\) - Assistant Professor
C.-I. Tan - Assistant Professor
R. N. Silver - Research Associate
B.-K. Chung - Graduate Research Assistant
C.-L. Jen - Graduate Research Assistant
S. Kasdan - Graduate Research Assistant
B. J. Kirby - Graduate Research Assistant
S.-Y. Mak - Graduate Research Assistant
S. M. A. H. Rizvi - Graduate Research Assistant
P. Shen - Graduate Research Assistant
N. J. Snyderman\(^2\) - Graduate Research Assistant
K. S. Soh\(^2\) - Graduate Research Assistant

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2. From 1 June 1972.