THEORETICAL HIGH ENERGY PHYSICS RESEARCH AT
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MASTER

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Task A

TECHNICAL PROGRESS REPORT

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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), R. Keith Ellis (Fermilab and Chicago), Research Associates Peter Bowcock and Anne Taormina, and graduate students in elementary particle physics at the University of Chicago. Glenn Boyd and Petr Horava have recently joined our group as a Research Associate and a McCormick Fellow, respectively.

The present report deals with work performed during the last three months of Calendar Year 1990 and the first nine months of Calendar Year 1991. For earlier work, see previous Technical Progress Reports.

Dr. R. Keith Ellis of Fermilab visited the University of Chicago during three months in the spring of 1991. He performed research on heavy quark production and gave lectures on perturbative quantum chromodynamics.

II. RESEARCH ACTIVITIES

A. J. ROSNER, COLLABORATORS, AND STUDENTS

J. Rosner's lectures at the TASI-90 summer school in Boulder in June of 1990 (see previous year's Progress Report) have been published.¹ He delivered four lectures on electroweak physics at a winter school in Mexico.² He gave invited talks on the same subject at a workshop in Santa Barbara in February of 1991; at the Spring, 1991, Washington Meeting of the American Physical Society;³ and at a conference on the intersections of particle and nuclear physics in Tucson in May of 1991.⁴ In August of 1991 he participated in a workshop on "Frontiers of Electroweak Physics" in Santa Fe and served as a co-organizer of a parallel session on electroweak interactions at the DPF Meeting in Vancouver.

1. *CP violation and Cabibbo-Kobayashi-Maskawa matrix*

Present experimental information constrains parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. These constraints depend on quantities whose magnitudes are governed by poorly known aspects of hadron physics - particularly the B meson decay constant f_B . An update of a joint work with C. S. Kim and C. P. Yuan⁵ was performed in collaboration with Geoffrey Harris, a student at Chicago, in order to explore remaining uncertainties in CKM matrix elements. Recent lattice gauge theory calculations of f_B indicate that it could be larger than naive quark model estimates, and the degree to which the data permit such a possibility were of special concern. Experiments which would shed light on the value of f_B and on CKM matrix elements were studied. This work is in progress; a preliminary version⁶ was found to have a programming error and is undergoing revision.

A review of the CKM matrix was written;⁷ this review is based in part on the work of Ref. 6 and hence similar revisions are necessary for it.

Further investigations regarding possible quark mass matrices leading to the observed form of the KM matrix were performed. Model hamiltonians were

constructed in order to visualize the effects of mixing in three-state systems, such as the spin-1/2 particles formed out of three spin-1/2 and one spin-1 constituent. This work is continuing. It may involve participation by a new graduate student, Mihir Worah, who received top marks on the Candidacy Exam.

Implications of CKM parameters for CP violation will be explored once more is known about the top quark mass (see subsection 5, below).

2. *Strongly interacting Higgs sector*

Work on implications of a very heavy top quark for non-universal couplings of the weak axial current, explored by R. Rosenfeld and J. Rosner using analogues of the Goldberger-Treiman and Adler-Weisberger relations for the strongly interacting Higgs sector, has been completed and is to be published.⁸

3. *Radiative corrections and electroweak observables*

An investigation by W. Marciano and J. Rosner of constraints on electroweak theories following from atomic parity violation (see last year's Progress Report) experiments has been published.⁹

Further LEP data has been incorporated into later analyses by J. Rosner of similar constraints.²⁻⁴ Upper limits on the top quark mass remain around 200 GeV/ c^2 , while the central value of the parameter S (as defined in Ref. 10) appears to be about -1 , with errors consistent with $S = 0$. Both the atomic parity violation experiment of Ref. 11 and forward-backward asymmetries in $e^+e^- \rightarrow b\bar{b}$ at the Z^0 favor $S < 0$, but with large errors. Prospects for improved experiments were discussed in Refs. 2-4.

4. *Top quark physics*

L. Orr's Ph. D. thesis on top quark fragmentation and decay in hadronic production processes (see last year's Progress Report) has been published.¹² Ms. Orr accepted an SSC Fellowship and is now at the University of California, Davis.

Waikwok Kwong's work on the threshold behavior of $t\bar{t}$ production in e^+e^- collisions (see last year's Progress Report) has been published.¹³

The work in collaboration with G. Harris on the CKM matrix, described in subsection 1 above, was partly performed in anticipation of forthcoming searches at Fermilab by the CDF and D0 Collaborations. If the top quark is found in the 1992-3 Collider run (with a mass of $140 \text{ GeV}/c^2$ or less), a positive value of ϵ'/ϵ in the kaon system of order 10^{-3} is expected.^{1,14} [At present, the experimental values are $6.0 \pm 6.9 \times 10^{-4}$ (Ref. 15) and $23 \pm 7 \times 10^{-4}$ (Ref. 16).] The analysis of Ref. 6 will be updated further if new information is forthcoming on the top quark.

5. *Pseudoscalar meson decay constants and heavy quark symmetry*

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. An estimate of heavy meson decay constants, mentioned in last year's Progress Report,¹⁷ was updated for the Snowmass 90 proceedings.¹⁸

J. Amundson, a graduate student, is currently studying the insight heavy quark symmetry¹⁹ provides into the decays of charmed mesons. The pattern of (appreciable) deviations of predictions from experiment is expected to provide warning signals in similar applications to decays of B mesons, where the symmetry is expected to be better (but not perfect).

6. *Heavy meson spectroscopy*

W. Kwong and J. Rosner have analyzed the range of likely mass values for mixed-flavor heavy mesons such as $\bar{B}_s (= b\bar{s})$ and $\bar{B}_c (= b\bar{c})$. This work has been published.²⁰

7. *Hadronic string theory*

P. Freund and J. Rosner have examined the implications of a recent observation²¹ that in tachyon-free string theories the ratio of the densities of bosonic and

fermionic states must approach unity with increasing energy. It was concluded²² that the result implies the existence of a large number of as yet unseen meson states above $1.7 \text{ GeV}/c^2$.

8. *Composite models of quarks and leptons*

Davison Soper (now back at Oregon after a year at CERN) and J. Rosner continued a collaboration begun during J. Rosner's visit to CERN in October of 1990. Recent studies of radiative corrections to electroweak processes restrict the particle content of dynamical symmetry breaking schemes. (See subsection 3, above.) The minimal anomaly-free model with one doublet of Dirac fermions $F = (U, D)$ having charges $Q = \pm 1/2$ is consistent with such restrictions. These fermions may be regarded as the constituents of a strongly interacting Higgs sector, so that the longitudinal W and Z , and higher-spin excitations of them, are all composites of F 's. It is then natural to ask if these fermions can be the sole carriers of weak $SU(2)$, so that quarks and leptons would also have to be composed of them. Some tests of this hypothesis in hadronic and e^+e^- collisions were suggested.²³

Gerard Jungman (a graduate student at Chicago) and J. Rosner studied bounds on rare processes which can provide severe constraints on non-standard interactions which arise, for example, in composite models of quarks and leptons. The most strict bounds were found to come from $K^0 - \bar{K}^0$ mixing, with somewhat more model-dependent ones from $\mu \rightarrow e\gamma$.²⁴

9. *Rare kaon decays and chiral dynamics* (Pyongwon Ko)

a) The role of vector mesons was studied in K_{e4} decays, which have recently been measured by Greg Makoff (a member of the Fermilab E731 Collaboration) for his Ph. D. thesis at Chicago. It was found that vector mesons generate appropriate form factor dependence, thus improving the lowest order prediction of the chiral Lagrangian. A branching ratio $B(K_L \rightarrow \pi^0 \pi^\pm \pi^\mp e^\pm \nu) = 5.2 \times 10^{-5}$ was predicted.²⁵

b) The vector meson contributions to the dispersive part of the $K_L \rightarrow \mu^+ \mu^-$ amplitude due to two-photon intermediate states were reconsidered. It was found that this dispersive part could be appreciable, and that this piece and the short-distance contribution tend to cancel one another.²⁶ Thus, in contrast to some recent claims, a considerable short-distance contribution (even as large in magnitude as the absorptive two-photon part⁵) is permitted, so that one cannot extract stringent bounds on m_t from $B(K_L \rightarrow \mu^+ \mu^-)$.

c) The interference between direct and indirect CP-violating amplitudes in $K_L \rightarrow \pi^0 e^+ e^-$ was studied²⁷ in the framework of Ko's hidden symmetry approach, which predicts a very large indirect contribution,²⁸ and within more conventional chiral perturbation theory schemes.²⁹ In either case, the relative phase of the two amplitudes is about 45° , implying constructive interference as in other treatments.

10. *Intermittency in multiparticle production* (J. Amundson)

J. Amundson has been pursuing the question of intermittency in high-energy multi-particle production, following a previous interest³⁰ in light of new experimental data from LEP and CDF.

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2. Jonathan L. Rosner, Enrico Fermi Institute report EFI 91-21, May, 1991, lectures delivered at Fourth Mexican School of Particles and Fields, Oaxtepec, Morelos, December, 1990, proceedings to be published by World Scientific.
3. Jonathan L. Rosner, Bull. Am. Phys. Soc. **36**, 1396 (1991).

4. Jonathan L. Rosner, Enrico Fermi Institute report EFI 91-28, June, 1991, to be published in Proceedings of the 4th Conference on the Intersections between Particle and Nuclear Physics, Tucson, AZ, May 24-29, 1991 (New York, AIP, 1991).
5. C. S. Kim, Jonathan L. Rosner, and C.-P. Yuan, Phys. Rev. D **42**, 96 (1990).
6. Geoffrey R. Harris and Jonathan L. Rosner, Enrico Fermi Institute report EFI-91-38, Aug., 1991, revised version in preparation, to be submitted to Phys. Rev. D.
7. Jonathan L. Rosner, Enrico Fermi Institute report EFI 91-49, September, 1991, revised version in preparation, to be published as a chapter of the book *B Decays*, edited by Sheldon L. Stone (World Scientific, Singapore, 1991).
8. Rogerio Rosenfeld and Jonathan L. Rosner, Enrico Fermi Institute report EFI 91-09, to be published in Phys. Rev. D **44**, October, 1991.
9. William J. Marciano and Jonathan L. Rosner, Phys. Rev. Lett. **65**, 2963 (1990).
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12. Lynne H. Orr, Phys. Rev. D **44**, 88 (1991).
13. Waikwok Kwong, Phys. Rev. D **43**, 1488 (1991).

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15. Fermilab E731 Collaboration, presented by B. Winstein at International Symposium on Lepton and Photon Interactions, Geneva, Switzerland, July, 1991.
16. CERN NA31 Collaboration, presented by G. D. Barr at Lepton-Photon Symposium (see Ref. 15).
17. Jonathan L. Rosner, Phys. Rev. D **42**, 3732 (1990).
18. Jonathan L. Rosner, Enrico Fermi Institute report EFI 90-80, November, 1990, to be published in *Research Directions for the Decade* (Proceedings of the 1990 DPF Snowmass Workshop), edited by E. L. Berger (World Scientific, Singapore, 1991).
19. 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).
20. Waikwok Kwong and Jonathan L. Rosner, Phys. Rev. D **44**, 212 (1991).
21. David Kutasov and Nathan Seiberg, Nucl. Phys. **B358**, 600 (1991).
22. Peter G. O. Freund and Jonathan L. Rosner, Enrico Fermi Institute report EFI 91-36, August, 1991, submitted to Phys. Rev. Letters.
23. Davison E. Soper and Jonathan L. Rosner, Enrico Fermi Institute report EFI-90-75, March, 1991, submitted to Phys. Rev. D.
24. Gerard Jungman and Jonathan L. Rosner, Enrico Fermi Institute report EFI 91-37, August, 1991, submitted to Phys. Lett. B.

25. Pyongwon Ko, Enrico Fermi Institute report EFI-91-40, March 1991, submitted for publication.
26. Pyungwon Ko, Enrico Fermi Institute report EFI-91-46, August 1991, submitted for publication.
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28. Pyongwon Ko, Phys. Rev. D **44**, 139 (1991).
29. G. Ecker, A. Pich, and E. de Rafael, Nucl. Phys. **B291**, 692 (1987); **B303**, 665 (1988).
30. H. von Gersdorff, J. Amundson, *et al.*, Phys. Rev. C **39**, 1385 (1989); J. F. Amundson, Phys. Rev. C **41**, 1292 (1990).

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

Research Activities

Random surfaces coupled to simple 2d field theories are simple laboratories in which to explore string geometry. The work of David, Migdal and Kazakov rewrote the string partition function in terms of large N matrix dynamics. It has been known since the work of 't Hooft that the $1/N$ expansion of these integrals is a series organized by the topology of matrix 'Feynman graphs'. What is surprising is that one can use this approach to solve long-standing problems in 2d gravity; the evaluation of the 2d partition function in the continuum Polyakov approach an issue that is just beginning to be understood. However Douglas and Shenker, Gross and Migdal, and Brezin and Kazakov have solved pure 2d quantum gravity to all orders in string perturbation theory using these methods.

My student Geoff Harris and I succeeded¹ in extending these results to gravity on nonorientable surfaces.

In addition I became intrigued by a feature of these models related to their exact solvability, which is that the equations satisfied by the continuum partition function can be derived from the KdV integrable system, as was shown by Douglas. I wanted to understand what feature of the original matrix integral is responsible for this relation to KdV. It turns out that the matrix integral itself is the partition function for a Toda chain,¹ another (discrete) integrable system which is well-known to yield KdV in a certain scaling limit. The result of this work was a better understanding of integrability in these toy models of string theory, as well as a method to study the approach to the continuum limit from the finite N matrix theory.

One feature of the matrix approach to solvable string models is a somewhat different packaging of the operator content. In particular there are scaling dimensions in the matrix model that initially were not found in world sheet analyses. A study² (in collaboration with G. Moore and N. Seiberg) of the effects of surfaces with boundaries in the matrix model and in Liouville theory was undertaken; specifically, what sorts of measurements can one make in quantum gravity on the boundary of a fluctuating surface? We identified the simplest such operator, the length of the boundary, and showed how it appears in the matrix model and the resulting KdV equations as the simplest of these extra scaling operators. Boundary operators have subsequently been shown (by Moore and Seiberg) to have profound consequences in unraveling the short distance behavior and other properties of the $1 + 1$ -dimensional string.

At present I am collaborating with Samson Shatashvili on the solution to another toy solution of string theory recently proposed by E. Witten. The $SO(2, 1)$ Wess-Zumino-Witten model (the theory of 2d current algebra) yields, when the $SO(2)$ subgroup generated by J_3 is gauged, a 2d nonlinear sigma model on a 2d target space with the geometry of the Schwarzschild solution in its maximally

extended Kruskal coordinatization. Shatashvili and I have succeeded [3] in reducing the problem of quantization of this theory by reducing it to the problem of 2d gravity coupled to a free scalar field, versions of which have already been solved by matrix techniques. The Liouville-like theory we find has indefinite sign of the cosmological constant. The cosmological constant $|\mu|$ of Liouville theory is related to the mass of the black hole. The connection to Liouville theory should provide the exact solution for correlation functions in the Euclidean black hole geometry using matrix models and Liouville theory; for the Lorentz signature Schwarzschild geometry it gives us a tool to investigate the properties of singularities in string theory. It is our hope that we can use this exact solution to discover the fate of black hole singularities in string theory.

1. On the Origin of Integrability in Matrix Models, EFI preprint EFI-90-67, Comm. Math. Phys. 138 (1991).
2. Boundary Operators in 2d Gravity, with G. Moore and N. Seiberg, Phys. Lett. 263B (1991) 190.
3. Black Hole Physics and Liouville Theory, with S. Shatashvili, EFI preprint 91-22; to appear in Nucl. Phys. B.

C. R. G. SACHS AND STUDENTS

1. *Resolution of the strong CP problem (R. G. S.)*

As reported earlier it has been shown that the P, T and C properties of the θ vacuum are such that P cannot be a physical operator of conventional QCD if $\theta \neq 0$ since it does not satisfy the superselection rule $\Delta\theta=0$. Thus parity is not an observable of conventional QCD.

PRL referees raised technical issues concerning my attempt (reported in my previous progress report as reference 3, EFI 90-44) to restore the meaning of parity for arbitrary θ but I have now resolved these issues. The physical consequences are the same as reported earlier but new, significant insights into the meaning of P (and T) in QCD have resulted.¹

2. *Alternate phenomenological theory of CP violation (R.G.S)*

A "natural" phenomenological theory involving no ad hoc phase (i.e., all coupling constants are real numbers) has been constructed. As a consequence of the constraint imposed by the experimental upper limit on the electric dipole moment of the neutron the results of the theory are equivalent to those of a superweak theory. The theory fits into the structure of the Standard Model but requires 2 independent Higgs fields. It also requires the use of the P, T-invariant QCD.¹ The paper is now being prepared.

3. *Renormalization of neutron edm calculations (M. Booth)*

Calculation of the magnitude of the electric dipole moment (edm) of the neutron predicted by either the KM model or the Weinberg model must take into account renormalization effects arising from Weinberg operators. The calculation of the effect of the 3 gluon operator that has been carried out for the latter model required the calculation of many diagrams and its extension to the KM model (4 gluon operators) by the same methods would require many more diagrams. Booth has shown how these calculations can be greatly simplified and has completed

the calculation of the anomalous dimension for each case.² He is now using the results to determine the effect on calculations of the edm for the KM model.

1. R. G. Sachs, Formulation of QCD as a P, T and C Invariant Theory, EFI 91-42 (submitted to Phys. Rev. D1).
2. M. Booth, Anomalous Dimensions of Weinberg Operators, EFI 91-44 (to be submitted to Phys. Rev. D1).

D. PETER BOWCOCK

We have examined the problem of modelling tunnelling phenomena in more than one dimension. We found that existing techniques are inadequate in a wide class of situations, due to their inability to deal with concurrent classical motion. We showed how to generalize these methods to allow for complex momenta, and demonstrated the improved techniques with a selection of illustrative examples, and commented on possible applications.¹

1. Multi-Dimensional Tunnelling and Complex Momentum (with Ruth Gregory), Enrico Fermi Institute report EFI 91-19.

E. ANNE TAORMINA

Non trivial modular properties of characters of the doubly extended $N = 4$ superconformal algebras $\mathcal{A}_\gamma \tilde{\mathcal{A}}_\gamma$ were derived from two different points of view. The two results were then combined to give stringent constraints on the modular invariant $\tilde{\mathcal{A}}_\gamma$ partition functions, which gave rise to a partial classification of the latter, closely related to that of affine $SU(2)$.¹

1. Modular Invariant Partition Functions for the Doubly Extended $N = 4$ Superconformal Algebras (with Hirosi Ooguri and Jens Lyng Petersen), Enrico Fermi Institute report EFI 91-15.

RECENT PUBLICATIONS

(*denotes an updated reference from last year)

JAMES AMUNDSON

Single particle and multiparticle analysis of nucleus-nucleus collisions at 14.6-A/GeV, 60-A/GeV and 200-A/GeV, H. von Gersdorff, J. Amundson, *et al.*, Phys. Rev. C **39**, 1385.

Intermittency and relativistic heavy ion Monte Carlo simulators, J. F. Amundson, Phys. Rev. C **41**, 1292 (1990).

JADWIGA BIENKOWSKA

*The Renormalization Group Flow in $2 - D$ $N = 2$ SUSY Landau-Ginsberg Models, Enrico Fermi Institute report EFI-90-62-Rev, August, 1991.

PETER BOWCOCK

*Quasi-primary fields and associativity of chiral algebras, Nucl. Phys. **B356**, 367 (1991).

Multidimensional tunneling and complex momentum, with Ruth Gregory (Fermilab), Enrico Fermi Institute report EFI-91-19, April 1991.

Tunneling from nonlocalized initial states, with Ruth Gregory (Fermilab), FERMILAB-PUB-91-142-A, April 1991.

GEOFFREY HARRIS

*Unoriented Strings and Matrix Ensembles, with Emil J. Martinec, Phys. Lett. B **245**, 384 (1990).

Loops and unoriented strings, Nucl. Phys. **B356**, 685 (1991).

Resolving a two fold ambiguity in CP violation parameters, with Jonathan L. Rosner, Enrico Fermi Institute report EFI-91-38, Aug., 1991, revised version in preparation, to be submitted to Phys. Rev. D.

GERARD JUNGMAN

New Vector-Line Interactions: Constraints from Kaon Physics and from $\mu \rightarrow e\gamma$, with Jonathan L. Rosner, Enrico Fermi Institute report EFI 91-37, August, 1991, submitted to Phys. Lett. B.

PYUNGWON KO

*Analysis of 2γ and $\pi^+\pi^-\gamma$ Decays of η and η' using Chiral Anomalies, with Tran N. Truong, Phys. Rev. D **42**, 2419 (1990).

$K_L \rightarrow 2\gamma$ and $K_L \rightarrow \pi^+\pi^-\gamma$ decays, with Tran N. Truong, Phys. Rev. D **43**, R4 (1991); **44**, 1616(E) (1991).

*The Role of Vector Mesons in Nonleptonic Kaon decays, Phys. Rev. D **44**, 139 (1991).

$K_L \rightarrow \pi^0\pi^+e^\pm\nu$ and vector symmetry, Enrico Fermi Institute report EFI-91-40, March 1991, submitted for publication.

$K_L \rightarrow \mu^+\mu^-$, the top mass and other related topics, Enrico Fermi Institute report EFI-91-46, August 1991, submitted for publication.

Interference between direct and CP violating amplitudes in $K_L \rightarrow \pi^0e^+e^-$, Enrico Fermi Institute report EFI-91-47, August 1991, submitted for publication.

WAIKWOK KWONG

*Threshold Production of $t\bar{t}$ pairs by e^+e^- Collisions, Phys. Rev. D **43**, 1488 (1991).

Masses of New Particles Containing b Quarks, with Jonathan L. Rosner, Phys. Rev. D **44**, 212 (1991).

EMIL J. MARTINEC

On the origin of integrability in matrix models, Commun. Math. Phys. **138**, 437 (1991).

Boundary operators in 2-d gravity, with G. Moore and N. Seiberg, Phys. Lett. B **263**, 190 (1991).

Black hole physics and Liouville theory, with Samson L. Shatashvili, Enrico Fermi Institute report EFI-91-22, May 1991.

See also: Geoffrey Harris

LYNNE ORR

Decay versus hadronization for top quarks produced in hadron colliders, Phys. Rev. D **44**, 88 (1991).

ROGERIO ROSENFELD

Adler-Weisberger relation for scattering of longitudinal W bosons, with Jonathan L. Rosner, Enrico Fermi Institute report EFI 91-09, to be published in Phys. Rev. D **44**, October, 1991.

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JONATHAN L. ROSNER

*Radiative Corrections and Electroweak Observables, Phys. Rev. D **42**, 3107 (1990).

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*Atomic Parity Violation as a Probe of New Physics, with William J. Marciano, Phys. Rev. Lett. **65**, 2963 (1990).

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Determining heavy meson decay constants, Enrico Fermi Institute report EFI-90-80, November, 1990, to be published in *Research Directions for the Decade* (Proceedings of the 1990 DPF Snowmass Workshop), edited by E. L. Berger (World Scientific, Singapore, 1991).

Non- $B\bar{B}$ decays of the $\Upsilon(4S)$, Enrico Fermi Institute report EFI-90-81, November, 1990, to be published in *Research Directions for the Decade* (Proceedings of the 1990 DPF Snowmass Workshop), edited by E. L. Berger (World Scientific, Singapore, 1991).

Proposal for measurement of V_{ub}/V_{cb} , with Isard Dunietz, CERN report CERN-TH-5899-90, November, 1990 (unpublished).

Tests of a composite model of quarks and leptons, with Davison E. Soper, Enrico Fermi Institute report EFI-90-75, March, 1991, submitted to Phys. Rev. D.

Status of precise tests of the electroweak theory, Enrico Fermi Institute report EFI 91-21, May, 1991, lectures delivered at Fourth Mexican School of Particles and Fields, Oaxtepec, Morelos, December, 1990, proceedings to be published by World Scientific.

Probing new physics with precise electroweak tests, Enrico Fermi Institute report EFI 91-28, June, 1991, to be published in Proceedings of the 4th Conference on the Intersections between Particle and Nuclear Physics, Tucson, AZ, May 24-29, 1991 (New York, AIP, 1991).

The Densities of Meson and Baryon States, with Peter G. O. Freund, Enrico Fermi Institute report EFI 91-36, August, 1991, submitted to Phys. Rev. Letters.

The Cabibbo-Kobayashi-Maskawa Matrix, Enrico Fermi Institute report EFI 91-49, September, 1991, to be published as a chapter of the book *BDecays*, edited by Sheldon L. Stone (World Scientific, Singapore, 1991).

See also: Geoffrey Harris, Gerard Jungman, Waikwok Kwong, Rogerio Rosenfeld.

ROBERT G. SACHS

P, T and C transformations in QCD: Is there a strong CP problem? EFI-91-18, Apr 1991 (revised version of EFI-91-07).

Formulation of QCD as a P, T and C invariant theory, EFI-91-42, Aug 1991.

ANNE TAORMINA

Modular properties of doubly extended $N=4$ superconformal algebras and their connection to rational torus models. 1. With Jens Lyng Petersen. Nucl. Phys. **B354**, 689 (1991).

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THEORETICAL HIGH ENERGY PHYSICS RESEARCH AT
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CP GROUP (DOE TASK B AND TASK J) PROGRESS REPORT FOR 1991*
(FERMILAB E-731/773/799 COLLABORATION)

The year 1991 marks the culmination of four years of continuous analysis of the E-731 experiment's 1987-88 data sample. A preliminary value for the 2π mode Direct CP violating amplitude $\epsilon'/\epsilon = (6.0 \pm 6.0 \text{ (stat)} \pm 3.2 \text{ (syst)}) \times 10^{-4}$ was reported this summer from the full data set. This value is consistent with zero, and hence with the superweak model. In addition to ϵ'/ϵ , the values for the K_S lifetime, the K_L - K_S mass difference, and the CPT violating phase difference $\Delta\phi$ were announced concurrently¹. These results were based on 330K of $\pi^+\pi^-$ and 224K of $2\pi^0$ CP violating decays of the K_L .

Amongst the other physics results that have come out recently from the 1987-88 data was a simultaneous measurement of the K_L and K_S into the decay mode $\pi^+\pi^-\gamma$ with a fully analyzed sample of 8748 decays². The photon energy spectrum of the direct emission decay component of this decay indicates the presence of a ρ propagator form factor.

The group is currently busy with the ongoing run of E773, which is expected to measure the CPT violating phase difference $\Delta\phi$ to better than a degree precision. The experiment has already collected approximately 500 million triggers on tape in ten weeks of running. The data quality appears to be good, and the switchover to the E799 configuration for the rare decay $K_L \rightarrow \pi^0 e^+ e^-$ search is planned very soon.

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*26 SEP 1991

Fermilab E799, with the primary goal of searching for multibody kaon rare decays, particularly the $K_L \rightarrow \pi^0 e^+ e^-$, will officially start on the 30th of September 1991 for a two and a half months of data taking period. A set of three transition radiation detectors (TRD's), which is the responsibility of Task J was constructed at the University of Chicago during the past two years, and was delivered to Fermilab early September. The initial data shows that they perform satisfactorily and are expected to have a π/e rejection ratio of 75. A subset of sixteen sense wires of a TRD are also further instrumented with 100MHz Flash ADC system to elucidate the issue of the differences of cluster finding and total charge deposition methods. Understanding these data will help determine the design and construction of the next generation TRD's for E799 Phase II.

The current run of E799 Phase I in the next two months is expected to reach a 1.0×10^{-10} sensitivity on the $K_L \rightarrow \pi^0 e^+ e^-$ mode. The Phase II, which is scheduled to run in 1994, is expected to have a 0.8×10^{-12} sensitivity. The current upper limit on this branching ratio is 3.3×10^{-9} . There are other interesting kaon decay modes that we will trigger on, namely the dimuon, the muonic Dalitz decay, the $\pi^0 \rightarrow e^+ e^-$, and the kaon double Dalitz decay.

During the upcoming E799 run, we have designed, constructed and installed a trigger board to trigger on the Λ beta decay. The expected rejection factor due to this board is approximately 50. This measurement will illuminate the question of the second class currents in the Standard Model.

The group is also involved with the design and planning for further experiments in the kaon system. A proposal for next generation ϵ'/ϵ experiment (P832) at the Fermilab Tevatron beam using a brand new CsI calorimeter was submitted recently (draft enclosed). A design report for the kaon experiments at the proposed Fermilab Main Injector facility (P804) was also prepared (draft enclosed).

1. B. Winstein, Proc. Joint Int. Lepton-Photon and Europhysics Conf., Geneva, Switzerland, July-August, 1991 (in preparation), also, S.V. Somalwar, Proc. Fourth Conf. on Intersections of Particle and Nuclear Physics, May 1991, Tucson, AZ (enclosed).
2. G.J. Bock et al., to be submitted to Phys. Rev. Lett. (draft enclosed).

LEON LEDERMAN (Task D)

Brief Description of Current and Planned Research

Continuation of Fermilab experiment E789, a study of beauty mesons via their two-body decay. Work with Georges Charpak and senior thesis student David Chen on novel instrumentation methods for achieving an improved trigger will continue. The stakes in reading B-meson signatures in a fixed target experiment are very high in view of proposed beauty-factories.

THEORETICAL HIGH ENERGY PHYSICS RESEARCH AT
THE UNIVERSITY OF CHICAGO

Progress Report
for period October 1, 1990 - September 30, 1991

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Research Accomplishments Since December 1990

Constraints to Particle Properties

We have derived important astrophysical and cosmological constraints to the properties of Nambu-Goldstone bosons, axions, and neutrinos. To mention two noteworthy results, we have shown that primordial nucleosynthesis precludes a mass for the tau neutrino in the range of 0.5 MeV to 25 MeV. The current laboratory limit to the tau-neutrino mass is 35 MeV; when this limit is improved to less than 25 MeV, the combination of the laboratory limit and the nucleosynthesis limit will imply that the tau-neutrino mass must be less than 0.5 MeV. A *prima facie* case has been made for the existence of a neutrino-mass eigenstate of 17 keV that mixes with the electron-flavor eigenstate at the 1% level. We showed that astrophysical and cosmological arguments severely constrain the properties of this neutrino (if it indeed exists): it must have a lifetime of less than about 10^{13} sec (and most likely shorter than 10^7 sec) and if it is Dirac like, the wrong-helicity states must have interactions of strength comparable to the ordinary weak interactions.

Dark Matter

We carried out an unsuccessful telescope search for the decays of relic axions of mass 3 eV to 8 eV, thereby closing one of two mass windows for the axion. The remaining mass window, 10^{-6} eV to 10^{-3} eV, is of great cosmological interest, as relic axions in this mass range would provide closure density and are an extremely promising dark-matter candidate. We are currently involved in a collaboration that seeks to build a Sikivie-type detector with sufficient sensitivity to detect relic axions in our own galactic halo in the mass range 10^{-6} eV to 10^{-4} eV. We have also studied two methods of indirect detection of another promising dark-matter candidate: the neutralino. The first scheme involves the production of

high-energy positrons through the annihilation of halo neutralinos into W^+W^- and Z^0 pairs, whose subsequent decays produce high-energy positrons. The second method involves the production of high-energy neutrinos from neutralino annihilations in the center of the sun and of the earth and their detection in large, underground detectors (e.g., IMB, Kamiokande II, and MACRO).

Inflationary Cosmology

We studied a new and very promising type of inflation, first-order inflation. The key feature of first-order inflation is that the inflationary epoch is terminated by a first-order phase transition. Our work on first-order inflation has included the topics of baryogenesis, bubble nucleation and percolation, production of gravitational waves, and density perturbations. First-order inflation is particularly attractive as it offers the possibility that inflation can be associated with a first-order symmetry-breaking phase transition (as Guth had originally envisioned).

Publications since December 1990

1. Microwave Distortions from Collapsing Domain-wall Bubbles, Michael S. Turner, R. Watkins, and L.M. Widrow, *Astrophys. J. Letters* **367**, L43 (1991).
2. Inflationary Axion Cosmology, Michael S. Turner and Frank Wilczek, *Physical Review Letters* **66**, 5 (1991).
3. Relic Gravitational Waves and Extended Inflation, Michael S. Turner and Frank Wilczek, *Physical Review Letters* **65**, 3080 (1990).
4. Can Oscillating Physics Explain an Apparently Periodic Universe? Christopher T. Hill, Paul J. Steinhardt, and Michael S. Turner, *Physics Letters B* **252**, 343 (1990).

5. Coherent Peculiar Velocity Fields and Periodic Red Shifts, Christopher T. Hill, Paul J. Steinhardt, and Michael S. Turner, *Astrophys. J. Letters* **366**, L57 (1991).
6. A Positron Feature from Heavy-WIMP Annihilations in the Galactic Halo, Mark Kamionkowski and Michael S. Turner, *Physical Review D*, in press (1991).
7. Telescope Search for Multi-eV Axions, M. Bershadsky, M.T. Ressell, and Michael S. Turner, *Physical Review Letters* **66**, 1398 (1991).
8. Cosmological Implications of Axinos, K. Rajagopal, Michael S. Turner, and F. Wilczek, *Nuclear Physics B*, in press (1991).
9. Constraints from Primordial Nucleosynthesis to the Mass of the Tau Neutrino, E.W. Kolb, Michael S. Turner, A. Chakravorty, and D.N. Schramm, *Physical Review Letters* **67**, 533 (1991).
10. The Tilted Universe (and other remnants of the pre-inflationary Universe), Michael S. Turner, *Physical Review D*, in press (1991).
11. Astrophysics and Cosmology Confront the 17 keV Neutrino, E.W. Kolb and Michael S. Turner, *Physical Review Letters* **67**, 5 (1991).
12. The Tilted Universe, Michael S. Turner, *General Relativity and Gravitation*, in press (1991). (First Award, 1991 Gravity Research Foundation Essay Competition)
13. Dirac Neutrinos and SN 1987A, Michael S. Turner, *Physical Review D*, in press (1991).
14. Baryogenesis in Extended Inflation I. Baryogenesis via Production and Decay of Supermassive Bosons, J. D. Barrow, E. J. Copeland, E.W. Kolb, and A. R. Liddle, *Phys. Rev. D* **43**, 977 (1991).

15. Baryogenesis in Extended Inflation II. Baryogenesis via Production and Evaporation of Primordial Black Holes, J. D. Barrow, E. J. Copeland, E.W. Kolb, and A. R. Liddle, *Phys. Rev. D* **43**, 984 (1991).
16. Kaluza-Klein Extended Inflation, R. Holman, E.W. Kolb, S. L. Vadas, and Y. Wang, *Phys. Rev. D* **43**, 995 (1991).
17. Scale-Invariant Extended Inflation, R. Holman, E.W. Kolb, S. L. Vadas, and Y. Wang, *Phys. Rev. D* **43**, 3833 (1991).
18. Phase Transitions with Sub-Critical Bubbles, M. Gleiser, E.W. Kolb, and R. Watkins, *Nucl. Phys. B*, in press (1991).
19. Plausible Double Inflation, R. Holman, E.W. Kolb, S. L. Vadas, and Y. Wang, *Phys. Lett. B*, in press (1991).
20. Statistical Mechanics of Soft-Boson Phase Transitions, A. K. Gupta, C. T. Hill, E.W. Kolb, and R. Holman), *Phys. Rev. D*, submitted (1991).
21. Dark Matter in the Universe, Michael S. Turner, *Proceedings of the Nobel Symposium No. 79: The Birth and Early Evolution of Our Universe*, eds. B. Gustafsson, Y. Nilsson, and B.-S. Skagerstam.
22. The Best-fit Universe, Michael S. Turner, *Proceedings of the IUPAP Conference on Primordial Nucleosynthesis and the Early Evolution of the Universe*, ed. K. Sato (Kluwer, Dordrecht, 1991).
23. Dark Matter in the Universe, Michael S. Turner, *Proceedings of the UCLA Conference on Trends in Particle Astrophysics*, eds. D. Cline, G. Gelmini, et al.
24. A Proposed Experimental Search for Dark Matter Axions, K. van Bibber et al. *Proceedings of the UCLA Conference on Trends in Particle Astrophysics*, eds. D. Cline, G. Gelmini, et al.

25. First-order Inflation, E.W. Kolb, *Proceedings of the Nobel Symposium No. 79: The Birth and Early Evolution of Our Universe*, eds. B. Gustafsson, Y. Nilsson, and B.-S. Skagerstam.
26. Indirect Detection of Neutralino Dark Matter, M. Kamionkowski, *Phys. Rev. D*, in press (1991).
27. Astrophysical Constraints to the Radiative Decays of Axions, M.T. Ressell *Phys. Rev. D*, in press (1991).
28. Aspects of Reheating in First-order Inflation, R. Watkins and L.M. Widrow, *Phys. Rev. D*, in press (1991).
29. Astrophysical and Cosmological Constraints to Pseudo-Nambu-Goldstone Bosons, A. Jaffe and J. Frieman, *Phys. Rev. D*, submitted (1991).

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