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DOE/ER/40560--1

DE91 001944

THEORETICAL HIGH ENERGY PHYSICS RESEARCH AT THE UNIVERSITY OF CHICAGO

Progress Report
for period May 1, 1990 - April, 1991

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September, 1990

Prepared for

THE U.S. DEPARTMENT OF ENERGY
AGREEMENT NO. DE-FG02-90ER-40560

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TECHNICAL PROGRESS REPORT

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DOE DE FG02 90-ER 40560
TECHNICAL PROGRESS REPORT
Theoretical High Energy Physics Research
at the University of Chicago

I. INTRODUCTION

The present contract supported work by Jonathan L. Rosner (principal investigator), Emil J. Martinec (co-investigator) Robert G. Sachs (co-investigator), Chris Quigg (Fermilab and Chicago), Research Associates, and graduate students in elementary particle physics at the University of Chicago.

The present report deals with work performed during the first nine months of calendar year 1990. For earlier work, see previous Technical Progress Reports.

Professor Tran N. Truong of the Ecole Polytechnique visited the University of Chicago during a month in March, 1990. Dr. Keith Ellis of the Theory Group at Fermi National Accelerator Laboratory will visit during the first three months of 1991.

II. RESEARCH ACTIVITIES

A. J. ROSNER AND COLLABORATORS

J. Rosner continued to serve on HEPAP. He delivered eight lectures at the TASI-90 summer school in Boulder in June of 1990 (see below) and participated as a session co-organizer at the workshop on Research Directions for the Decade in Snowmass, CO, June 15 - July 13, 1990.

1. *CP violation and Kobayashi-Maskawa matrix*

Present information on $|V_{ub}/V_{cb}|$, CP violation in the kaon system, and $B-\overline{B}$ mixing leads to constraints on parameters of the Kobayashi-Maskawa (KM) matrix. These constraints depend on quantities whose magnitudes are governed by poorly known aspects of hadron physics - particularly the vacuum-saturation parameter B_K and the B meson decay constant f_B. In the published version of a joint work with C. S. Kim and C. P. Yuan,[1] the sensitivity of certain CP asymmetries in the B meson system to these parameters was explored. [Other aspects of this work were described in last year's Technical Progress Report.]

Investigations regarding possible quark mass matrices leading to the observed form of the KM matrix were performed. It was concluded that no compelling *ansatz* for quark mass matrices exists at this time, especially in view of the large parameter space available for the KM matrix elements.[1,2]

2. *Strongly interacting Higgs sector*

An analysis of possibilities for TeV scale physics, delivered as a colloquium for the Theoretical Physics Institute at the University of Minnesota, was published.[3] Recent work on a strongly-interacting Higgs sector[4–6] was described in non-technical terms. It was concluded that the possible existence of this sector is one of the strongest motivations for construction of multi-TeV hadron colliders.

The implications of a very heavy top quark for non-universal couplings of the weak axial current were explored by R. Rosenfeld and J. Rosner, using analogues of the Goldberger-Treiman and Adler-Weisberger relations for the strongly interacting Higgs sector. Many, but not all, of the results for strong interactions can be carried over by the replacement of $f_\pi = 93$ MeV with $v = 2^{-1/4}G_F^{-1/2} = 246$ GeV, but the violation of weak isospin implicit in the large $t - b$ mass difference presents special problems. This work is continuing.

3. *Right-handed W bosons*

Work begun in collaboration with E. Takasugi (Osaka University) during J. Rosner's visit to Japan in September of 1989 was concluded and published.[7] The possibility was explored that a relatively light right-handed W ("W_R") could have escaped detection because the right-handed neutrino N to which it would normally decay (via $W_R \to eN$) is too heavy. If the channel $W_R \to eN$ is closed, an alternative channel suitable for W_R searches might be $W_R \to t + (\bar{d}, \bar{s}, \text{ or } \bar{b})$, followed by $t \to Wb$. The suitability of this channel for searches in present and future hadron collider experiments was studied. It was found that there already exists a region of sensitivity in present CDF data to $M(W_R) \approx 250$ GeV/c^2, $m_t \approx 100$ GeV/c^2, and this region is expected to grow appreciably with future Tevatron operation.

4. *Radiative corrections and electroweak observables*

During the 1989 Breckenridge workshop on "Physics at Fermilab in the 1990's," work was begun on a description of the impact of any given electroweak measurement on parameters affecting radiative corrections. Initial results of that investigation[8] were systematized and extended.[9] Specifically, it was shown how different electroweak observables probe different combinations of the parameters $\bar{\theta}$ (the weak mixing angle as defined in terms of couplings at the Z pole) and $\rho \equiv M_W^2/(M_Z^2 \cos^2 \bar{\theta})$. A simple, approximate method was given for relating these parameters to the angle θ defined in terms of gauge boson masses by $\cos^2 \theta \equiv M_W^2/M_Z^2$, and it was shown how these various observables shed light on θ and on quantities such as the top quark mass that directly affect ρ.

The approach described above does not allow for certain degrees of freedom, associated with nonstandard physics, leading to different wave function renormalizations of the W and Z.[10,11] In the analysis of Ref. 9 it was noticed that the measurement of parity-violation in atomic cesium[12] does not provide separate information from recent precise Z mass measurements[13] within the context of the radiatively corrected standard model. Such a measurement *can* provide powerful constraints on certain unconventional models, including those with extra Z's[14] or those involving extra heavy fermions or technicolor particles.[10,11] W. Marciano and J. Rosner investigated these constraints using the parametrization[11] of weak isospin conserving *(S)* and violating *(T)* quantum loop corrections.[15] It was found that the atomic parity violation experiment of Ref. 12 is particularly sensitive to S, with the dependence on $T \equiv (\rho - 1)/\alpha$ almost cancelling. Existing data and atomic physics calculations[12] give $S = -2.7 \pm 2.0 \pm 1.1$, with substantial potential for error reduction in future measurements and calculations. A typical technicolor model with a full generation of technidoublets gives $S \approx 2$, and thus is likely to be ruled out fairly soon. Versions of technicolor[16] in which one has a single technidoublet in an $SU(N_T)$ multiplet, such as those described in Sec. 2, above, give $S \approx 0.1\ N_T$, and thus provide a benchmark for precision in future electroweak measurements.

5. *Top quark physics*

An estimate was performed by L. Orr and J. Rosner on the relative times for top quark fragmentation and decay as a function of m_t in the reaction $e^+e^- \to t\bar{t}$.[17] An extension of this work to hadronic production of $t\bar{t}$ will constitute L. Orr's Ph.D. thesis (see L. Orr's section of this Technical Progress Report). A simple model was used in which hadronization becomes important when the top quarks are separated from one another by more than a distance of order 1 fm. It was shown that hadronization can be important for quite large values of m_t provided the $t\bar{t}$ system has large c.m. energy.

Work begun in collaboration with Waikwok Kwong on the threshold behavior of $t\bar{t}$ production in e^+e^- collisions was continued by W. Kwong and reported for publication.[18] The interplay of the top quark width for decay to $W + b$ and the level spacing in bound $t\bar{t}$ systems was investigated, following upon work of previous authors.[19,20] This work will form Mr. Kwong's Ph.D. Thesis and is described in more detail in his section of this Technical Progress Report.

The studies described above in subsections 1 and 4 have bearing on the top quark mass. Very large values of m_t are disfavored if the CERN value[21] of ϵ'/ϵ in CP-violating kaon decays is substantiated by further, more precise studies. A value of ϵ'/ϵ consistent with zero, obtained at Fermilab,[22] provides little constraint on m_t.

The most stringent limits on m_t come from direct searches:[23] $m_t \geq 89$ GeV/c^2, and from electroweak radiative corrections (see, e.g., Refs. 9 and 15), $m_t \lesssim 200$ GeV/c^2, where this conclusion depends to some extent on the mass of the Higgs boson and the pattern of nonstandard physics at high masses, if any. Informal discussions with members of the CDF Collaboration were held regarding plans for top quark searches in the next Collider run, and the importance of the proposed upgrades in muon detection continued to be stressed.

6. *Pseudoscalar meson decay constants*

The crucial nature of heavy meson decay constants such as f_B in interpreting mixing data and anticipating CP asymmetries was stressed above in subsection 1. Nonrelativistic scaling arguments, with QCD corrections of order 10%,[24] allow one to relate f_B and f_{B_s} to f_D and f_{D_s}, which have some prospects of being measured soon. Indeed, a recent measurement[25] of the branching ratios for $\overline{B}^0 \to D^+ D_s^-$ and $B^- \to D^0 D_s^-$, combined with progress on understanding form factors for $B \to (D, D^*)$ transitions[26] and a factorization hypothesis, has led to the estimate[27] $f_{D_s} = 259 \pm 74$ MeV. (Here we use units in which $f_\pi = 132$ MeV.) Branching ratios implied by this rather large value are $B(D_s \to \tau\bar{\nu}_\tau) = (4.6 \pm 2.6)\%$, $B(D_s \to \mu\bar{\nu}_\mu) = (0.5 \pm 0.3)\%$. Scaling laws and QCD corrections[24] imply

$f_D = 207 \pm 60$ MeV, $f_B = 140 \pm 40$ MeV, and $f_{B_s} = 175 \pm 50$ MeV. Other consequences of the approach include a prediction that the branching ratio of $\overline{B}^0$ to $D^{*+}D^{*-}$ is about 0.06%, of which 94% occurs in the $CP = +$ final state. A very recent analysis by two members of the CLEO Collaboration[28] makes use of the observed spectrum[29] in $\overline{B} \to D^* l \nu$ and a factorization test proposed by Bjorken[30] to obtain similar values of f_{D_s} from the $\overline{B} \to DD_s$ and $\overline{B} \to D^* D_s$ data of Ref. 25.

7. *Summer school lectures*

J. Rosner delivered a set of eight lectures on heavy quarks, quark mixing, and CP violation at TASI-90 (theoretical Advanced Study Institute), Boulder, Colorado, in June of 1990. The manuscript of these lectures is in preparation.[31]

8. *Heavy meson spectroscopy*

W. Kwong and J. Rosner have begun to analyze the range of likely values for mixed-flavor heavy mesons such as $\overline{B}_s (= b\bar{s})$ and $\overline{B}_c (= b\bar{c})$. This work is continuing.

1. C. S. Kim, Jonathan L. Rosner, and C.-P. Yuan, Phys. Rev. D **42**, 96 (1990).

2. Claudio O. Dib, Isard Dunietz, Frederick J. Gilman, and Yosef Nir, Phys. Rev. D **41**, 1522 (1990).

3. Jonathan L. Rosner, in *Trends in Theoretical Physics*, Vol. 2, edited by P. J. Ellis and Y. C. Tang (Addison-Wesley, Redwood City, CA, 1990), p. 141.

4. Michael S. Chanowitz and Mary K. Gaillard, Phys. Lett. **142B**, 85 (1984); Nucl. Phys. **B261**, 379 (1985); Michael S. Chanowitz, in *Results and*

Perspectives in Particle Physics, proceedings of the Rencontres de Physique de la Valle d'Aoste, La Thuile, March, 1987, edited by M. Greco (Editions Frontières, Gif-sur-Yvette, France, 1987), p. 335, and references therein; Michael Chanowitz, Mitchell Golden, and Howard Georgi, Phys. Rev. Lett. **57**, 2344 (1986); Phys. Rev. D **36**, 1490 (1987).

5. Pham Quang Hung and H. B. Thacker, Phys. Rev. D **31**, 2866 (1985); J. D. Bjorken, in *New and Exotic Phenomena*, proceedings of the 7th Moriond Workshop, Les Arcs, France, 1987, edited by O. Fackler and J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, France, 1987), p. 1; Pham Quang Hung, T. N. Pham, and Tran N. Truong, Phys. Rev. Lett. **59**, 2251 (1987).

6. Rogerio Rosenfeld and Jonathan L. Rosner, Phys. Rev. **D38**, 1530 (1988); Rogerio Rosenfeld, Phys. Rev. D **39**, 971 (1989); Rogerio Rosenfeld, Phys. Rev. D **42**, 126 (1990).

7. Jonathan L. Rosner and Eiichi Takasugi, Phys. Rev. D **42**, 241 (1990).

8. Jonathan L. Rosner, in *Proceedings of the Workshop on Physics at Fermilab in the 1990's*, edited by D. Green and H. J. Lubatti (World Scientific, Singapore, 1990), p. 15.

9. Jonathan L. Rosner, Enrico Fermi Institute report EFI 90-18-Rev., August, 1990, to be published in Phys. Rev. D **42**, November, 1990.

10. Mitchell Golden and Lisa Randall, Fermilab-Pub-90/83-T, May, 1990 (unpublished).

11. Michael E. Peskin and Tatsu Takeuchi, Phys. Rev. Lett. **65**, 964 (1990).

12. M. C. Noecker, B. P. Masterson, and C. E. Wieman, Phys. Rev. Lett. **61**, 310 (1988). Atomic physics calculations needed to interpret this result with greater precision were performed by V. A. Dzuba, V. V. Flambaum,

and O. P. Sushkov, Phys. Lett. A **141**, 147 (1989), and S. A. Blundell, W. R. Johnson, and J. Sapirstein, Phys. Rev. Lett. **65**, 1411 (1990).

13. See, e.g., F. Dydak, rapporteur's talk at 25^{th} International Conference on High Energy Physics, Singapore, Aug. 2-8, 1990.

14. See, e.g., Paul Langacker, Richard W. Robinett, and Jonathan L. Rosner, Phys. Rev. D **30**, 1470 (1984); David London and Jonathan L. Rosner, Phys. Rev. D **34**, 1530 (1986); Ugo Amaldi *et al.,* Phys. Rev. D **36**, 1385 (1987).

15. William J. Marciano and Jonathan L. Rosner, Brookhaven National Laboratory report BNL-44997 and Enrico Fermi Institute report EFI-90-55, submitted to Phys. Rev. Letters.

16. S. Weinberg, Phys. Rev. D **19**, 1277 (1979); L. Susskind, Phys. Rev. D **20**, 2619 (1979).

17. Lynne H. Orr and Jonathan L. Rosner, Phys. Lett. B **246**, 221 (1990).

18. Waikwok Kwong, Enrico Fermi Institute report EFI-90-22, May, 1990, submitted to Phys. Rev. D.

19. J. H. Kühn and P. M. Zerwas, Phys. Rep. **167**, 321 (1988).

20. V. S. Fadin and V. A. Khoze, *JETP Lett.* **46**, 525 (1987); V. S. Fadin, V. A. Khoze and T. Sjöstrand, CERN preprint CERN-TH-5394/89, and in *Moriond 1989: Hadronic: 19* (proceedings of the 24th Rencontres de Moriond: High Energy Hadronic Interactions, Les Arcs, France, Mar. 12-18, 1989); CERN preprint CERN-TH-5687/90, Mar. 1990; Y. Hara, preprint UTHEP-201, Feb. 1990.

21. H. Burkhardt *et al.* (NA31 Collaboration), Phys. Lett. B **206**, 169 (1988): $\epsilon'/\epsilon = (3.3 \pm 1.1) \times 10^{-3}$.

22. J. R. Patterson *et al.*, Phys. Rev. Lett. **64**, 1491 (1990): $\epsilon'/\epsilon = (-0.4 \pm 1.4 \pm 0.6) \times 10^{-3}$.

23. F. Abe *et al.* (CDF Collaboration), presented by K. Sliwa at 25^{th} Rencontres de Moriond: *High Energy Hadronic Interactions*, Les Arcs, France, Mar. 11-17, 1990; manuscript in preparation for submission to Phys. Rev. Letters.

24. M. B. Voloshin and M. A. Shifman, Yad. Fiz. **45**, 463 (1987) [Sov. J. Nucl. Phys. **45**, 292 (1987)]; H. David Politzer and Mark B. Wise, Phys. Lett. B **206**, 681 (1988); **208**, 504 (1988).

25. CLEO Collaboration, D. Bortoletto *et al.*, Phys. Rev. Lett. **64**, 2117 (1990).

26. B. Grinstein, M.B. Wise, and N. Isgur, Phys. Rev. Lett. **56**, 286 (1986); N. Isgur, D. Scora, B. Grinstein, and M.B. Wise, Phys. Rev. D **39**, 799 (1989); Nathan Isgur and Mark B. Wise, Phys. Lett. **B237**, 527 (1990); Timothy Altomari and Lincoln Wolfenstein, Phys. Rev. Lett. **58**, 1583 (1987); Phys. Rev. D **37**, 681 (1987); Howard Georgi, Harvard Univ. preprint HUTP-90/A007, January, 1990 (unpublished); Adam F. Falk, Howard Georgi, Benjamin Grinstein, and Mark B. Wise, Harvard Univ. preprint HUTP-90/A011, February, 1990 (unpublished); J. D. Bjorken, SLAC report SLAC-PUB-5278, June, 1990, invited talk presented at Les Rencontres de Physique de la Vallee d'Aoste, La Thuile, Aosta Valley, Italy, Mar. 18-24, 1990; Nathan Isgur and Mark B. Wise, Phys. Lett. **B232**, 113 (1989).

27. Jonathan L. Rosner, Enrico Fermi Institute report EFI 90-62, August, 1990, to be puboished in Phys. Rev. D.

28. Daniela Bortoletto and Sheldon Stone, Cornell report CLNS 90/1018, Sept., 1990 (unpublished).

29. ARGUS Collaboration, H. Albrecht et al., Phys. Lett. B **219**, 121 (1989); Daniela Bortoletto, Ph.D. Thesis, Syracuse University, 1989; Sheldon Stone, presented at conference on Weak Decays of Heavy Quarks, Santa Barbara, CA, May, 1990, proceedings to be edited by M. Witherell and F. Gilman.

30. J. D. Bjorken, Nucl. Phys. (Proc. Suppl.) **11**, 325 (1989).

31. Jonathan L. Rosner, Enrico Fermi Institute report EFI 90-63, September, 1990 (in preparation), to be published in Proceedings of TASI-90, edited by M. Cvetic and P. Langacker (World Scientific, Singapore, 1991).

B. E. J. MARTINEC and students G. Harris and J. Bienkowska

1. *Matrix Models of String Dynamics*

Recently a great deal of progress has been made in the nonperturbative formulation of low-dimensional toy models of string theory – two-dimensional gravity coupled to $c < 1$ matter – by formulating the theory in terms of matrix integrals[1]. Soluble matrix integrals give the full partition function for string theory in simple backgrounds. By considering worldsheets which are triangulated (or more generally, cut up into polygons), one can map these theories onto 'random matrix models'. The correlation functions of observables in these polygonated lattice models can be expressed in terms of functional integrals over $N \times N$ matrices in the $N \to \infty$ limit. Recently, a large amount of attention has been focused on integrals over Hermitian matrices, which describe matter coupled to oriented worldsheets. In a landmark discovery, Brezin and Kazakov, Douglas and Shenker, and Gross and Migdal[2,3] showed that exact nonperturbative expressions for the free energy and correlation functions of these systems could be computed in the continuum limit. One of the most exciting features of the matrix approach is its radical departure from standard descriptions of string theory. Although the string partition function is expressed as a functional integral over matrices, it is not a field theory in the usual sense; the asymptotic expansion of the partition function in powers of the *string* coupling constant has no string Feynman graph representation as far as we know. At the same time in these simple cases it is a powerful analytical tool giving us the first glimpses of nonperturbative structure in string theory.

We performed[4] an analysis similar to that of Ref. [2] for the real-symmetric matrix model, which describes matter coupled to unoriented worldsheets. Using standard orthogonal polynomial techniques[5] to manipulate the random matrix functional integrals, we obtained an expression for the free-energy of unoriented surfaces in terms of solutions to a pair of coupled non-linear differential equations. We computed the coefficients of the weak-coupling expansion of the free energy, and the asymptotic form of the leading non-perturbative corrections. The asymptotic analysis indicated that the differential equations (with appropriate boundary conditions) that we had obtained only determined the free-energy up to a three-parameter family of ambiguities. With the aid of arguments based on the graphical expansion of the matrix models, we also argued that the symplectic matrix ensemble, as studied by Myers and Periwal[6] (in which one integrates over real self-dual quaternionic matrices) also describes unoriented surfaces. The free energy of the symplectic ensemble is given by a different branch of the solution of the differential equations we derived for real-symmetric matrices. By inspection of the weak-coupling expansion of this solution, one can see that the symplectic theory is non-unitary. (Similar results were also obtained by Brezin and Neuberger[7]).

Our attempts to compute correlation functions of the scaling operators in the real-symmetric theory using standard orthogonal polynomial and field-theoretic methods have been mainly unsuccessful. In the case of orientable surfaces one represents the partition function in terms of matrix elements in a Hilbert space spanned by a set of polynomials orthogonal with respect to the measure induced by the matrix potential. In our case this is a difficult problem because the Jacobi operator, which describes the insertion of the matrix, is non-local in the orthogonal polynomial basis; there is also no simple Hilbert space representation of the partition function. Thus, to compute correlation functions, we derived and studied the Schwinger-Dyson (loop) equations for these models. We found that we were indeed able to calculate the correlation functions perturbatively (in $1/N$). In the Hermitian case, the Schwinger-Dyson equations in the double-scaling limit are equivalent to Virasoro constraints on the partition function. An analysis of these constraints allows one to determine the correlation functions in terms of quantities that appear in the study of the KdV hierarchy. We had only some limited partial success in performing a similar analysis for the corresponding S-D equations for unoriented strings. We derived equations that related insertions of continuum relevant operators, but unfortunately were unable to extract the relations describing the insertion of irrelevant operators. (In the real-symmetric case, we found that we needed, but could not easily determine, exact expressions for the irrelevant operators in terms of the matrix polynomials.) We are in the process of writing up this work.

2. *Integrability and Matrix Models*

One of the most remarkable features is that the continuum theory is governed by an integrable system – the KP hierarchy of commuting differential operators[3][8][9]. The Lax operators of KP provide different realizations of the Heisenberg algebra of the matrix spectral parameter and its conjugate momentum[9] and the commuting KP flows parametrize the space of gravitational field theories for low c_{matter}. Continuum analyses suggest[8][10] that the partition function is a tau function of the KP hierarchy (determinant of the Dirac operator in a special flat background gauge field). I showed that as soon as one passes to the orthogonal polynomial formulation of the matrix problem[5] an integrable system governs changes in the matrix potential. This system is the Toda lattice hierarchy, and the times (angle variables) of the commuting flows are the coupling constants of the matrix potential. Fundamentally commutativity is simply well-definedness of correlation functions. The Hilbert space formulation in terms of orthogonal polynomials translates this into a classical integrable system. Thus the differential operator formalism of the continuum is rooted in a discrete integrable matrix dynamics. The partition function proves to be a tau function of the Toda lattice hierarchy. The associated linear problem is equivalent to finding the polynomial basis which diagonalizes the partition function. The cases of one Hermitian matrix (related to the 1d Toda hierarchy), one unitary matrix (the quaternionic Toda system), and Hermitian matrix chains (the 2d Toda hierarchy) all fall within this framework. The continuum dynamics is very closely reflected in that of the lattice theory, as is common in integrable field theories. Currently I am pursuing extensions of this work: the nature of the Toda tau function that arises in the matrix model, derivation of the scaling limit for multimatrix models, and the search for connections to more standard field theoretic approaches to 2d gravity. Preliminary results indicate that it should be possible to derive Douglas' ansatz[9] for the KP system from the two-matrix problem. In addition I am pursuing the possibility of extending this integrability to large-N gauge theory in two and perhaps higher dimensions.

3. *Supersymmetric RG flows and nonrenormalization*

My student J. Bienkowska and I have recently completed a study of the renormalization group flows between the simplest solvable series of N=2 supersymmetric 2d conformal field theories. This study was undertaken to see whether nonrenormalization theorems proven in the context of the loop expansion are still valid in the vicinity of nontrivial infrared fixed points. To this end, following the general program of Zamolodchikov[11] we calculated in composite operator perturbation theory the beta function and anomalous dimensions along the simplest trajectory (perturbing by the highest dimension relevant operator). We verified the nonrenormalization theorem in lowest nontrivial order, and presented a geometrical picture of the space of coupling constants.

1. F. David, Nucl. Phys. **B257** (1985) 45; V. Kazakov, Phys. Lett. **150B** (1985) 285.

2. E. Brezin and V. Kazakov,"Exactly Solvable Field Theories of Closed Strings", Phys. Lett. **236B** (1990) 144; M. Douglas and S. Shenker,"Strings in Less than One Dimension", Nucl. Phys. **B335** (1990) 635.

3. D. Gross and A. Migdal,"Nonperturbative Two-Dimensional Quantum Gravity", Phys. Rev. Lett. **64** (1990) 127.

4. G. Harris and E. Martinec, "Unoriented Strings and Matrix Ensembles" (EFI-90-30) to appear in Phys. Lett. B.

5. D. Bessis, C. Itzykson, and J.-B. Zuber,"Quantum Field Theory Techniques in Graphical Enumeration", Adv. Appl. Math. **1** (1980) 109.

6. R. Myers and V. Periwal, ITP preprint NSF-ITP-90-50.

7. E. Brezin and H. Neuberger, Rutgers preprint RU-90-39.

8. T. Banks, M. Douglas, N. Seiberg, and S. Shenker,"Microscopic and Macroscopic Loops in Nonperturbative 2d Quantum Gravity", Phys. Lett. **238B** (1990) 279.

9. M. Douglas,"Strings in Less than One Dimension and the Generalized KdV Hierarchies", Phys. Lett. **238B** (1990) 176.

10. M. Fukuma, H. Kawai, and R. Nakayama,"Continuum Schwinger-Dyson Equations and Universal Structures in 2d Quantum Gravity", Tokyo preprint UT-562 (May 1990); R. Dijkgraaf, E. Verlinde, and H. Verlinde,"Loop Equations and Virasoro Constraints in Nonperturbative 2d Quantum Gravity", Princeton preprint PUPT-1184 (May 1990).

11. A. B. Zamolodchikov, Yad. Fiz. **46** (1987) 1819 [Sov. J. Nucl. Phys. **46** (1987) 1090].

C. R. G. SACHS AND COLLABORATORS

1. *Resolution of the θ vacuum degeneracy problem*

The P, T, and C properties of the θ vacuum state $|\theta$ vac have been reexamined. It has been shown that

$$P|\theta,\ \text{vac}\rangle = |-\theta,\ \text{vac}\rangle \quad ; \quad T|\theta,\ \text{vac}\rangle = |-\theta,\ \text{vac}\rangle \quad ; \quad C|\theta,\ \text{vac}\rangle = |\theta,\ \text{vac}\rangle \quad . \tag{1}$$

Therefore the θ vacuum is CPT invariant. However the vacuum states with $\theta = \pm|\theta|$ are still found to be degenerate with one another not because of the CPT invariance of the Lagrangian as suggested earlier[1] but because the instanton coupling between n-states is the same for increasing and decreasing values of n[2].

I have suggested[3] that the problem of strong CP violation may be circumvented by requiring as a boundary condition on QCD that the physical vacuum be invariant under P and T. Then, according to Eq. (1), the physical vacuum state is the linear combination of degenerate states

$$|\text{vac}\rangle = [|\theta,\ \text{vac}\rangle + |-\theta,\ \text{vac}\rangle]/\sqrt{2} \tag{2}$$

All other pure QCD states are then similar linear combinations of θ states. As a result all P and T violating effects are eliminated from pure QCD.

In particular electric dipole moments of particles, like that of the neutron, vanish unless there is some other source of P and T violation. As a consequence the measured value of the edm of the neutron cannot be used to place a limit on the value of θ. Other methods of determining θ include a comparison of the original calculations of the neutron edm[4] with the anomalous magnetic moment of constituent quarks estimated[5] from the measured magnetic moments of the baryons. Inaccuracies in both theory and the phenomenological estimates of quark anomalous moments make it impossible at this time to limit the range of possible values of θ. It is noteworthy that, under the boundary conditions specified here, any magnetic monopole moment induced by the θ term in QCD would vanish.

2. *Phenomenological estimate of neutron electric dipole moment for strong CP violation[6]*

Strong CP violation is a consequence of the P- and T-violating term in the Lagrangian of the gluon field when it is in interaction with fermions (quarks) of finite mass. Therefore it should be possible to demonstrate that this pure form of QCD leads to P- and T- violating physical phenomena, like the edm of the neutron, without invoking any other aspects of the theory, such as broken $SU(2)\otimes SU(2)$ which is usually[4] used to calculate the edm by chiral perturbation theory.

I have been able to make use of the structure of pure QCD to show that the expectation values of P- and T-violating observables and P- and T-invariant observables are related by a chiral rotation by the angle θ. In particular the electric dipole moment of a constituent quark is $\tan\theta$ times the anomalous magnetic moment of the quark.

Estimates of the anomalous moments of the quarks by Brekke[7] based on a phenomenological analysis of the magnetic moments of the octet of baryons have been used to obtain a phenomenological estimate of the edm of the neutron due to strong CP violation. Within the uncertainties the numerical results are in good agreement with theoretical estimates based on chiral perturbation theory.

On the basis of this numerical agreement I suggested[6] that the seemingly intractable problem[8] of calculating the anomalous magnetic moment of a constituent quark might be susceptible to treatment by means of chiral perturbation theory. Since then Weinberg[9] seems to have confirmed that speculation.

3. *An alternate formulation of the CP question.*

The work on this problem described in detail in last year's Technical Progress Report has now been published[10]. Related new work is reported in 1 and 2 above and work on this problem is continuing.

4. *Electric dipole moment of the neutron, relationship to ϵ'*

This work on conventional weak interaction effects, described in detail in last year's Technical Progress Report, has now been published[11]. (6 copies of the reprint were forwarded early last year for attachment to the 1990-91 proposal.)

5. *Relationship between neutron dipole moment and ϵ'*

M. Booth reports below on this work, which was outlined in last year's proposal as Proposed Research.

6. *Correlations between jets from e^+e^- collisions as a test of CP violation*

This work by M. Kamionkowski, also described in last year's Technical Progress Report, has been published[12]. (6 copies of the reprint are attached.)

1. Question about the CPT Theorem, Nucl. Phys. (Proc. Suppl.) **6**, 90 (1989).
2. See J. D. Bjorken, Proceedings of Summer Institute on Particle Physics: Quantum Chromodynamics, ed. A. Mosher (1979), Stanford Linear Accelerator Center-224 (unpublished), p. 284.
3. Preprint No. EFI 90-44, submitted to Phys. Rev. Letters (copy attached).
4. V. Baluni, Phys. Rev. D **19**, 2227 (1979); R. J. Crewther, P. Di Vecchia, G. Veneziano and E. Witten, Phys. Lett. **88B**, 123 (1979).
5. L. Brekke, University of Chicago thesis, unpublished Enrico Fermi Institute preprint No. EFI 87-52 (1987).
6. R. G. Sachs, preprint EFI 90-17 (1990). Submitted to Phys. Rev. Lett. (copy attached).
7. See Item II A.6. of Technical Progress Report with Task A proposal for 1988-89 and reference 5 above.

8. See D. A. Geffen and W. Wilson, Phys. Rev. Lett. **44**, 370 (1980).

9. S. Weinberg, Phys. Rev. Lett. **65**, 1181 (1990).

10. R. G. Sachs, CP or T violation? in *CP Violation in Particle Physics and Astrophysics*, edited by J. Tran Thanh Van, Gif-sur-Yvette, France: Editions Frontières (1990), p. 205.

11. M. J. Booth, R. A. Briere and R. G. Sachs, Phys. Rev. D **41**, 177 (1990).

12. M. Kamionkowski, Searching for CP violation in "charge-blind" jets, Phys. Rev. D **41**, 1672 (1990).

D. C. QUIGG AND COLLABORATORS

Upon completing my work as deputy director of the SSC Central Design Group in October, 1989, I spent a year as visiting scientist in the Theoretical Physics Group at Lawrence Berkeley Laboratory. My principal physics research interest was in the scientific possibilities of multi-TeV hadron colliders. I investigated several questions independently or in association with Ian Hinchliffe, and provided informal advice to Berkeley members of the collaboration proposing a solenoidal detector for the SSC.

In January 1990, I served on the Drell subpanel reviewing physics options for the SSC.

In February 1990, I presented a course of five lectures on supercollider physics to the elementary particle physics department at Saclay, outlining the range of physics possibilities and important detector issues for experimentation at the SSC and LHC.

In May 1990, I participated in the Santa Barbara workshop on physics of heavy quarks.

In June 1990, I presented a course of four lectures on supercollider physics at the Beijing Symposium / Workshop on physics of the TeV scale. A written version of these lectures, which incorporates some of the calculations I carried out during the year, will be published in the proceedings of the workshop.

I am currently investigating various possibilities for gauge-boson scattering at energies approaching 1 TeV to understand how resonant and nonresonant structures in low partial waves can distinguish among models for electroweak symmetry breaking.

E. PETER BOWCOCK

In the last year, I have completed a project examining the associativity of chiral algebras in conformal field theory using quasi-primary fields. An explicit expression for Jacobi's identity was found, using the crossing symmetry of four-point functions to define a generalisation of Racah coefficients which are needed [1]. I have also been collaborating with Ruth Gregory, studying the problem of two-dimensional tunneling. For the potentials we consider, the particle is only bound in one direction, while classically free to move in the other. The problem is motivated by the recent interest in calculating bubble nucleation rates in extended inflation, where such potentials arise. We are presently writing this work up [2].

1. Quasi-primary fields and associativity of chiral algebras, Enrico Fermi Institute report EFI 90-54.

2. Tunneling in extended inflation, in progress (with R. Gregory)

F. ANNE TAORMINA

The study of 2-dimensional conformal field theory and its extensions by different kinds of continuous or discrete symmetries is a keystone in the understanding of string theory and statistical mechanics.

In particular, all conformal algebras extended by N supersymmetry generators appear as subalgebras of an $N = 4$ superconformal algebra (SCA) with two central extensions. This is the largest possible SCA (under conventional hypothesis) and it is associated with the symmetries of a superstring compactified on an absolutely parallelizable group manifold of the type 'quaternionic symmetric space' $\times SU(2) \times U(1)$. I have continued this year my analysis of the representation theory of this algebra. Indeed, the particle content of the theory is encoded in the partition function, which is a modular invariant bilinear in the characters of the unitary representations. Therefore, the derivation of the characters [1,2] and the knowledge of their modular properties [3] is extremely valuable in any attempt to use this SCA in a physical application.

Some (extended) CFT's are rational, which means that only a finite number of representations of the associated chiral algebra are involved in the description of the Hilbert space. Such theories are therefore particularly attractive and have been successfully used in both statistical mechanics and string theory. In general, a rational CFT cannot be based on the doubly extended $N = 4$ SCA I am currently studying since it does not have discrete series representations. Nevertheless, rather simple extensions of this chiral algebra do give rise to finite dimensional representations of the modular group and therefore, to rational theories [3,4].

1. Petersen J. L. and Taormina A., Nucl. Phys. **B331** (1990) 556,
"Characters of the N=4 superconformal algebra with two central extensions."

2. Petersen J. L. and Taormina A., Nucl. Phys. **B333** (1990) 833,
"Characters of the N=4 superconformal algebra with two central extensions. II Massless representations."

3. Petersen J. L. and Taormina A., EFI-90-61 and NBI-90-43, preprint, August 1990,
"Modular transformations of doubly extended N=4 superconformal algebras and their connections to rational torus models I."

4. Petersen J. L. and Taormina A. (in preparation)
"The biggest of all conventional superconformal algebras : modular properties and coset constructions."

G. M. BOOTH (Adviser: R. G. Sachs)

Connection between ϵ' and D_n.

This work was an effort to elaborate on the connection between ϵ' and D_n which was established in Ref [1]. I wanted to see if one could use information about the *sign* of D_n to predict the sign of ϵ' (strictly speaking, limits on D_n constrain only the magnitude, but recent experiments have reported negative central values). The predictions for ϵ' have changed so much over time because of problems in accounting for the long distance contributions. My hope was that the sign, at least, would be insensitive to these effects. To establish this connection, one must know the sign of the hadronic matrix element $< \pi\pi|\bar{s}\sigma^{\mu\nu}\gamma_5\frac{\lambda^a}{2}dG^a_{\mu\nu}|K^o >$. $\langle\pi\pi|\bar{s}\sigma^{\mu\nu}\gamma_5\frac{\lambda^a}{2}dG^a_{\mu\nu}|K^o\rangle$. This matrix element has been estimated in the past[2], but never with attention to the sign. I established that the sign is insensitive to the approximations used in the calculation of the matrix element.

Unfortunately, the connection between D_n and ϵ' requires that D_n be dominated by the individual quark moments. This was believed to be true because the exchange moments are suppressed by small quark masses. However, it is now believed that the so-called Weinberg Mechanism[3] dominates, so that the connection no longer holds.

Isospin Violation in Neutral K_{e4} decays.

K_{e4} decays, that is, $K \to \pi\pi e\nu$, are usually thought of as tests of current algebra and as a means of measuring the $\pi\pi$ scattering phase shift δ_1. However, in neutral K_{e4} ($K^\circ \to \pi^-\pi^\circ e\nu$), one can also look for isospin violation. Isospin symmetry requires the two pions to be in a P-wave state. Thus, finding the pions in an S-wave is a signal of isospin violation. This has an aesthetic and experimental advantage over the observation of isospin violation in K_{e3} decay, in that it can be seen directly in the decay distribution of one particle. In K_{e3} the effect can only be seen by comparing the rates in charged and neutral modes[4], which are usually measured in different experiments. Isospin violation should occur at the 3% level and should be seen in the next generation of E731 at Fermilab. It may even be visible in the current K_{e4} sample, though it will be difficult to separate from the electromagnetic corrections which also produce an S-wave decay.

Background Field Method, Operator Formalism and CP violation.

In this work, which I am currently preparing for publication, I show how the background-field calculations of Weinberg type operators (that is, operators of the form $Tr_{dirac,color}((\sigma^{\mu\nu}G_{\mu\nu})^n\gamma_5)$) simplify when one uses the operator formalism of NSVZ[5]. This simplification is important because it allows the calculation of these operators for the Standard Model.

1. M. J. Booth, R. A. Briere and R. G. Sachs, Phys. Rev. D**41**, 177 (1990).
2. John F. Donoghue and Barry R. Holstein, Phys. Rev. D **32**, 1152 (1985).
3. S. Weinberg, Phys. Rev. Lett. **63**, 2333 (1989).
4. Tran N. Truong, preprint Print-89-0037 (ECOLE POLY) (1988).
5. V. A. Novikov, M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Fortschr. Phys. **32**, 585 (1984).

H. P. KO (Adviser: J. Rosner)

I have been studying the role of vector mesons in nonleptonic rare decays, such as $K^+ \to \pi^+e^+e^-$, $K_S \to \pi^0e^+e^-$, $K_L \to \gamma e^+e^-$, $K_L \to \pi^0\gamma\gamma$, etc.

In the hidden symmetry scheme with the Wess-Zumino anomaly, we can study weak VV, $V\gamma\pi$, $V\pi$ vertices, which contribute to the above processes.

I. W. KWONG (Adviser: J. Rosner)

I have just finished a paper titled "Threshold production of $t\bar{t}$ pairs by e^+e^- collisions". I used a QCD-inspired potential to study the resonance production due to toponium formation for top quarks of 100 and 130 GeV/c^2. This is the region where toponium formation is expected to be the most relevant. The result is compared to that of open flavor production. The strong interaction involved in the process comes from final state interactions; the energy scale is therefore governed by that of the final state quarks. By recognizing this observation, it can be shown that open flavor production can also be used to describe production much closer to threshold than previously believed. This is a consequence of the large width of the top quark at these masses.

J. L. ORR (Adviser: J. Rosner)

My current and future research involves top quark phenomenology. During the past year I have investigated the interplay between top quark hadronization and decay, by comparing time scales to determine under what circumstances nonperturbative Quantum Chromodynamic (QCD) effects are likely to come into play before top decays weakly. Such questions are important for understanding the experimental signatures of top. In collaboration with J. L. Rosner I studied the case of top production in e^+e^- colliders. I am now completing the case of hadronic production, which has immediate relevance for the top search at the Fermilab Tevatron. In this case I determine in which kinematic regions hadronization is likely to be important for a given collision energy, and how this varies with top mass.

K. R. ROSENFELD (Adviser: J. Rosner)

In this past year I have finished and published my thesis work concerning resonances in the strongly interacting Higgs sector (Phys. Rev. D **42**, 126

(1990)). I used a certain prescription to unitarize the scattering amplitudes of longitudinally polarized electroweak gauge bosons (V_L). This unitarization prescription introduces resonances whose masses were estimated by demanding that crossing symmetry is minimally violated. I also computed the effects of these resonances in the cross section for $V_L - V_L$ scattering in proton-proton colliders and compared it with the Standard Model predictions.

RECENT PUBLICATIONS

(*denotes an updated reference from last year)

JADWIGA BIENKOWSKA

The Renormalization Group Flow in $2-D$ $N=2$ SUSY Landau-Ginsberg Models, with Emil Martinec, Enrico Fermi Institute report EFI-90-62, August, 1990.

MICHAEL BOOTH

*Interpretation of the Neutron Electric Dipole Moment: Possible Relation to ϵ', with R. Briere and R. G. Sachs, Phys. Rev. **D41**, 177 (1990).

PETER BOWCOCK

Quasi-primary fields and associativity of chiral algebras, Enrico Fermi Institute report EFI 90-54, July, 1990.

GEOFFREY HARRIS

Unoriented Strings and Matrix Ensembles, with Emil J. Martinec, Enrico Fermi Institute report EFI 90-30, April, 1990.

MARK KAMIONKOWSKI

*Searching for CP Violation in "Charge-Blind" Jets, Phys. Rev. D **41**, 1672 (1990).

PYUNGWON KO

*Vector-meson Contributions to the Processes $\gamma\gamma \to \pi^0\pi^0, \pi^+\pi^-$, $K_L \to \pi^0\gamma\gamma$ and $K^+ \to \pi^+\gamma\gamma$, Phys. Rev. D **41**, 1531 (1990).

Analysis of 2γ and $\pi^+\pi^-\gamma$ Decays of η and η' using Chiral Anomalies, with Tran N. Truong, Enrico Fermi Institute report EFI 90-40, May, 1990.

The Role of Vector Mesons in Nonleptonic Kaon decays, Enrico Fermi Institute report EFI 90-66, September, 1990.

WAIKWOK KWONG

Threshold Production of $t\bar{t}$ pairs by e^+e^- Collisions, Enrico Fermi Institute report EFI 90-22, May, 1990, submitted to Phys. Rev. D.

MICHAEL MATTIS

*Nonrenormalization Theorem for Large N_c selection Rules, Phys. Rev. Lett. **63**, 1455 (1989).

* $1/N_c$ corrections to π-Nucleon Scattering Relations in Chiral Soliton Models, with R. D. Amado and M. Oka, Phys. Rev. D **40**, 3622 (1989).

EMIL J. MARTINEC

*Criticality, Catastrophes, and Compactifications, to appear in the V. G. Knizhnik Memorial volume, L. Brink et al. (eds.), World Scientific Publishing Co., 1990, p. 389-433.

See also: Jadwiga Bienkowska, Geoffrey Harris

LYNNE ORR

Comparison of Top Quark Hadronization and Decay Rates, with Jonathan L. Rosner, Phys. Lett. B **246**, 221 (1990).

CHRIS QUIGG

"The Superconducting Super Collider: A New Instrument for Particle Physics," in *International Research Facilities,* Proceedings of the IV European Physical Society Seminar, Zagreb, Yugoslavia, March 17-19, 1989, edited by Ivo Slaus (European Physical Society, Ruder Boskovic Institute, Zagreb, 1989), p. 69.

"Uses of Particle Identification for Supercollider Physics," in *Proceedings of the Symposium on Particle Identification at High-Luminosity Hadron Colliders,* Fermilab, April 5-7, 1989, edited by Treva J. Gourlay and Jorge G. Morfín (Fermilab, Batavia, Illinois, 1989), p. 3.

*SSC Status Report, to appear in *New Results in Hadronic Interactions,* Proceedings of the XXIV Rencontres de Moriond, Les Arcs, France, March 12-18, 1989, edited by J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, France, 1990), p. 145.

*The Physics Program of the SSC, *Proceedings of the Workshop on Tracking Systems for the Superconducting Super Collider*, Vancouver, July 24-28, 1989, p. A23.

Report of the 1990 HEPAP Subpanel on SSC Physics, with Sidney D. Drell *et al.*, DOE/ER-0434 (January, 1990).

Hadron Supercolliders: The 1-TeV Scale and Beyond, LBL-29453, August 10, 1990, to appear in the Proceedings of the Workshop/Symposium on TeV Physics, Beijing, May 28-June 8, 1990, to be published by Gordon and Breach.

ROGERIO ROSENFELD

*Resonance Production in a Strongly Interacting Higgs Sector, Mod. Phys. Lett. **A4**, 1999 (1989).

*Resonances in the Higgs Sector for Large, Finite Higgs-boson Mass, Phys. Rev. D **42**, 126 (1990).

JONATHAN L. ROSNER

*Heavy Flavor Theory, in *Particles and Fields 3* (Proceedings of the Banff Summer Institute (CAP) 1988, Banff, Alberta, Canada, August 14-26, 1988), edited by A. N. Kamal and F. C. Khanna (World Scientific, Singapore, 1989), p. 395.

*Reflectionless Approximations to Potentials with Band Structure, Ann. Phys. **200** 101 (1990).

*Physics at Fermilab in the 1990's: Workshop Summary, in *Proceedings of the Workshop on Physics at Fermilab in the 1990's*, edited by D. Green and H. J. Lubatti (World Scientific, Singapore, 1990), p. 15.

*Impact of New $\mid V_{ub}/V_{cb} \mid$ and ϵ'/ϵ Measurements on Weak Mixing Angles, with C. S. Kim and C.-P. Yuan, Phys. Rev. D **42**, 96 (1990).

*Comment on "Two-Angle Parametrization of the Kobayashi-Maskawa Matrix", Phys. Rev. Lett. **64**, 2590 (1990).

Particle Physics at the Crossroads, in *Trends in Theoretical Physics*, Vol. 2, edited by P. J. Ellis and Y. C. Tang (Addison-Wesley, Redwood City, CA, 1990), p. 141.

Some Signatures of Right-Handed W Bosons at Hadron Colliders, with E. Takasugi, Phys. Rev. D **42**, 241, 1990.

Radiative Corrections and Electroweak Observables, Enrico Fermi Institute report EFI 90-18, to be published in Phys. Rev. D **42**, November, 1990.

Determination of Pseudoscalar Charmed Meson Decay Constants from B Meson Decays, Enrico Fermi Institute report EFI 90-52, August, 1990, to be published in Phys. Rev. D.

Atomic Parity Violation as a Probe of New Physics, with William J. Marciano, Enrico Fermi Institute report EFI 90-55, August, 1990, submitted to Phys. Rev. Letters.

Heavy Quarks, Quark Mixing, and CP Violation, Enrico Fermi Institute report EFI 90-63, Sept., 1990 (in preparation), based on lectures delivered at TASI-90, Boulder, CO, June, 1990, proceedings to be published by World Scientific.

See also: Lynne Orr.

ROBERT G. SACHS

*CP or T violation? in *CP Violation in Particle Physics and Astrophysics*, edited by J. Tran Thanh Van, (Editions Frontières Gif-sur-Yvette, France 1990), p. 205.

Phenomenological Estimate of Neutron Electric Dipole Moment for Strong CP Violation, Enrico Fermi Institute report EFI 90-17, March, 1990 (submitted to Phys. Rev. Lett.)

A Possible Resolution of the Strong CP Problem, Enrico Fermi Institute report EFI 90-44, June, 1990 (submitted to Phys. Rev. Lett.)

See also: Michael Booth.

ANNE TAORMINA

*Extended Conformal Field Theories, Nucl. Phys. B. (Proc. Suppl.) **16**, 612 (1990).

Characters of the $N = 4$ Superconformal Algebra with Two Central Extensions, with J. L. Petersen, Nucl. Phys. **B331**, 556 (1990).

Characters of the $N = 4$ Superconformal Algebra with Two Central Extensions: 2. Massless Representations, with J. L. Petersen, Nucl. Phys. **B333**, 833 (1990).

TRAN N. TRUONG

Unitarized Chiral Perturbation Theory and Rare Decay of Mesons, Enrico Fermi Institute report EFI 90-26, Jan., 1990, lectures given at Ettore Majorana International School on Low Energy Antiproton Physics, Erice, Italy, Jan. 25-31, 1990.

See also: Pyungwon Ko.

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