COO-3285-4
December 1972

RECEIVED BY TIC FEB 13 1973

RESEARCH IN THEORETICAL PHYSICS

Annual Progress Report

Gabor Domokos

The Johns Hopkins University
Baltimore, Maryland

April 1, 1972 - March 31, 1973

PREPARED FOR THE U. S. ATOMIC ENERGY COMMISSION
UNDER CONTRACT NO. AT(11-1)-3285

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, 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.

MASTER

YAK
3/8/73

PATENT

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

Phenomenological parton models and the short distance behaviour of hadronic scattering amplitudes were investigated. The kinematical structure of parton models (null plane dynamics) was clarified. Phenomenological interactions were investigated in the Hartree-Fock approximation. The system under consideration exhibits many-body properties including collective excitations. A model amplitude was constructed by summing over collective models in intermediate states. The amplitude exhibits approximate Regge behaviour at high energy and fixed momentum transfer. The short distance behaviour of amplitudes was investigated under the following main assumptions:

i) hadrons are "composite" objects. ii) The theory is conformally invariant at short distances. The description of composite objects in a conformally invariant framework was clarified. Explicit integral representations of n -point scattering amplitudes were constructed in the conformal limit and their momentum-space properties were analyzed, independently of specific models. It is found in particular that amplitudes in the conformal limit exhibit weak duality. Investigation of a simple model shows that physically reasonable scaling laws are obtained for amplitudes at large momentum transfers.

This Annual Report also summarises briefly the main results of earlier investigations.

MASTER

1. Preamble

This Annual Report (AR) summarises briefly the activity of the executing JHU research group over the past $3\frac{3}{4}$ years. This is done in order to comply with a request received from AEC (Dr. B. Hildebrand, Dec. 1, 1972). The contract numbers have been AT(30-1)-4076 (from April 1, 1969 thru October 31, 1971) and AT(11-1)-3285 (from November 1, 1971 to present), respectively. The research project described in the present AR started on April 1, 1969.

The research staff has consisted of Professor G. Domokos (principal investigator app. 40% avg. of full time), Dr. S. Kovesi-Domokos (100% of full time), Dr. E. Schonberg[†] (67% of full time for a period of approximately two years) and one graduate student working towards his Ph. D. degree, as research assistant.^{††}

Thus, over the $3\frac{3}{4}$ year period the average research staff has been:

Research workers with a Ph. D. degree..... ≈ 1.8 (yr. full time)⁻¹

Research assistants..... ≈ 0.44 (yr. full time)⁻¹

The average output in the form of publications of the group is computed under the assumptions that i) a research assistant may be counted as $\frac{1}{2}$ of a research worker with a Ph. D. degree, ii) the present average publication rate can be used to extrapolate the number of publications to the full contract period, ending March 31, 1973. This gives the average publication rate of the group:

$$R = 3.0 \text{ publications (yr. man full time)}^{-1}$$

The average length of a publication is approximately 6.1 equivalent Phys.

Rev. pages. (Remark. It is evident that with a group of this size, average figures are subject to considerable fluctuations, as research progresses.

Nevertheless, they provide some measure of the activity of the group.)

2. Outline of the Research

The main research interest of the group has centered around the problem of strong interactions at high energies and/or hadron structure. This problem

has been attacked along two - interconnected - lines, which can be schematically classified as follows:

1. "Model independent" investigations, mainly into the space-time structure of scattering amplitudes, using general principles. The methods applied are principally group theoretical ones.

2. Construction and analysis of simple models in order to study some general features of hadronic interactions.

Research belonging to class 1 includes investigations into a description of hadronic amplitudes in space-time, an analysis of the structure of dual resonance amplitudes, investigations into some general aspects of a quantum theory defined on null planes, and a model independent analysis of asymptotic conformal symmetry. Class 2 comprises the construction of a resonance model of inelastic lepton scattering, the study of a field theoretic model quantized on a null plane and the study of a "Parton" model.

The logical connection between these studies is visualized in a block-diagram (Fig. 1). In what follows, a brief description of these studies and their main results will be given. The reader is invited to reexamine Fig. 1 after having read the remainder of this chapter.

2.1. Background

Despite intensive research done during the past decade, the nature of strong interactions at high energies and the structure of hadrons is still largely unknown. Nevertheless, as a result of experimental and theoretical investigations, a certain pattern is emerging, which is quite suggestive.

The following is a schematic summary of some of the relevant facts.

- a) Hadronic states can be ordered into excitational sequences. Each excitational sequence contains states of the same internal quantum numbers, but of different masses and spins. As a consequence of the analyticity pro-

properties of various matrix elements, there exist smooth functions (Regge trajectories) which interpolate between the physical states. In the region of low excitations the Regge trajectories are approximately linear. There is increasing theoretical evidence that the degeneracy of the states increases rapidly (perhaps exponentially) with the mass. A direct observation of this fact is made practically impossible by the circumstance that the imaginary parts of the Regge trajectories seem to be roughly proportional to their real parts, as evidenced by the empirical total width formula:¹⁾

$$M \Gamma_{\text{tot}} \approx a (M^2 - m^2), \quad (1)$$

where $a \approx 0.13$ for $Y = 1$ baryon resonances, M and m stand for the masses of the resonance and ground state, respectively (cf. Fig. 2) (Incidentally, the slope, a , is found to be roughly independent of the isospin, but decreases rapidly with decreasing hypercharge.) There may be, however, indirect ways of observing the average properties of the spectrum, cf. section 2.5.

b) Distributions of secondary hadrons in hadron-hadron collisions decrease rapidly (roughly exponentially) at moderate transverse momenta, although (according to recent experiments done on ISR), the distribution seems to flatten out (perhaps into a power law) at large transverse momenta.

c) Inclusive semileptonic reactions ($ep \rightarrow e'X$, $\nu p \rightarrow \mu X$, etc., and - to a smaller degree of accuracy - $ep \rightarrow e'\pi X$, etc) exhibit Bjorken scaling.

By analogy with well-known composite systems bound by short-range forces (e. g. nuclei), it has been repeatedly conjectured that hadrons are composite systems, although various attempts to find constituent particles different from the presently known hadrons (quarks, etc.) have so far failed.

Nevertheless, a large amount of experimental information can be summarised in the form of a few (phenomenological) theoretical principles.

i.) Duality. Following the original work of Dolen, Horn and Schmidt, it is generally assumed that an appropriate sum over a sufficiently large set of resonances in a certain channel of a reaction amplitude is equivalent to the exchange of Regge poles in a suitably chosen crossed channel. The most consistent realisation of duality is found in the form of dual resonance models, studied extensively during the past few years. (For a recent review, cf. Fubini CERN prep. (1972). Erice lectures. et al.) It should be kept in mind, however, that duality is probably a principle which is more general than the context in which it has been studied so far.

ii.) It is generally assumed that the photon and the hypothetical "W-meson" couple to hadrons (or to their "constituents") locally. In other words, it is assumed that the matrix elements of the products of electromagnetic and weak currents taken between hadron states vanish outside their relative light cones. Bjorken scaling of the inclusive semileptonic cross sections can then be stated in various forms (all of them being equivalent from the phenomenological point of view, although not necessarily of the same predictive power.) Some of the typical statements are:

-- Matrix elements of currents obey a DGIS spectral representation, with an appropriate behaviour of the spectral density (Brandt and Preparata, cf. Brandt²⁾)

-- The commutators of current densities possess canonical singularities on the light cone (Fritsch and Gell-Mann³⁾)

-- The photon and "W-meson" couple to "structureless" constituents of hadrons ("partons"). The "partons" in turn behave as if they were (perhaps superpositions of) free particles in a limiting reference frame which moves with the velocity of light. (Feynman, Bjorken and Paschos, cf. also Kuti

and Weisskopf⁴⁾)

Lacking any consistent theory of hadronic interactions, it seems reasonable to investigate the consequences of such principles in the hope that either a sufficiently rich structure will be discovered (leading, ultimately, to a theory of reasonable predictive power), or one may discover a contradiction which perhaps forces one to modify one or more of the "well-established" present theoretical concepts.

Remark: In what follows, it will be always assumed that the scattering operator is invariant under inhomogeneous Lorentz transformations; the consequences of any other principle are investigated in that framework.

2.2. The problem of a space-time description of hadrons

The discovery that relativistic invariance and analyticity properties of matrix elements (as abstracted from field theoretical models) necessarily lead to families of Regge trajectories,⁵⁾ is certainly not a new one. However, it has been realised relatively recently that it has some non-trivial consequences as far as the description of hadronic states is concerned.

Apart from technical details, these consequences are the following.

a) One can assign a local "field" to hadronic excitational sequences, which transform according to infinite dimensional representations of covering group of the homogeneous Lorentz group, $SL(2, c)$. This is a generalisation of wellknown results about "elementary" fields entering a Lagrangian theory. (It should be observed that $SL(2, c)$ is shown to be only the minimal group describing degenerate hadronic states. Other physical principles, such as strict local duality, require larger degeneracy groups, of which $SL(2, c)$ is a subgroup.)

b) It can be shown⁵⁾ (and has been amply demonstrated in the literature) that the lowest-lying excited states of hadrons can be consistently described

in terms of reducible representations of the approximate degeneracy group, $SL(2, c)$.

In order to fully exploit the consequences of the physical principles just stated, it was imperative to create an appropriate technical framework. This was done in two papers⁶⁾. It was shown in particular that the Gel'fand-Naimark formalism, utilizing a space of homogeneous functions (and other spaces isomorphic to them) gives an appropriate formalism which can accommodate simultaneously the requirements of local interactions (with e. g. the electromagnetic field) and the existence of infinite excitational sequences of hadrons.

In order to illustrate the main idea of the papers just quoted, let us consider any conventional local field operator, say $A_\mu(x)$, where $A_\mu(x)$ describes a vector meson. One notices that A_μ transforms according to the $(j_1, j_2) = (\frac{1}{2}, \frac{1}{2})$ representation of the homogeneous Lorentz group. Instead of considering $A_\mu(x)$, one may just as well consider other, more convenient, labeling of the "spin" indices. In particular, by contracting A_μ with the lightlike vector:

$$\pi_\mu = \xi \sigma_\mu \xi^\dagger,$$

(2.2)

where $\xi = (z, 1)$, one arrives at "fields" $A(x, z, \bar{z})$. The important point is that "fields" of the type $A^{(j_1, j_2)}(x; z, \bar{z})$ can be consistently defined for any representation (j_1, j_2) of $SL(2, c)$, thus providing the framework for the local description of infinite sets of - approximately degenerate - Regge trajectories.

In particular, a set of Feynman-like diagram rules could be formulated for "composite" hadrons.

Remarkably, the introduction of the Gel'fand-Naimark labeling of "spin" has also lead to a hitherto unsuspected unification of the representations of

(by putting
 $SL(2, c)$, "elementary" and "composite" fields on the same footing⁷⁾.

2.3. Composite fields and duality: generalised dual resonance models

Consider the (generally off-mass-shell) scattering amplitude of composite states as described in the previous section.

What are the principal requirements such an amplitude has to satisfy? In addition to the usual requirements of Lorentz covariance, etc., one's physical intuition dictates that such amplitudes have to be analytic functions (in a suitably large domain) of the representation labels characterising the external "legs". From a physical point of view, such a requirement is necessary in order to have suitable factorisation properties of multiparticle amplitudes, together with general Regge behaviour.

A set of reaction amplitudes were constructed satisfying these requirements ("fully Reggeized amplitudes".)

If, in addition, a resonance dominance requirement is imposed on such amplitudes, they turn out to be locally dual; in fact, one obtains a set of generalized Virasoro amplitudes.⁸⁾

Thus, the main result of this investigation can be stated schematically as follows:

From a technical point of view, the construction of fully Reggeized amplitudes is equivalent to the construction of analytic covariants of the group $SL(2, c)$. To our knowledge, the procedure leading to their construction has not been described previously (except for the two-point function, which was known in the mathematical literature).

The detailed study of such amplitudes⁹⁾, (done mainly by the MIT, Yale and University of Rome groups) clarified a number of their properties. Besides manifest crossing symmetry, (which follows automatically from the analyticity properties) the following main physical properties were found:

- i) Oscillator-like spectrum
- ii) Factorisation of pole residues
- iii) Finite degeneracy of poles (absence of "ancestors")
- iv) Exponentially increasing level density (suggesting "infinitely composite" hadrons). The level density increases somewhat more rapidly than in Veneziano-type models.

Unfortunately, the amplitudes suffer of similar diseases as other dual resonance amplitudes. (A recent paper by Sciarrino et al⁹⁾ raises some hope that part of these can be cured.) Nevertheless, it is remarkable that a simple set of physically well-motivated assumptions leads to reaction amplitudes enjoying so many reasonable properties.

2.4. Quantum theory on null planes.

The purpose of this investigation was twofold. First, we wished to generate models (starting from standard Lagrangian field theory, treated in the usual, formal way) on which one can understand certain aspects of purely hadronic and semileptonic processes (Bjorken scaling, the "exponentiation" of operators, characteristic of dual models, etc.). Second, we wished to clarify general features of null-plane quantum theory (cf. ref. 4 for a general review), with the purpose of seeing whether it is more suitable for calculations in hadron physics than standard formulations. In particular, we wished to clarify whether "nonrelativistic intuition" can be used to generate phenomenological interactions, beyond those obtained by transcribing local Lagrangian models. Such a hope arose some time ago after it was discovered by Dirac¹⁰⁾

(and rediscovered in the works of the Stanford group¹¹⁾) that null-plane quantum theories possess a Galilean structure in transverse space.

a) The Langrangian model considered¹³⁾ was a "quark"-model, with Nambu-Jona-Lasinio¹²⁾ interaction, $\mathcal{L}_{int} = \int [(\bar{\psi}\gamma_{\mu}\psi)^2 - (\bar{\psi}\gamma_5\gamma_{\mu}\psi)^2]$

This theory is not renormalisable in the conventional perturbation theoretic treatment. It has, however, the advantage that it can be easily manipulated in a null-plane quantisation.

The study of this model leads to the following qualitative conclusions.

i) Denote by φ the two-component object which can be independently quantised on the null plane chosen. Elimination of the constrained components of ψ leads to an effective exponential interaction in φ . (This "exponentiation" of the interaction is now known to be model-dependent. However, it is suggestive that were "quarks" the fundamental fields, such an exponentiation does indeed take place.)

ii) The exponential interaction contains bilinear expressions of φ and φ^+ , which can be interpreted as collective fields. However, we were unable to find transverse collective excitations, which seem to be essential in physically reasonable theories.

iii) It is found that the commutators of the current densities possess canonical singularities on the light cone (Bjorken scaling), provided the ground state is strongly degenerate.

This result is interesting from several points of view. In particular, studies of other models (dual resonance models among others) also suggest that a realistic description of hadronic processes necessitates the consideration of theories with degenerate ground states. We plan to investigate this point further in the future.

b) General properties^{14, 15, 16)} (in particular, space-time symmetry

properties) of null plane quantum theories were investigated. It was discovered, among other things, that the stability group of a null plane (or, equivalently, the lightlike longitudinal momentum) contains an $SU(1,1)$ subgroup. As a consequence, n -particle systems exhibit collective oscillations¹⁷⁾ which are analogs of the Goshen-Lipkin collective oscillations in nonrelativistic many-body physics.¹⁸⁾ Thus it is very tempting to identify (in some, so far unclarified sense) the "harmonic oscillator operators" of dual models with Goshen-Lipkin collective operators of a many-body (many-parton?) system. A phenomenological model was constructed¹⁹⁾ (with a null-plane Hamiltonian composed of the appropriate generators of this $SU(1,1)$ subgroup.) The result, however, is somewhat disappointing. We found that Lorentz covariance is extremely difficult to maintain, unless one works in a Hartree-Fock approximation (as we did). In particular, beyond the first non-trivial Hartree-Fock approximation, the modifications in the effective interaction required by Lorentz covariance make calculations extremely awkward.

Because of this circumstance, unless a radically new and simpler approach is discovered, at the moment we do not plan to pursue this research further.

2.5. Resonances in inelastic lepton scattering: collective aspects of hadronic excitations.

Given the hints obtained on the basis of various models that hadronic excitations exhibit collective aspects, the question arises: can one verify from experiment the (qualitative) correctness of this picture? The cleanest tests are offered by inelastic lepton scattering experiments.

It has to be realised that so far the predictions of the various models can be taken-at best- as qualitatively correct. Therefore, in order to be able to compare the results of a model with experimental data, certain phenomenological assumptions have to be made.

The main assumptions made (abstracted from models of the types described in the previous Sections) were the following. (See ref. 25 for a review.)

i) Hadrons behave as a complicated many-body system does. In particular, they possess "collective excitations" of increasing widths (as reaction channels keep opening up), see Sec. 2.1.

ii) Due to the increasing overlap of resonances, it is only certain average quantities which are physically significant. Therefore, the theory should be formulated in terms of such, suitably defined averages.

iii) As a consequence of the practically random behaviour of the system (very large number of channels open), the excitation mechanism should be more-or-less independent of the projectile. Hence, several aspects of purely hadronic reactions are reflected in electro- and neutrino-excitations.

In particular, one expects diffractive and resonance ("collective") excitations to be separable to a large extent. (cf. "two-component duality" in purely hadronic reactions)

On the basis of general considerations, one expects resonance excitation to dominate the semileptonic cross sections in the "deep inelastic" region, $1-x \ll 1$, where (in the usual notation) $x = -q^2(2m\nu)^{-1}$.

A "resonance model" of inelastic lepton scattering has been constructed, based on the physical assumptions just spelled out.²⁰⁻²⁵ The model gives a one parameter - fit to all the inelastic structure functions of electro - and neutrino - excitation reactions. By comparing the results with the available experimental data, one learns the following.

1) Good agreement between theoretical predictions and available experimental data (both for $ep \rightarrow e'X$ and $\nu(\bar{\nu})W \rightarrow \mu(\bar{\mu})X$) is obtained in the interval $1 \gg x \gtrsim 0.3$, cf. (Figs. 3, 4) For $x \lesssim 0.3$ apparently, diffraction takes over.

2) The theory predicts the polarisational asymmetry in polarised beam-polarised target experiments, cf. Fig. 5. The results disagree with the "free parton" prediction. Hence such experiments to be performed at SLAC and NAL in the foreseeable future, should be able to distinguish between the "free particle" ($\approx$ parton) and "collective" ($\approx$ resonance) models of hadronic excitations. Perhaps the same result could be achieved if the accuracy of neutrino experiments (Gargamelle, NAL?) were increased to the point where the structure functions W_3 , W_4 can be reliably extracted from the data, cf. Fig. 6.

3) The theory can be further tested (in a somewhat indirect way) by computing its prediction of the hadronic contribution to the hyperfine structure of the H-spectrum. The predicted value is well within the experimental limits.²⁶⁾

4) Excitation functions of well-distinguished (low-lying) nucleon resonances should obey a certain scaling law, at least approximately. Comparison with the available (not very accurate) data seems to verify this prediction, cf. Fig. 7.

5) The resonance model does not automatically predict the presently observed ratio²⁷⁾ $W_2(\text{neutron})/W_2(\text{proton})$, (in particular near $x \approx 1$) although it can accommodate it. If the "collective excitation" picture is at least qualitatively correct, one should expect the average form factors of the neutron to fall off more rapidly than those of the proton for large q^2 .

6) The resonance model does not "saturate" the Adler sum rule²⁴⁾. As a matter of fact, the value of the Adler integral predicted by the resonance model is somewhat closer to the experimental number than the value predicted by the "free quark model". Unfortunately, presently available data are not sufficiently accurate to allow a clear distinction. The question of the saturation of the Adler sum rule has recently attracted some attention; further investigations into this matter may be in order.

7) The resonance model predicts that the Bjorken limit of the structure functions is the semi-local average of individual resonance excitation functions. This phenomenon has been discovered independently (by a careful study of the SLAC-data) by Bloom and Gilman²⁸⁾. As an amusing by product of these investigations, one finds that nuclear structure functions obey the same kind of "duality", cf. ref. 25) for an approximate verification.

2.6. Asymptotic conformal invariance

This research begun last year and so far only its first results are available at the time of this writing.

There is reason to believe that off-mass-shell scattering amplitudes are asymptotically invariant under conformal transformations.²⁹⁾ If this were indeed the case, one would have a powerful tool to investigate the short distance behaviour ($\approx$ scaling properties) of current matrix elements. In addition, the short distance (large momentum) behaviour of the matrix elements plays a decisive role in the determination of the structure of any (future) dynamical theory.

Investigations were undertaken in order to explore the consequences of asymptotic conformal invariance of scattering matrix elements. Instead of investigating specific models, however, so far the general structure of hadronic matrix elements was investigated, under the compositeness assumption discussed in the previous sections. (A similar, model independent investigation had been undertaken by Gatto and his collaborators³⁰⁾ some time ago. However, those authors investigated the restrictions imposed by conformal invariance on Wilson expansions of operators. Hence their method is not suitable to take compositeness conditions explicitly into account.)

The two main results of the investigations performed so far are:³¹⁾

1) Asymptotic conformal invariance leads to an integral representation of scattering amplitudes, independently of any specific dynamical scheme. The integral representation predicts that scattering matrix elements scale according to power laws at large energies and momentum transfers. This seems to agree qualitatively with recent experimental results concerning inclusive reactions. A quantitative comparison has not been possible yet, due to our present lack of understanding of the mechanism by which the asymptotic symmetry is broken.

2) The short distance limits of the amplitudes are automatically dual in a certain generalised sense. (Evidently, one cannot expect duality to hold in the same sense as it does e. g. in the Veneziano model, since in the conformal limit the amplitudes have a purely continuous spectrum.) Thus duality appears to hold both in the short distance limit and in the limit of a purely discrete spectrum. (Veneziano model.)

2.7. Conclusion and outlook

As a result of the investigations outlined here, one begins to see a definite pattern of hadronic interactions emerging. In particular, one finds that apparently, duality (in some general sense) plays a decisive role in the dynamics of hadrons, even at short distances. At the same time, hadrons seem to behave as complicated many-body systems do.

At present, lacking any, even approximately consistent, dynamical scheme, in our opinion it is justified (or even necessary) to continue the investigation of the general properties of such relativistic "many-body" systems. In fact, unless analogies taken from non-relativistic many-body systems³²⁾ and model field theories prove to be completely misleading, the observable physical properties of such systems are largely independent of the specifics of the underlying dynamics. The decisive role seems to be played however by the various symmetry properties of the system.

Footnotes and References

† Dr. E. Schonberg (presently at Yeshiva University) from 7/1/1969 thru 6/30/1971.

†† Dr. F. Mansouri (presently at Yale University), from 7/1/1969 thru 6/30/1970

Mr. B. C. Yunn, from 6/1/1971 to present. Mr. Yunn is expected to complete his thesis before the end of the current academic year.

1. Cf. e.g. ref. 25.
2. R. Brandt, lectures at Erice Summer School, CERN preprint (1972).
3. Fritsch and M. Gell-Mann, in Center for Theoretical Studies, University of Miami Tracts in Mathematics and Natural Science, Vol. 2, (Gordon and Breach, New York, 1971)
4. A concise review of parton models can be found in "Symposium on Electron and Photon Interactions at High Energies" - Cornell U. (1971) by K. G. Wilson.
5. Cf. G. Domokos and M. Toller, Talks at Nobel Symposium VIII for a review. (Wiley-Interscience, New York, 1969).
6. G. Domokos, S. Kövesi-Domokos and E. Schonberg, Phys. Rev. D2, 1026 (1970).
7. I. Bars and F. Gürsey, Jour. Math. Phys. 13, 131 (1972).
8. G. Domokos, S. Kövesi-Domokos and E. Schonberg, Phys. Rev. D2, 1026 (1970).
9. E. Del Giudice and P. DiVecchia, MIT preprint
I. Bars and F. Gürsey, Phys. Rev. D4, 1769, (1971).
R. Musto, F. Nicodemi, M. L. Paciello and B. Taglienti, Nuovo Cim. 7A, 407 (1972).
M. L. Paciello, A. Sciarrino, B. Taglienti, U. of Rome preprints, No. 386, 388 (1972).
S. W. MacDowell and R. Roskies, Jour. Math. Phys. (to be published).
10. P. A. M. Dirac, Rev. Mod. Phys. 21, 392, (1949).
11. J. B. Kogut - D. E. Soper, Phys. Rev. D1, 2901 (1970).
12. Y. Nambu and G. Jona - Lasinio, Phys. Rev. 122, 345 (1961); ibid. 124, 246 (1961).
13. G. Domokos, Phys. Rev. D4, 3708 (1971).

14. G. Domokos, in Lectures in Theoretical Physics, Vol. XIVA, (A. O. Barut and W. E. Brittin, editors) Colorado Associated University Press, 1972.
15. B. C. Yunn, C00-3285-3 (1972) Nuovo Cimento (accepted for publication).
16. G. Domokos, Commun. Math. Phys. 26, 15, (1972).
17. E. Del Giudice, P. DiVecchia, S. Fubini and R. Musto, MIT preprint CTP271, (1972).
18. S. Goshen and H. J. Lipkin, Ann. Phys. (N. Y.) 6, 301 (1959).
19. G. Domokos and S. Kövesi-Domokos, C003285-1, 1972. (JHU technical report, unpublished.).
20. G. Domokos and S. Kövesi-Domokos, Nuovo Cim. 2A, 270 (1971).
21. G. Domokos, S. Kövesi-Domokos and E. Schonberg, NYO-4076-11 (1970). Unpublished.
22. G. Domokos, S. Kövesi-Domokos and E. Schonberg, Phys. Rev. D3, 1184 (1971).
23. G. Domokos, S. Kövesi-Domokos and E. Schonberg, Phys. Rev. D3, 1191 (1971).
24. G. Domokos, S. Kövesi-Domokos and E. Schonberg, Phys. Rev. D4, 2115 (1971).
25. G. Domokos, S. Kövesi-Domokos and E. Schonberg, Fields and Quanta (to be published).
26. D. Jensen, S. Kövesi-Domokos and E. Schonberg, Phys. Rev. D5, 1398 (1972).
27. A. Bodek et al, paper presented at the ~~XVI~~^{XVII}th International Conference on High Energy Physics, Chicago, 1972.
28. E. D. Bloom and F. Gilman, Phys. Rev. Letters 25, 1140 (1970).
29. See the recent review by G. Mack, University of Bern preprint (1972).
30. S. Ferrara, R. Gatto and A. F. Grillo, Frascati report, LNF - 71/79 (1971).
31. G. Domokos and S. Kövesi-Domokos, C00-3285-2 (1972), Nuovo Cim. (accepted for publication).
32. ~~S~~^B. B. Kogut and K. G. Wilson, Princeton U. lecture notes (1972).

Figure captions

Fig. 1. Block diagram indicating the logical connections between areas of investigation.

Fig. 2. Total widths of $Y=1$ baryon resonances. $I=\frac{1}{2}$, $3/2$ states marked by circles and triangles, respectively.

Fig. 3. Structure function νW_2 of proton together with a sample of SLAC-MIT data in electroproduction. For comparison, the function νW_2 in neutrino-production is plotted on the same scale.

Fig. 4. Predicted and observed event-rate in the CERN neutrino experiment. (Target is assumed to consist of equal number of free protons and neutrons.)

Fig. 5. Predicted polarisational asymmetry for polarised target-polarised beam electroproduction experiment in the scaling region

$$A = (d\sigma_{\uparrow\uparrow} - d\sigma_{\uparrow\downarrow}) (d\sigma_{\uparrow\uparrow} + d\sigma_{\uparrow\downarrow})^{-1}$$

Fig. 6. Calculated value of W_3 for neutrino-production.

3. Computing facilities

The group has access to the computer IBM 7094 located at the JHU Computing Center. (Some ^{minimal} departmental funds are available for that purpose.). Through cooperative assistance received from the JHU High Energy Group, we have had access to the XDS Sigma 7 computer used by that group. We expect this cooperation to continue in the future. For the purposes of shorter calculations, the group has also access to the University-owned PDP-11 computer. There is an adequate number of various calculators in the Department, which the group can use on an unlimited basis.

4. Budget and University Support

Enclosed is a copy of the present working budget indicating University support to the research performed under this Contract. The level of the University support for the next year will increase from 6.5% to 9% for the principal investigator's salary.

"Model independent"
investigations

Models

Space-time description
of
hadrons

Fully Reggeized
amplitudes

Duality
at
short distances

Null-plane
theory

Resonances
in inelastic lepton
scattering

Interacting
parton model

Fig. 1.

Fig.2.

Fig. 3.

Fig. 4.