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The following is a review of work done under the present contract. It covers the period February 1, 1981 to approximately November 1, 1981.

Footnote numbers refer to the numbers of the listed papers completed, see pages 11, 12, and 13

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(I) Mathematical Physics and Formal Results

(a) It has been suggested that the concepts of complete integrability and self-duality in quantum field theories may be related. Completely integrable systems possess an infinite set of conserved charges. As an example of the possible connection between these two properties, an attempt was made to find an infinite set of conserved charges in the one-space-dimensional quantum Ising model in an external magnetic field, one of the archetypes of self-dual theories. For the X-Z model an explicit form of the Nth charge was found. A transformation which related the X-Z model to two independent Ising models was discussed, and this led to a derivation of an infinite set of conserved charges for a single Ising model. This example served as a guide to the formulation of a general theorem relating self-duality and complete integrability in a large class of theories discussed below in section II of this report.¹²

(b) Borel summability techniques have been useful in calculations in three dimensional field theories, statistical mechanics, and quantum mechanics. However, they fail to be applicable to four dimensional field theories. Two mathematical theorems that elucidate the reasons for this failure were reviewed in detail. They deal with the physically relevant cases of QCD and ϕ^4 field theories, both in four dimensions. An invited paper on this subject was given at the 1981 Sanibel Symposium.⁵

(II) Gauge Theories

Work to develop some systematic nonperturbative analysis of non abelian gauge theory was continued. Two results were achieved this past year in the pursuit of this program:

(a) The symmetry responsible for the infinite set of non-local conserved currents in the two-dimensional chiral models was identified to be a Kac-Moody subalgebra or equivalently the current algebra. This infinite parameter Lie algebra is also known to be relevant to dual resonance models. This fact, together with the analogy of the chiral theory to Yang-Mills loop space, is suggestive that the Yang-Mills theory also carries a representation of this infinite parameter non-abelian algebra. This result has several implications:

i) The extraction of the abstract form of the algebra makes the search for the hidden symmetry precise, ii) Exactly integrable systems have as a hallmark an infinite parameter commuting algebra. Given the above Kac-Moody subalgebra, an infinite parameter commuting algebra can be extracted. Therefore, the identification of the charges in four-dimensional gauge theory may lead to the appropriate variables to diagonalize the system, iii) As an alternative to the local gauge theory, this algebra may serve as a guide to building interactions of free strings in order to preserve exact integrability.¹⁰

(b) The second result involves a different approach to the explicit construction of the infinite set of commuting charges in four-dimensional $SU(N)$ gauge theory. It gives for any self-dual quantum Hamiltonian, linear in the coupling constants and with a conserved first charge, an explicit algebraic prescription for

constructing an infinite set of commuting conserved charges. For the Ising model and X-Z model, the charges constructed from this prescription are the known charges which result from the exact integrability of these models. For four-dimensional gauge theory, which also has a self-dual feature, the result is directly applicable for $Z(2)$. This second result has established a rigorous connection between a certain class of self-dual theories and an infinite set of symmetries (corresponding in all known examples to the diagonalizability of the Hamiltonian). The applicability to four dimensional non-abelian theory is under current investigation.¹⁶

Another area of activity in our group has been supersymmetry and its cosmological implications. Three publications related to this area have been completed:

(c) A persistent problem in quantum field theory is the observed absence of any vacuum energy (or cosmological term) which in general one would expect to be present. Such a vacuum energy from matter could be simply set to zero or cancelled against a cosmological term from gravity but such a cancellation must be viewed as unnatural unless it has a basis in symmetry. It is shown that such a symmetry is indeed present in a supersymmetric classical Lagrangian in which the supersymmetry is spontaneously broken up to terms of order K^2 , where K is the gravitational coupling. This is the first example that the absence of vacuum energy or cosmological term may have a basis in a symmetry principle.⁶

(d) The standard hot big bang model of the universe if extrapolated backward in time implies a singularity. A model was proposed which avoids this singularity by postulating that the universe was originally a static configuration of matter and geometry - a de Sitter Universe. This configuration can however decay by quantum tunneling into a hot big bang configuration. If this phase transition indeed describes the origin of the universe, then the universe must be spatially

compact. The idea developed in this article could be expressed as a dimensional phase transition and this prospect is being investigated. ⁷

(e) Assuming a spontaneously broken $N=1$ local supersymmetry then the universe is filled with a gas of spin $3/2$ gravitinos. It was shown that the observed bound on the mass density of the universe implies the gravitino mass is less than 1 KeV. This bound implies that the order parameter for spontaneously broken supersymmetry is bounded by 10^3 TeV. Using an exact sum rule (the analogue of the Adler-Weisberger sum rule for supersymmetry), it was shown that the threshold for new states required by supersymmetry is below 10^4 TeV - a model independent conclusion. If one assumes that the universe is indeed gravitino dominated then the Jean's mass corresponding to condensates in the gravitino gas is about $10^{12} M_{\odot}$, accounting for both the existence and size of galaxies. This new solution to the old problem of galaxy formation is being further explored. ¹⁹

Finally in the area of dynamical symmetry-breaking one contribution was completed:

(f) Some model-independent physical implications of a class of hypercolor-based theories of dynamical symmetry-breaking were described and discussed. The role which e^+e^- colliders can play, in distinguishing between such theories and the canonical methodology, was underlined. ¹

III. Composite Models

(a) Composite models of quarks, leptons and Higgs bosons were described and discussed in an invited plenary report to the Lisbon Conference. The fermion models considered were those in which the basic concepts are abstracted from the quark model of nucleon structure; the quark model paradigm thus served as a convenient frame of reference for discussion of the problems encountered in describing quarks and leptons as composite entities. The hypercolor based scenario, for dynamical symmetry breaking and generation of composite Higgs bosons, was briefly reviewed and the contribution of hyperquarks to the problem of quark proliferation was noted. Experimental signatures of composite fermions and the hypercolor scenario were contrasted with those of the canonical theory with elementary quarks, leptons and spin-0 bosons. It was tacitly assumed that the structure of elementary particle interactions, at the energy-regimes considered, can be discussed in a meaningful way without bringing gravity into the picture. ¹⁴

IV Phenomenology

The problem of CP violation is the focus of two papers completed during the period of this report. The underlying theme is the importance of observing CP violation in heavy quark decays.

(a) A paper was presented at the Z^0 Theory Workshop at Cornell for CESR II. Since Z^0 decays to heavy quarks, $b\bar{b}$, $c\bar{c}$, etc., it is possible to collect millions of B decay events when a luminosity of $10^{31} \sim 10^{32}/\text{cm}^2 \text{ sec}$ is achieved at CESR or at LEP. This makes CP violating effects in B decay, which may be as small as 0.1%, experimentally accessible. A systematic discussion of such an effect was carried out. ²

(b) The question of observability of CP violation in B-decay was discussed, incorporating as much as possible the known facts on B decay and charmed meson decays. ⁹

Other papers on phenomenology were:

(c) An invited talk entitled, "What Can We Learn from Lepton-Lepton Interactions," was presented at a Conference on Physics in Collision attended mainly by experimentalists. The paper is a collection of comments intended for those thinking about experiments on high energy e^+e^- interactions. Some of the comments were: (1) $M_Z < 97 \text{ GeV}$ for $\sin^2 \theta_w = .222 \pm .012$ irrespective of any higher order corrections, (2) Measurement of Γ_Z is very important as it is influenced by the total number of neutrinos, (3) The Z^0 is a good heavy quark factory, (4) Something as delicate as $B^0 - \bar{B}^0$ mixing and CP violation can be studied at the Z^0 peak. ¹¹

(d) A 30 GeV on 30 GeV e^+e^- colliding beam facility, TRISTAN, has been funded in Japan. It is argued that the top quark might be produced at TRISTAN. Assuming such a production, the weak decays of toponium were discussed. The importance of raising the beam energy to 50 GeV + 50 GeV was also emphasized.¹³

(e) A proposal has been made by S. Ting's group to observe μ -mesons in pp collisions at ISABELLE. As the multiplicity of B mesons in pp collisions should increase rapidly with energy, $B\bar{B}$ pair production turns out to be the major source of $pp \rightarrow 3\mu + \dots$ for certain momentum cuts of 3μ 's. This point is used to study the possibility of $B^0\bar{B}^0$ mixing at ISABELLE. It is concluded that, if a luminosity of $10^{33}/\text{cm}^2\text{sec.}$ is achieved, it is possible to study such an effect.¹⁵

(f) The study of nucleosynthesis (in the early universe) is of importance for the critical discussion of cosmological models and also for the understanding of processes involved in thermonuclear reactions. The fundamental step in nucleosynthesis is the conversion of Hydrogen into Helium, and it has been pointed out by Dyson that this process is slow because it involves weak interactions in the rate determining step. Dyson furthermore points out that if a bound diproton system were possible the production of Helium would be substantially increased. It was shown that strong magnetic fields will give rise to a proton-proton bound state provided that the Larmor radius of the proton is less than the radius of nuclear forces. The fields necessary for this are of the order of 10^{18}G , so that while the process may be important in certain early cosmological situations and can be used in the analysis of certain evolutionary models, it will not play a part in nucleosynthesis in stars or in experimentally realizable situations.⁸

V General

(a) Physical implications of new theoretical ideas, which can be subjected to experimental scrutiny at e^+e^- and pp colliders, were discussed in an invited talk at the "Workshop on Physics Opportunities at ISABELLE", held at Brookhaven National Laboratory. 18

VI HISTORY OF PHYSICS

(a) One of us, A. Pais, completed work on the first scientific biography of Einstein. The book, entitled "Subtle is the Lord...The Science and the Life of Albert Einstein", is due to appear in 1982 at the Oxford University Press. The work assesses Einstein's role in statistical physics, special and general relativity, unified field theory, and quantum theory.

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