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Principal Investigators:

M.A.B. Bég, N.N. Khuri*, A. Pais

Rockefeller University, New York, N.Y., 10021

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The following is a review of work done under the present contract. It covers the period February 1, 1976 to approximately February 1, 1977. Footnote numbers refer to the report numbers of papers completed, see pages 11 and 12.

* person-in-charge

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(I) Rigorous and Formal Results

Under this heading we list some rigorous results which follow from field theory, in addition we include results of continuing work which follow from generally accepted principles of physical theory, occasionally combined with additional assumptions of a general nature:

- (a) The renormalization-group method was originally used to study the asymptotic behavior of Green's functions for large Euclidean momenta. Although this gives us useful information, it has long been hoped that this method could be directly used for determining the asymptotic behavior of physical scattering amplitudes. Recently, Tiktopoulos, and independently Callan and Gross, have shown that the renormalization-group method can be used to determine the asymptotic behavior in energy of the fixed angle scattering amplitude on the mass-shell, albeit only for a certain class of field theories. This method does not apply directly to forward scattering. It was shown, however, that one can apply the method to integrals of the Green's functions over the angle variable. The resulting restriction on these integrals lead to a new strong upper bound on the total cross section, $\sigma_{\text{tot}}(s)$, in the massive ϕ^4 case. The additional input used to obtain this result is, like many of the assumptions of the renormalization-group method, valid at least order by order in perturbation theory.¹⁰³
- (b) In 1966, Coleman proved a theorem which has been useful in discussions of the symmetries of physical systems. It states that if the generators of a group are realizable in the physical Hilbert space, and if they annihilate the vacuum, then they are constants of the motion. The theorem was proved within the framework of the general principles of field theory, under the restriction that there are no massless particles.⁹⁵ It has been shown that the theorem can be freed from this last restriction and holds even if massless particles are present.⁹⁵

(II) Symmetries

- (a) The question of whether the emergence of Weinberg type spectral sum rules in association with exact symmetries is a feature that is model-dependent or not was answered. It was shown that if the underlying theory is a local field theory, and if a group G contains a subgroup g , which is known to be an invariance group of the theory, then the full set of Weinberg sum rules for G imply invariance of the theory under G .⁹³
- (b) It was shown by Bég that the $U(6) \times U(6)$ algebra of Feynman, Gell-Mann, and Zweig exists in Quantum Chromodynamics (QCD). The question arises as to whether the full $U(12)$ algebra also exists in QCD. The answer to this question has been found to be negative.¹¹⁵

(III) Gauge Theories

This section comprises the studies of questions arising in connection with the problem of unifying weak and electromagnetic forces and the harmonization of such attempts with strong interactions.

- (a) The currently fashionable theory of strong interactions, Quantum Chromodynamics (QCD), is plagued by the so called $U_A(1)$ problem⁹⁸ (i.e. the existence of a fourth zero mass pseudoscalar particle and the forbiddenness of $\eta \rightarrow 3\pi$ in the chiral $SU(2) \times SU(2)$ limit) It was shown that a topological solution to this problem proposed earlier by Pagels, could be realized by the dyon solutions to QCD with Higgs fields. The desired failure of chiral charge conservation is now understood to be a general feature of QCD.¹⁰⁰
- (b) In a continuing line of investigation of the role of spontaneously broken symmetries in particle physics, a collective model of the hadrons has been constructed using QCD as the model. Assuming that the gluon propagator becomes singular at small momenta (confinement), allows an exact solution to the Dyson-Schwinger equation for the fermion propagator. The bilocal quark anti-quark gap excitations (mesons) satisfy simple wave equations, and the resulting eigenvalue problem leads to a low lying meson spectrum, in agreement with observation. The main point of this work was to establish the phenomenological content of QCD consistent with confinement, PCAC, and relativity. This is the only example of a model that satisfies these three requirements.¹⁰²
- (c) Work was continued on topological solitons. Configurations describing multiply charged magnetic monopoles were constructed and their stability properties elucidated. Such multiply charged monopoles become possible for higher rank groups. The gravitational analog of the instanton was also discovered and the nature of periodic vacua in gravity theory discussed.¹⁰⁸

- (d) A new derivation of the Ward-like identities for non-abelian gauge theories in the axial gauge was given. The merit of this derivation is its extreme simplicity. It allows an extension of the identities on the renormalization constants, written down by Kummer, to the case in which Fermions are also included, a result relevant for QCD.

(IV) Phenomenology

(A) Weak Interactions

Events of the type $e^+e^- \rightarrow e^+\mu^+$ + missing momentum, as well as $e^+e^- \rightarrow \mu^\pm$ + hadrons + neutrinos, have been observed by the LBL-SLAC group at rates far beyond those expected from any conventional processes. The most exciting and most likely explanation for these events is that they are due to the pair production of some new heavy lepton, $L^\pm$. If such heavy leptons exist, the determination of their properties would be essential for our understanding of the weak interactions. Our group has been quite active in the past year in looking at problems related to heavy leptons. A description of the results follows:

- (a) The determination of the properties of charged heavy leptons is made very difficult by their short lifetimes. The implications of this situation was analyzed in detail. In particular, it was shown how one can determine the production structure functions for $e^+e^- \rightarrow L^+L^-$ from information on the decay products.⁹⁶
- (b) It was shown that the transverse beam polarization provides a powerful tool for probing the dynamics of the purely leptonic decays of heavy leptons. The effects of transverse beam polarization of the incident e^+e^- colliding beams on the process $e^+e^- \rightarrow \gamma^* \rightarrow L^+L^- \rightarrow e^+\bar{\nu}_e + \nu_L$ were investigated in detail.⁹⁹

$$\downarrow \rightarrow \mu^+ + \nu_\mu + \bar{\nu}_L$$

- (c) A great deal about the heavy lepton can be learned from studies of the direct single muon process $e^+e^- \rightarrow L^+L^- \rightarrow \mu^\pm$ + hadrons + neutrinos. A systematic study of this process was carried out in order to determine how information on weak decay properties of the $L^\pm$, $L^+L^- \gamma$ coupling, mass of the neutrino m_{ν_L} , and the nature of weak currents which couple to hadrons, can be obtained.¹⁰⁵

- (d) The general differential cross-section for the process, $e^+e^- \rightarrow \gamma^* \rightarrow L^+ + L^- \rightarrow \mu^+ + \nu_L + \bar{\nu}_\mu + e^+ + \bar{\nu}_L + \nu_e$, was obtained. The results hold for V,A,S,P,T couplings and do not depend on the μ -e universality assumption. Dependences on arbitrary beam polarizations, final state electron and muon longitudinal polarizations, and final state electron and muon masses were included. It was shown that it is possible to investigate the leptonic decay of $L^\pm$ to the same level as that for muon decay.¹⁰⁹
- (e) A comprehensive study of W^0 effects in e^+e^- annihilation producing heavy lepton pairs was carried out. The emphasis was on what information can be obtained by measuring the one-particle-inclusive distribution of a final μ or e . A knowledge of W^0 couplings to heavy leptons is especially interesting for the construction of unified gauge models.¹¹⁰
- (f) Finally, the measurement of the electromagnetic form factors and weak decay parameters of heavy leptons in the reaction $e^+e^- \rightarrow L^+ + L^- \rightarrow (\ell \nu \bar{\nu}) pX$, was considered. A sensitive test which can be done if the initial beams are transversely polarized is to measure the azimuthal distribution of the ℓ .¹⁰⁴

Results on the phenomenology of weak interactions not necessarily related to heavy leptons are described briefly in what follows:

- (g) A study of weak effects caused by W^0 exchange in e^+e^- annihilations producing two particle final states was undertaken. The motivation for this work was to suggest ways of measuring effective derivative couplings at PEP and PETRA. Although these couplings are expected to be small in the usual theories, they should be measured as a check. A non-vanishing result could have interesting consequences for second class currents and CP violation.⁹⁷

- (h) The effect of strong interactions on the ratio $R = \frac{\Gamma(\pi \rightarrow e + \bar{\nu}_e) + \Gamma(\pi \rightarrow e + \bar{\nu}_e + \gamma)}{\Gamma(\pi \rightarrow \mu + \bar{\nu}_\mu) + \Gamma(\pi \rightarrow \mu + \bar{\nu}_\mu + \gamma)}$, was

examined. This precisely computed number, $R = 1.233 \times 10^{-4}$, is presently being tested to within .5% accuracy experimentally. It is important to know whether the strong interactions significantly affect the value of R . It was found that they change this value only by either + .055% or + .28% (an experimental ambiguity) independent of any model of the strong interactions. Therefore, this ratio provides a precision check which any viable theory of the weak and electromagnetic interactions must satisfy. On the basis of this analysis one can in the future examine various models and compare the value of R they give with $R_{\text{exp.}}$, thus narrowing down the field of viable theories.¹⁰¹

- (i) It was shown that the present experimental bounds for the electric and weak magnetic dipole moments for muons are too small for them to be measurable in μ^+ pair production at PEP and PETRA. In the case of heavy lepton pair production, there are no experimental bounds on these moments, however the information needed to measure them is lost in the subsequent decays. If CP violation is observed in $e^+e^- \rightarrow \ell^+\ell^-$, it will not be due to an electric dipole moment.¹⁰⁶
- (j) It was found that the experimental observation of $\delta\sigma_0 = \sigma_{nc}^{vN^0} - \sigma_{nc}^{\bar{v}N^0} > 0$, where $\sigma_{nc}^{v(\bar{v})N^0}$ is the $v(\bar{v})$ - induced neutral current inclusive cross section on an isoscalar target, provides a strong constraint on the quark representation of the $SU(2) \times U(1)$ gauge models. There are only five classes of gauge models which satisfy the constraint. In the framework of the $SU(2) \times U(1)$ gauge models, the correct unified model of weak interactions must be looked for among the five classes of models with $\delta\sigma_0 > 0$.¹⁰⁷
- (k) Weakly unstable charmed hadrons are probably too short-lived to allow direct determination of their lifetimes without extreme difficulties. It was demonstrated, however, that the life time ratios of charmed mesons are deducible from the production of charmed meson pairs in e^+e^- annihilation.¹¹²

- (1) The prevalent explanation for the rise in the ratio of $\bar{\nu}$ to the ν cross sections, and the high y anomaly, is that a parton with right-hand coupling and a fifth flavor is being excited. It is shown that the four-flavor parton model could explain these observations if the distributions of the s and $\bar{s}$ partons are skewed. If this is the case, a dramatic effect on models for hadrons will result. The main consequence in deep inelastic scattering will be an increase in strange particle production.¹¹³

(V) Other Topics

- (a) There has been renewed interest and progress in understanding the problem of the regularization of the energy momentum tensor of a matter field in a general background metric. In the dimensional regularization procedure conformal anomalies appear in the energy momentum tensor. Using this regularization procedure, the coefficients of conformal anomalies in a general background metric due to scalar, spin 1/2 fermion, gauge and gravitational fields, were explicitly calculated.¹¹⁴
- (b) An article on the electron was prepared for a new encyclopaedia of physics.⁹¹
- (c) The main results of the e^+e^- -colliding beam experiments are: (i) the existence of narrow states with masses below 4 GeV and broad states above 4 GeV, (ii) the rise in $R=\sigma(e^+e^-\rightarrow\text{hadrons})/\sigma(e^+e^-\rightarrow\mu^+\mu^-)$ at a center-of-mass energy of about 4 GeV, and (iii) the observation of the μ -e events, $e^+e^-\rightarrow e\mu$ + missing momentum at energies above 4 GeV. A unified explanation of these three results was proposed based on the existence of a new type of fermion with mass about 2 GeV. It interacts semi-strongly, and the narrow states are interpreted as its bound states with its antiparticle, while the μ -e events are in this model due to its purely leptonic decays. Tests of this model were suggested.⁹⁴

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