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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 1972 - 31 August 1973) 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.

The research of Professor Fried during the past year was devoted mainly to a continuing program of investigation of high-energy hadronic scattering, at both large and small momentum transfers, within the context of appropriate eikonal calculations. Some further inelastic predictions of the wide-angle hadronic bremsstrahlung model were obtained

(Ref. 268),¹ which were followed by predictions of the model for a large variety of wide-angle elastic reactions (Ref. 274); part of this material will appear in Mr. Kirby's doctoral thesis. The nature of high-energy limits to forward scattering and, in particular, examples of the inadequacy of the now-popular Cheng-Wu analysis were also studied (Ref. 266).²

In collaboration with Professors C. M. Bender and J. E. Mandula, Professor Guralnik has been investigating models of tightly bound "quarks" of the type proposed by Johnson³ within the framework of $\lambda\phi^4$ quantum field theory where the "quarks" are taken to have spin zero (Ref. 284). The basic assumption of the theory is that the matrix element $\langle \text{"quark"}, q | \lambda\phi^2 | \text{"quark"}, q' \rangle$ is singular at $(q - q')^2 = 0$ where the singularity is chosen to correspond to that of an r^2 potential; the "quarks" are thus made unavailable to measurable processes. The implications of this model for the eigenvalue spectrum and wave functions have been explored in detail in terms of a covariant differential-equation formulation of the theory. In order to simplify the model and examine further the consistency of the wave-function solutions with the assumed form of the binding singularity, Professor Guralnik and collaborators have also formulated and studied a one-dimensional model of permanently bound "quarks." They have also demonstrated that there is no inconsistency between the field-theoretic framework of the model and the basic assumption of permanent binding, despite the apparent violation of the Cluster Decomposition Theorem, since much of the structure of conventional field theories is precluded in these models (e.g., the "quark" propagator does not exist in coordinate space). Professor Guralnik and Mr. Kasdan have been examining gauge theories of weak interactions

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1. References cited are listed in Section II of this report.
 2. See also R. Blankenbecler and H. M. Fried, "Eikonal Estimates and Cancellations at High Energies," Phys. Rev. D (in press) (Report No. COO-3130TA-262).
 3. K. Johnson, Phys. Rev. D 6, 1101 (1972).

with a view toward trying to understand if it is possible to produce theories in which the physical spin-one particles become massive because of the time dependence of some matrix elements of the charge⁴ and without introducing scalar bosons into the Lagrangian; they have confirmed that this does indeed take place in the Nambu model⁵ coupled to axial electrodynamics. Finally, Professor Guralnik and Mr. Snyderman have begun a study of the use of the superpropagator technique of Isham et al.⁶ to control the divergences of field theories with the gravitational field.

In a joint effort on the part of Professor Kang and Dr. P. Shen, the single-particle distribution predicted by the dual-resonance model was analyzed systematically for the energy range presently available, i.e., from conventional accelerator to ISR energies (Ref. 267); the conclusions drawn in this work for scaling criteria and pion production are of direct relevance to experiments recently performed and in progress at ISR and at NAL. Subsequently, these authors considered inclusive vector-meson production within the context of a multi-particle dual-resonance model (Ref. 270). The factorizability of the vector-meson vertex was examined and the vertex function as well as the vector-meson production cross section were obtained in the factorizable limit; the decay correlations and the polarization states in the different kinematic regions of scaling were also studied. Motivated by the recent interesting and as yet controversial development in Regge-cut theory, Professor Kang, in collaboration with Drs. R. Moore and B. Nicolescu, has suggested the use of non-forward inclusive-type sum rules in the study of such cuts (Ref. 277); a review of the history of Regge-cut theories and related problems was subsequently presented by Professor Kang (Ref. 285). Although the detailed

4. G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Letters 13, 585 (1964). Related work with a somewhat different approach is to be found in F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964) and P. W. Higgs, Phys. Letters 12, 132 (1964).

5. Y. Nambu and G. Jong-Lasinio, Phys. Rev. 122, 345 (1961).

6. C. J. Isham, A. Salam, and J. Strathdee, Phys. Rev. D 3, 1805 (1971).

numerical values are still uncertain, the recent high-statistics experiments of K decay have cast some doubt on the use of linear parametrization of the $K_{\ell 3}$ form factors; assuming that quadratic parametrization of the form factors is indeed required, as these recent experiments indicate, Professor Kang, together with Drs. P. X. Yem and P. Pond, has derived a new theorem for the parameters of the $K_{\ell 3}$ scalar form factor (Ref. 281). Professor Kang has also prepared a set of lectures on inclusive phenomenology (Ref. 278) as well as a résumé of the current status of multiparticle models used in the analysis of high-energy data (Ref. 286). Finally, we note the completion, under Professor Kang's direction, by Dr. P. Shen of his doctoral thesis entitled, "Model Studies for Inclusive and Exclusive Processes: I. Multiparticle Production in Dual Resonance Model, II. A Bootstrap Model for the 1^+8 Meson in $\pi\omega$ Scattering," and by Dr. C.-L. Jen of his thesis entitled, "I. Unitarization of the Pion-Pion Scattering Amplitudes of Current Algebra and Veneziano's Models, II. Reggeon Amplitude and Duality Sum Rule."

The qualitative success of the short-range correlation (SRC) hypothesis for high-energy inclusive processes requires serious attention regarding its implications for exclusive multiplicity distributions. A major effort was made by Professor Tan in examining both the internal consistency of this hypothesis and its experimental validity. Accordingly, in collaboration with Professors W. R. Frazer, R. D. Peccei, and Dr. S. S. Pinsky, Professor Tan reexamined the implications of the "two-component" picture, and found that multiplicity distributions in the energy range which includes the Batavia machine is in agreement with the SRC picture if 20% low-multiplicity diffraction is added (Ref. 269). Encouraged by this result, Professor Tan began to investigate various specific consequences of the SRC hypothesis. Together with Dr. Jen and Mr. Mak, he first demonstrated that the approach to the scaling limit of the single-particle distribution is in accord with this hypothesis (Ref. 276). This

result was then elaborated and explained from the viewpoint of rapidity clusterings (Refs. 280, 282). Professor Tan and Mr. Mak then proceeded to demonstrate that the generating function of the multiplicity distribution under the Mueller-Regge hypothesis satisfies a multiperipheral-like integral equation, thus allowing one to express this distribution completely in terms of inclusive parameters (Ref. 283). In this connection, we observe that, under Professor Tan's supervision, Mr. Mak has completed his doctoral dissertation entitled, "An Integral Equation Approach for the Multiplicity Generating Function." Mr. Mak has also independently examined the structure of inclusive sum rules in the "helicity pole" limit, which are shown to lead to the concept of space-like Reggeon amplitudes (Ref. 275).

Professor Westervelt has demonstrated a one-to-one correspondence between the displacement of a particle in a pulsed gravitational wave and the motion of the particle in the field of an end-fire acoustic source. He has also cast the nonlinear equations of motion for an ideal fluid in a new form which is directly applicable to gravitational-radiation detectors (Ref. 287).

Professor Feldman and Dr. Chung have presented a unified treatment of the integral representations of the dual $\pi\pi$ partial-wave amplitudes one of the advantages of which is that the threshold coefficients for all partial waves are easily calculable; this was demonstrated in a computation of the scattering lengths and effective ranges for the s, p, d, and f waves (Ref. 272). They have also used the above representations to reduce all of the partial waves to sums involving s waves only, and to prove that the isospin-zero and -two partial waves are bounded by powers in the right half-plane of the energy-squared variable and diverge exponentially along any ray in the left half-plane; for the isospin-one waves, the derived bounds agree with those of Park and Desai.⁷ The discontinuities

7. R. T. Park and B. R. Desai, Phys. Rev. D 2, 786 (1970).

of the isospin-zero and -two partial waves diverge exponentially along the left-hand cuts and those for the isospin-one case are bounded by a power (Ref. 273). In addition, they have formulated a representation of the resonance widths of the dual $\pi\pi$ scattering amplitudes which was used to deduce the positivity conditions for the parent and the first three daughter trajectories.

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

- TA-266 H. M. Fried, "Eikonal Cancellations in a Solvable Model," Phys. Rev. D 6, 3562 (1972).
- TA-267 K. Kang and P. Shen, "Dual-Model Analysis of Single-Particle Production at Intermediate Energies," Phys. Rev. Letters 29, 1283 (1972).
- TA-268 H. M. Fried and T. K. Gaisser, "Tests of Hadronic Bremsstrahlung Production at Large Nucleon Momentum Transfer," Phys. Rev. D 7, 741 (1973).
- TA-269 W. R. Frazer, R. D. Peccei, S. S. Pinsky, and C.-I Tan, "Multiplicity Distributions Resulting from Multiperipheral Plus Diffractive Production," Phys. Rev. D 7, 2647 (1973).
- TA-270 K. Kang and P. Shen, "Inclusive Production of Vector Mesons in the Dual-Resonance Model," Phys. Rev. D 7, 164 (1973).
- TA-271 H. M. Fried, "Eikonal Mechanisms at High Energy," *Proceedings of the Cargèse Summer Institute, Corsica, France, July 1972*, in press.
- TA-272 B. K. Chung and D. Feldman, "Dual $\pi\pi$ Partial-Wave Amplitudes. I. Threshold Behavior," Phys. Rev. D (in press).
- TA-273 B. K. Chung and D. Feldman, "Dual $\pi\pi$ Partial-Wave Amplitudes. II. Asymptotic Behavior," Phys. Rev. D (in press).
- TA-274 H. M. Fried, B. Kirby, and T. K. Gaisser, "Elastic Wide-Angle (Rev) Hadronic Scattering," Phys. Rev. D (submitted).
- TA-275 S.-Y. Mak, "Unitary Sum Rules for Amplitudes Involving Space-Like Reggeons and Singularities in Pairs of Complex Helicity Variables," Nucl. Phys. (in press).
- TA-276 C.-L. Jen, S.-Y. Mak, and C.-I Tan, "Approach to Scaling in Central Region and Modified Short-Range Correlation Picture," Internal Report (1973).
- TA-277 K. Kang, R. W. Moore, and B. Nicolescu, "Cuts in the Angular-Momentum Plane and Inclusive-Type Sum Rules," Phys. Rev. D (submitted).
- TA-278 K. Kang, "Topics in the Inclusive Phenomenology," Lectures at the University of Paris, 1973.

- TA-279 H. M. Fried, "Hadronic Scattering at Small and Large Momentum Transfers," *Proceedings of the VIIIth Rencontre de Moriond, Méribel-les-Allues, France, 10-16 March 1973*, in press.
- TA-280 C.-I Tan, "Clusterings in Hadronic Production and Markovian Walk," *Proceedings of the VIIIth Rencontre de Moriond, Méribel-les-Allues, France, 10-16 March 1973*, in press.
- TA-281 K. Kang, P. X. Yen, and P. Pond, "A New Constraint for the Parameters of the $K_{\ell 3}$ Scalar Form Factor," *Phys. Letters B* (submitted).
- TA-282 C.-I Tan, "Rapidity Clusterings in Hadronic Productions," *Phys. Rev. D* (in press).
- TA-283 S.-Y. Mak and C.-I Tan, "Integral Equation Approach to the Multiplicity Distribution," *Phys. Rev. D* (submitted).
- TA-284 C. M. Bender, G. S. Guralnik, and J. E. Mandula, "Theories of Permanently Bound Quarks," *Phys. Rev. D* (submitted).
- TA-285 K. Kang, "On the Two-Reggeon Cut Problems," *Proceedings of the VIIIth Rencontre de Moriond, Méribel-les-Allues, France, 10-16 March 1973*, in press.
- TA-286 K. Kang, "High-Energy Multiparticle Models," *Proceedings of the Vème Journées de la Division de Physique Théorique de l'I.P.N. à Aussois, France, 1973*, in press.
- TA-287 P. J. Westervelt, "The Status and Future of Nonlinear Acoustics," *J. Acoust. Soc. Am.* (submitted).

III. Scientific Personnel Associated with the Theoretical Program.

1 September 1972 - 31 August 1973

D. Feldman - Professor
H. M. Fried - Professor
G. S. Guralnik¹ - Professor
P. J. Westervelt - Professor
K. Kang - Associate Professor
C.-I. Tan - Assistant Professor
B.-K. Chung - Research Associate
C.-L. Jen - Research Associate
S. C. Choi² - Graduate Research Assistant
S. Kasdan - Graduate Research Assistant
B. J. Kirby - Graduate Research Assistant
S.-Y. Mak³ - Graduate Research Assistant
S. M. A. H. Rizvi - Graduate Research Assistant
N. J. Snyderman - Graduate Research Assistant
K. S. Soh - Graduate Research Assistant

1. Promoted to Professor 1 January 1973.

2. From 1 June 1973.

3. Until 31 May 1973.