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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 multi-particle realization of the chiral group $SU(2) \times SU(2)$. The aim here has been to construct realizations where $\chi_S^i |n\rangle = \sum_m C_{nm}^i |m\rangle$. Here, χ_S^i is the axial charge generator of chiral $SU(2) \times SU(2)$, 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 $\sigma_T \sim \ln^2 s$ 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 σ_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, $\pi_n(p_1 \cdots p_n)$, and characterizes the low-energy limit by a parameter ζ (so that $p_i \rightarrow \zeta p_i$), it has been shown² that in the soft-pion ($\zeta \rightarrow 0$) and weak chiral-symmetry-breaking ($M_\pi^2 \rightarrow 0$) limits, π_n is of the form $\alpha \zeta^2 + \beta M_\pi^2 + \text{higher-order terms}$. The validity of this expansion has been challenged by Li and Pagels³ who have argued that with π_n determined from $L = L_0 + \lambda L'$ (where L_0 is realized by Goldstone bosons and L' breaks the symmetry with strength λ), it

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1. References cited are listed in Section II of this report.
 2. R. Dashen and M. Weinstein, Phys. Rev. Letters 22, 1337 (1969); Phys. Rev. 188, 2330 (1969).
 3. L.-F. Li and H. Pagels, Phys. Rev. Letters 26, 1204 (1971).

cannot be analytic in M_π^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 Haymaker⁴ have indicated that the radius of convergence of the $SU(3) \times SU(3)$ 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 $SU(2) \times SU(2)$ σ model (Ref. 250). This model has all the symmetry properties assumed by Li and Pagels; it can be solved exactly in λ 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 πN scattering amplitude. In all the matrix elements they have studied, they have found that the nonanalytic corrections vanish faster than ζ^2 or M_π^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

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4. P. Carruthers and R. W. Haymaker, Phys. Rev. D 4, 1808 (1971); Phys. Rev. Letters 27, 455 (1971).
 5. C.-L. Jen, K. Kang, P. Shen, and C.-I. Tan, Phys. Rev. Letters 27, 458 (1971) (Report No. NYO-2262TA-244).

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 $K\bar{K}$ 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 ρ 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 reported⁶ so as to apply to the realistic situation of present accelerator

6. C. E. DeTar, K. Kang, C.-I. Tan, and J. H. Weis, Phys. Rev. D 4, 425 (1971) (Report No. NYO-2262TA-237).

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. Clync has extended Professor Westervelt's work⁷ 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.⁸ 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 geodesic deviation.⁹ This work confirms the conjecture¹⁰ that passive receptors for gravitational waves are in principle not workable.

7. P. J. Westervelt, Phys. Rev. D 3, 2319 (1971) (Report No. NYO-2262TA-222).

8. R. P. Kerr, Phys. Rev. Letters 11, 237 (1963).

9. P. J. Turner, "A Theoretical Study of Gravitational Radiation 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 $\pi\pi$ 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.

- TA-246 C.-I. Tan, "High Energy Inclusive Processes," *Springer Tracts in Modern Physics; Ergebnisse der Exakten Naturwissenschaften*, G. Höhler, Editor (Springer-Verlag, Berlin, 1971), Vol. 60, p. 91.
- TA-247 C.-L. Jen, K. Kang, P. Shen, and C.-I. Tan, "Reggeon Amplitude and Duality Sum Rule," *Phys. Rev. Letters* 27, 754 (1971).
- TA-248 C. W. Price, Jr. and P. J. Westervelt, "Conservation of Momentum in General Relativity," *J. Math. Phys.* (submitted).
- TA-249 H. M. Fried and T. K. Gaisser, "Meson Multiplicity for the Reaction $pp \rightarrow ppX$ in a Bremsstrahlung Model," *Phys. Rev. D* 4, 3330 (1971).
- TA-250 G. S. Guralnik, B. W. Lee, H. S. Tsao, and T. F. Wong, "Low Energy Limit of the σ Model," *Phys. Rev. D* (submitted).
- TA-251 R. Olshansky, "Is $SU(3) \times SU(3)$ Realized with Goldstone Bosons?" *Phys. Rev. D* 4, 2440 (1971).
- TA-252 M.-L. Shen, "A Phenomenological Analysis of Single Particle (Rev) Distributions," *Nucl. Phys.* (submitted).
- TA-253 K. Kang, M. Lacombe, and R. Vinh Mau, "Unitarized Veneziano $\pi\pi$ Scattering Amplitude Consistent with Positivity and Crossing-Symmetry Constraints," *Phys. Rev. D* 4, 3005 (1971).
- TA-254 C.-I. Tan, "Construction of Multiperipheral Dynamical Equations and Inclusive Sum Rules," *Phys. Rev. D* 5, 1476 (1972).
- TA-255 C.-L. Jen, K. Kang, P. Shen, and C.-I. Tan, "Short-Range Correlations in Two-Particle Productions," *Physics Letters* 38B, 81 (1972).
- TA-256 C.-L. Jen, K. Kang, P. Shen, and C.-I. Tan, "Dual-Amplitude Analysis of Two-Particle Productions. II," *Ann. Phys. (N.Y.)* (in press).
- TA-257 S.-Y. Mak and C.-I. Tan, "Correlation Lengths, Inclusive Transverse Momentum Distributions, and Multiperipheralism," *Phys. Rev. D* (in press).
- TA-258 M.-L. Shen, "Note on Single-Particle Spectra at Cosmic Ray Energies," *Phys. Rev. D* (submitted).

- TA-259 S.-Y. Mak and C.-I. Tan, "Diagonalization of Inclusive Sum Rules and Inclusive Bootstrap," Phys. Rev. D (in press).
- TA-260 K. Kang, "Dual-Amplitude Analysis of Inclusive Distributions," *Proceedings of the VIIth Rencontre de Moriond on Electromagnetic Interactions, Méribel-les-Allues, France, 11-17 March 1972*, in press.
- TA-261 H. M. Fried and T. K. Gaisser, "Single Particle Distributions in a Hadronic Bremsstrahlung Model," Phys. Rev. D (in press).
- TA-262 R. Blankenbecler and H. M. Fried, "Eikonal Estimates and Cancellations at High Energies," Phys. Rev. D (submitted).
- TA-263 M.-L. Shen, "Asymmetry and Leading Particles," Phys. Rev. Letters 28, 1412 (1972).
- TA-264 H. M. Fried, *Functional Methods and Models in Quantum Field Theory* (The M.I.T. Press, Cambridge, 1972), 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. Cronin¹ - 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. Snyderman² - Graduate Research Assistant
K. S. Soh² - Graduate Research Assistant

1. Until 15 January 1972.

2. From 1 June 1972.