Theoretical Research in Elementary Particle Physics

Y. NAMBU has kept up his interests in the Veneziano (dual resonance) model. The key paper he read on this subject at the Wayne University Conference (1969) has now been published. In an invited talk at the American Physical Society in Chicago he proposed a dynamical model of hadrons as a natural outgrowth of the above work. As was already described in last year's report, the hadrons according to this picture have a molecule-like structure consisting of fundamental triplets (the Han-Nambu or DNA triplets) bound by "elastic strings", which are responsible for the duality of scattering amplitudes. These ideas were further developed in an article (Duality and Hadrodynamics, unpublished) originally prepared for the Copenhagen High Energy Symposium, in which he contemplated the possibility that the elastic strings themselves were ordered chains of fundamental triplets which in the space-time picture form a two-dimensional lattice.

With Freund and Chang, he considered a statistical approximation to Veneziano amplitudes in which "energy" (actually the channel variable s) is replaced by "temperature". This kind of approach promises to give a new and well-defined way of handling high energy phenomena in general. For example, the pomeron problem may be understood in terms of canonical or grand canonical ensembles of resonances.

*References given in the text are to the list of publications at the end of this report.
†Research described in the following pages was supported by AEC Contract AT(11-1)-264.
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.
The same method was used in his recent work with A. Hacinliyan on the inelastic electron-proton scattering. They obtained from the Veneziano model a simple asymptotic formula for the structure functions which showed satisfactory agreement with the SLAC data. Another paper is in preparation dealing with the problem of factorization for arbitrary external momenta, as is the case with electromagnetic interaction.

At the symposium "The Past Decade in Particle Theory" held at the University of Texas, he gave an invited talk reviewing the development and use of the concept of spontaneous breakdown of symmetries in particle physics since the early 60's.

M. Yoshimura considered in his thesis work the difficult problem of introducing the quark field into the Veneziano model. The main problem is to split the masses (spin-orbit coupling), eliminate parity doubling and the ghosts (negative probability states).

The method followed is slightly different from that of Freund (see below). The result was only partially successful in that the ghosts could not be completely eliminated.

The work Nambu and Yoshimura had done on the determination of the axial vector form factor of nucleon from electropion production has been published.

T. H. Chang's thesis work dealt with a theoretical analysis of the Dalitz process \((\pi^0 + \gamma + e^+ + e^-)\) and the generalized Primakoff effect \((\gamma + p + p + \pi^0 \text{ or } p + A_1^1)\) from the viewpoint of PCAC.

*Present address: University of California, Berkeley.

†Present address: International Institute for Theoretical Physics, Trieste, Italy.
Since they involve virtual photons, we get more insight into the structure of the axial vertex functions. A comparison with experiment casts some doubt about Adler's modified PCAC condition.

Y. M. Lam in his thesis paper studied the current algebra relations from the standpoint of dispersion theory under the assumption of single particle dominance but using more rigorous arguments than is usually done. He derives in this way various sum rules including Weinberg's, but finds that the Kawarabayashi-Suzuki relation is incompatible with them.

J. Willemsen studied the question of constructing Lovelace-type amplitudes for n pions, as this is highly desirable from the current algebra point of view. With operational techniques he discussed various schemes, although they were not very satisfactory. (See also Frampton, below.) For his earlier work on p-ω mixing, see R. G. Sachs below.

G. Barry wrote an article on the hypothesis that the Pomeranchuk trajectory, representing diffraction scattering, has a completely different nature from the normal resonance trajectories in that the former is independent of the mass scale of the resonances, and possesses the property of chiral (helicity) invariance. Some predictions are made on this basis.

P. G. O. Freund was engaged in work on dual hadrodynamics and on scale invariance and related topics. In a paper with L. N. Chang he showed that if the trace Θ of the energy momentum tensor were

*Present address: University of Pittsburgh.
dominated by SU(3)-nonet poles only, a contradiction would obtain. To avoid this a "tenth component" of \( \theta \) was introduced. (Similar results were obtained independently by P. Carruthers and M. Gell-Mann.) This predominantly SU(3)-singlet piece was shown to be saturated by background rather than meson poles. Field theories in which scalar mesons couple to the divergence of the dilation-current were also studied in this paper.

The diffraction mechanism suggested last year\(^{39}\) on the basis of the quark model was further investigated.\(^8\) The contribution of exotic hadrons was shown to be essential.

The rest of Freund's work concerns the dual resonance models. The models originally considered correspond to a quark model with spinless, SU(3)-singlet quarks. While SU(3) is readily incorporated in the model, the incorporation of spin (as usually) is non-trivial.

A detailed factorised dual resonance model that is SU(6)\(_w\) x 0(2)\(_Lz\) symmetric and avoids parity doubling by fixed branch points in the complex angular momentum plane has been constructed.\(^9\) The new aspects of duality due to the presence of these fixed branch points were explored.

It was found earlier (Freund and Rivers, above) that duality requires the existence of exotic hadrons, i.e. of hadrons of zero triality but of arbitrarily large total quark number (i.e. number of quarks + number of antiquarks). With Frampton\(^{10,11}\) he constructed a dual resonance model that includes exotic hadrons while respecting the earlier selection rules.\(^{40}\) The quarks and antiquarks must appear
only in certain very symmetric patterns\textsuperscript{11} in exotic hadrons if the theory is to be dual. They also found\textsuperscript{10} that all strong coupling constants (even any allowed exotic-exotic-exotic coupling) are fixed once one, say the $\rho\pi\pi$ -coupling, is known. This includes many known universality principles such as vector and tensor meson dominance. They also show that not all couplings of the exotic hadrons can be suppressed. The uniqueness of the model is forced on us by its conformal invariance that leads to duality. It is this conformal invariance that leads to the simplifying feature, namely that all active quarks must focus to a point at a hadronic vertex.

A. Ferber\textsuperscript{35} has made a detailed Regge pole + cut analysis of high energy meson-baryon scattering (including the Serpukhov data). He has shown that no good fit to the data emerges if one computes the Regge-cut contributions with the usual technique. That some people had obtained acceptable fits in the past is due to their introduction of ad hoc large Regge-cut terms.

H. C. Tze, under the actual supervision of Dr. S. Fenster (Argonne National Lab), has been working on the various mathematical problems concerning the dual resonance model. For the thesis, he is now investigating several problems, such as the properties of loop diagrams and their relation to the Pomeron.

REINHARD OEHME worked on a variety of subjects. Duality: The work has now been published.\textsuperscript{12} In the meromorphic limit, it provides a definition of the concept of duality in its relation to Regge
asymptotic behavior, and in the presence of unitarity branch
cuts, it assesses the meaning and the implications of duality.
This paper formed the basis of lectures on duality and Regge
theory, which he gave at the International Summer Institute for
Theoretical Physics in Heidelberg. Recent experiments on spin correlations in lambda beta decay seem
to give indications of deviations from the universal SU(3)-scheme.
For the purpose of speculations about possible causes for these
discrepancies, he found it helpful to introduce a way of analysing
the data in which their dependence upon specific form factors is
exhibited. In a joint paper entitled "Remarks on the Beta Decay
of Hyperons", he suggests particular functions of the presently
observed, integrated correlation coefficients. These functions
are constructed to be either particularly sensitive to the induced
tensor or pseudo tensor form factors, or to the vector-axial vector
interference term. These functions will be used in order to analyse
the preliminary experimental results of Romanowski and Winston. Within the
framework of V-A interactions, they find some indication for an
induced pseudotensor term. They also consider other possibilities,
including models with CP-violation. But irrespective of the outcome
of present and future experiments, these functions are of interest
as an analytic means for assessing the data.
Complex Regge Trajectories and Branch Cuts: In previous work
(Phys. Lett. 30B, 414 (1969)), Oehme had shown that Regge trajectories
can have left hand branch lines only as a consequence of the crossover
of two or more pole trajectories, and that one can use fixed or
moving branch points in the complex $\lambda$-plane in order to remove unwanted branches of these trajectories from the physical sheet. In a new paper,\textsuperscript{15} he discusses the general features of such pole-cut relationships, and described the possible shapes of the resulting physical trajectories. He also pointed out the relevance of the complex pole-cut structures for the description of amplitudes which do not satisfy the Pomeranchuk theorem.

In a separate paper,\textsuperscript{14} he described models for diffraction scattering which contain complex Pomeranchuk trajectories and moving branch points. The branch points are those which are naturally generated by the complex poles. Consistency requires that, in the neighborhood of the forward direction, the pole and the cut trajectories are of the same form $\alpha(t) = 1 \pm \text{const.} \sqrt{t} + \cdots$. The high energy behavior obtained with these $\lambda$-plane singularities is most interesting and physically intuitive. It is given by a finite superposition of Bessel functions which correspond essentially to absorptive (and emissive) rings with logarithmically increasing radii.

The complex pole-cut systems can be used in positive and negative signature amplitudes. They give rise to rather general models for amplitudes which violate the Pomeranchuk theorem, but which comply with the essential analytic and unitarity requirements in the direct channel and in the complex $\lambda$-plane corresponding to the crossed channel. These results concerning these models have been presented at the International Summer Institute for Theoretical Physics in Heidelberg (July, 1970), and they are being published as part of lecture notes entitled "Complex Angular Momentum."\textsuperscript{17}
These lecture notes also contain discussions of other topics of recent interest.

Further work is in progress concerning diffraction scattering, weak interactions, and other problems. In particular, he has shown that, for amplitudes which violate the Pomeranchuk theorem, it is easy to construct models without oscillations in the differential cross-section if only direct channel properties are considered. The situation is quite different if also crossed channel $t$-plane properties are taken into account.

R. F. Amann* has now published his thesis on Regge cuts and Veneziano model parametrisations of pion nucleon amplitudes. He has continued this work by exploring the influence of Carlitz-Kislinger cuts on the fits for pion-nucleon backward scattering. 29

A. Garcia Gonzalez has done extensive work on the analysis of recent experiments for lambda beta decay. He has completed his thesis which contains explicit formulae for all correlation coefficients of the present experimental data. In particular, he also studies the influence of scalar and tensor interactions.

D. D. Friedman is now writing up his thesis on models for diffraction scattering which involve fixed poles and related shielding cuts. He uses continued unitarity in the crossed channel in order to relate the discontinuity of the moving cut to the residuum of the pole.

*Present address: Syracuse University.
R. G. Sachs' interests have been primarily in electromagnetic and weak processes. The analysis with J. Willemsen of $\rho - \omega$ interference taking account of the special features of the propagator for vector particles and comparing the results with some experiments on electron-positron and strong interaction production processes has been published.\textsuperscript{41} (See also a paper by Willemsen.\textsuperscript{31})

There are many new interference experiments requiring further analysis and interpretation. In particular, vector meson photoproduction from nuclei has been observed by means of the electron-positron decay mode and by means of the $\pi^+\pi^-$ decay mode of the vector mesons. The precision of the experiments is such that the interference phenomena are very clear. A comparison of the two makes possible an independent determination of the production phase and the intrinsic mixing phase. Methods for amplifying this analysis are being developed with J. Lemke.

Experimental results on CP violation indicate more and more strongly that the phenomenon is an indirect one, i.e., that it appears only through the dispersive terms in the mass matrix. This suggests that strong CP violating effects may appear in high energy neutrino experiments. Methods for carrying out tests of CP, CPT and T by means of high energy neutrino experiments are being studied.

Some of Sachs' time has been devoted to reviewing the activities and plans for work in the U.S. on elementary particle physics in connection with the Elementary Particle Physics Panel. The results will be published as part of the report of the Physics Survey Committee of the NAS.
R. M. Barnett*, under the actual supervision of Dr. R. Arnold (Argonne National Lab), has written a paper on the Regge-Eikonal model of scattering. (Preprint ANL-HEP-7021). The result showed some lumps in total cross sections (in $\pi-\pi$ and $\pi-N$ processes) associated with Argand loops, and some improvements in Schmid's duality, but the effect was too small to be useful. He is now working on a thesis dealing with the possible role of exotic states in high energy processes.

W. K. TUNG joined our faculty in the latter half of the year. He had been interested in various problems concerning electromagnetic and weak processes at high energy, such as have been experimentally studied or are being planned at SLAC and NAL. For example, he had done work on low energy theorems and the problem of fixed poles in virtual Compton scattering, and on a complete kinematic analysis of lepton-hadron scattering using the Brick Wall frame, which enables one to write down differential cross sections in such a way as to exhibit and test the basic V-A nature of weak interactions.

With P. Frampton, he applied the same basic technique to the problem of hyperon beta decay, which is now drawing people's attention (see Oehme above). Tung intends to continue his work along the same general line of problems, maintaining close touch with the experimental activities at Chicago and NAL.

P. Frampton† continued his activity in the dual resonance model. He showed how an n-point dual amplitude with satellite terms could

*His financial support has been transferred to ANL.
†Present address: CERN.
be factorized by introducing an infinite set of scalar harmonic oscillators. Using this formalism he and R. Rivers examined the single planar loop diagram and found that the problem of divergence becomes more serious, and cannot be eliminated by manipulating the coefficients of the satellite terms.

With Gardiner (Syracuse U.) he derived conditions for Regge behavior when a scattering amplitude is an absolutely convergent series of Veneziano terms.

With L. N. Chang and A. P. Balachandran (Syracuse U.) he derived "No-Go" theorems which explain why one cannot eliminate the unphysical tachyon states in a general n-point amplitude (with positive Regge Intercepts, as in the case of n-plon amplitude) by a simple multiplicative modification of the usual amplitude. (See also Willemsen above.)

Frampton also collaborated 1) with Freund and others on the problem of many-quark systems (see Freund above), and 2) with W. K. Tung in a paper on hyperon beta decay (see Tung above).

R. Rivers' interests have also been in the dual resonance model. Besides the work with Frampton (above), he studied various properties of n-point amplitudes with satellites. He found that the Ward-like identities which were useful in eliminating ghosts from the usual Veneziano amplitudes did not help in the more general case. This makes, in his opinion, the satellite terms highly unphysical and objectionable. In another paper he showed that the level degeneracy of a satellite terms goes like $\sim \exp[bn^\gamma]$, as $n \to \infty$, where $\gamma = 1 - 1/2k+1$, $k = 1, 2, \ldots$. 

* Present address: Imperial College, London.
L. N. Chang collaborated with others on the statistical approximation to the Veneziano amplitudes (see Nambu above), on dilation currents (see Freund above), and on a "No-Go" theorem (see Frampton above). Recently he has been working on a geometrical interpretation of the harmonic oscillator (elastic string) description of the amplitude using the theory of minimal surfaces. This may throw light on such problems as ghost elimination and introduction of spin. He is also engaged in the study of high energy limits in various field theoretical models following the work of Chang and Wu, which makes use of canonical transformations in the infinite momentum frame. Because of its resemblance to the infra-red problem, coherent state formalism may prove to be useful. Another line of work he is interested in is an S-matrix study of massless particles without treating them as the limit m → 0 of massless particles.

K. Fujikawa* has finished a paper 37 on high energy weak leptonic processes \( \nu + p + \mu + p + \mu + \bar{\mu} \) and \( \bar{\mu} + p + \bar{\mu} + p + \nu + \bar{\nu} \). This is a continuation of his thesis work. With contact four-fermion interaction he finds an interesting feature different from that of the intermediate boson interaction.

He has most recently turned his attention on the deep inelastic e-\( p \) processes. He is examining several different lines of attack, such as a phase representation of production amplitudes (which has the problem of complex singularities in the photon mass), generalized

* New research associate.
vector meson dominance model with an infinite series of vector mesons universally coupled to the electromagnetic current, and the relation of scaling behavior to the widths of excited resonances. One gets in this way a clearer understanding of the various models that have been proposed.

F. Mansouri* before joining us, had worked on the dual resonance model. He is at present studying the group theoretic significance of various operators in the model. In particular he is looking for a scalar product defined on a representation of SL(2,R) which preserves the self-adjointness of dynamical variables. In this way he hopes, for example, to find a way of incorporating spin in the model.

He is also interested in the question of helicity conservation in high energy scattering. For this purpose he is examining the non-dual model with spin which he had constructed earlier.

C. Carlson* had been interested in the elponal approximation to the scattering of a Dirac particle by a neutral pseudoscalar field. Contrary to a naive expectation, he found the surprising result that the lower order diagrams do not dominate at high energy, and the perturbation series does not converge. (C. E. Carlson and T. L. Neff, SLAC preprint). He is continuing work along this line to see further consequences, and their implications in more realistic situations in hadron physics.

A. Karpt† just finished a paper in collaboration with S. Fenster (ANL) on the analytic structure of loop diagrams in the dual resonance model, based on the 2-dimensional Laplace equation.

*New research associate.
†On fellowship from Bundesministerium für Bildung und Wissenschaft, Bonn.
Y. Miyatake studied the dual resonance model during his stay here. In particular he considered the decay $\eta \rightarrow \pi^+ + \pi^- + \pi^0$ using Susskind's formulation of spurion currents. The result is not good if all multiperipheral diagrams are taken.

**Time Distribution.**

The approximate percentage of time or effort which the principal investigator has devoted to the project since the beginning of the current term of the agreement is 66% of 3 Quarters and 100% of 4th Quarter. The time or effort expected to be devoted during the remainder of the current term remains as above.


30. G. W. Barry, "Is the Pomeranchuk Decoupled from the Ordinary Regge Trajectories?" (to be published in Phys. Rev.).

32. J. Willemsen, "Operational Construction of Multiple Charged Pion Amplitudes," submitted to Nuclear Physics B.


34. Y. Miyatake, "η-3π Decay with Susskind's Model," to be published in Progress of Theoretical Physics.


37. K. Fujikawa, "The Self-Coupling of Weak Lepton Currents In High Energy Neutrino and Muon Reactions," to be published.


The following papers were listed in the December, 1969, report, but the annotations were incomplete:


List of Individuals Supported by Contract AEC AT(11-1)-264

RESEARCH ASSISTANTS

S. C. Soong
Yehuda Band
George Barry
David Friedman
A. Garcia-Gonzalez
A. Hacinliyan
Evangelos Manessis
John Steinhoff
H. C. Tze
Jorge Willemsen (NSF Fellow)*
Thomas Bell (NSF Fellow)*
J. Lemke

RESEARCH ASSOCIATES

Lay Nam Chang
Carl Carlson
Kazuo Fujikawa
Freydoon Mansouri
Armin Karpi*

FACULTY

P. G. O. Freund, Associate Professor
Y. Nambu, Professor
R. Oehme, Professor
R. G. Sachs, Professor
W. K. Tung, Assistant Professor

SECRETARIES

L. Cox
J. Reiffel

*Supplementary Support from the AEC Contract.