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PROGRESS REPORT FOR A RESEARCH PROGRAM
in
THEORETICAL HIGH ENERGY PHYSICS

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ABSTRACT

Research this past year was carried out in the fields of cosmic strings and galaxy formation, inflationary models of the universe, topological defects and phase transitions, group contractions and chiral fermions, low-frequency approximations in (QCD), loop bremsstrahlung of e^+e^- and $\mu^+\mu^-$ pairs in heavy-ion collisions, approximations to solutions of non-linear differential equations, the use of “continued functions” as solution to vortex problems, string theory and large-N matrix models, topological expansions in QCD, one-dimensional string theory and its infrared divergencies, strings in less than one-dimension, hadron-hadron interactions and the possible existence of the odderon, electroweak interactions and possible new physics in the TeV range, axions, quark flavor mixings and neutrino oscillations, large-N matrix models and their relation to string theories and two-dimensional quantized gravity, and the statistical mechanics of strings at high temperatures.

Progress Report for a Research Program in Theoretical High Energy Physics

The Department of Physics of Brown University, with the support of the U. S. Department of Energy under Contract DE-AC02-76ER03130, has been carrying out a research program in Experimental and Theoretical High Energy Physics since 1958. David Feldman, Herbert M. Fried, Antal Jevicki, Kyungsik Kang, and Chung-I Tan (Person-in-Charge) are principal investigators. This report serves to summarize the progress which has been made during the present contract period (1 January 1990 - 31 December 1990) by the Theoretical Group (Tast A).

The report is divided into four section:

- I.* Present Status of the Theoretical Group;
- II.* Individual Research Contributions;
- III.* Theoretical Papers Published during the Preceding Year and Papers in Press;
- IV.* Scientific Personnel Associated with the Theoretical Program.

I. Present Status of the Theoretical Group

The research activities of the high energy theory group at Brown University have always covered a broad spectrum of topics in the theory of elementary particles and fields commensurate with the research specialties of its personnel. During the past year the group has continued to produce a significant output of important papers in topics of high current interest. All of our staff have been actively involved in the theoretical physics of fundamental particles and fields, including some frontier areas of interest and importance, with considerable impact on their evolution and development. The research output in the overlapping fields of particle physics, strings and cosmology has also been actively pursued, and has attracted a large amount of attention. The output of Dr. S. Jain and Dr. A. M. Matheson and their interaction with others have been extraordinarily high. After a highly successful three-year period

of research at Brown, Dr. Jain will join the theory group at Harvard in September. Dr. J. Avan of the University of Paris will be his replacement, for an expected period of two years. Professor D. Feldman, who first started the Brown High Energy Physics Group in 1955, after many years of distinguished service is scheduled to retire at the end of the 1990 academic year. Mr. J. W. Kung has finished his doctoral dissertation this year.

We have continued to receive a large number of requests for support of long- and short-term visits and continue to attract the interests of many exceptionally capable young graduate students. Our ability to respond to all of this was still unfortunately not at the level that we would have liked. The University has been quite supportive, providing most of the funds for the visitors' programs. The research activities of the Group has also attracted a great deal of attention, as measured, for example, by the participations and the invited talks given by our members at major international conferences. Professor Fried was an invited speaker at the Kiev Meeting entitled "Nonlinear World" in October 1989. He is the Director of the NATO Advanced Study Institute on "Vacuum Structure in Intense Fields", to be held this summer in Cargese, Corsica (France). During the 1989-90 academic year, Professor Jevicki has given lectures at the VIth Meeting on Particle Physics, Dubrovnik, Yugoslavia and at the Meeting on Modern Quantum Field Theory, Tata Institute, Bombay, India. He was also invited to visit the University of Tokyo and the University of Kyoto, Japan. Professor Jevicki has also been invited to participate in the workshop "Physics Much Below the Planck Scale" at the Institute for Theoretical Physics, Santa Barbara. Professor Kang was invited to attend the 24th Moriond Workshop on High Energy Hadronic Interactions in March 1990. He is the organizer of a Conference on SSC Physics in Seoul in January 1990, and also a Workshop on Modern Physics at Yanbian University in Northeastern China in July. Professor Tan has been invited to lecture at the XIIIth Workshop on High Energy Physics/Field Theory at Protvino, USSR and at the Meeting on Thermal Field Theory in Japan. Professor K. Kang and Professor C-I Tan are expected to attend the XXV International Conference on High Energy Physics at Singapore in August. Professor R. Brandenberger has lectured at many international meetings, as detailed in the Task-K report.

II. Individual Research Contributions

Since June 1989 Prof. Robert Brandenberger's research has been devoted to early Universe cosmology. The four focal points have been:

- 1) Galaxy and large-scale structure formation with cosmic strings.
- 2) Quantum field theoretical effects near cosmic strings and their observational signatures.
- 3) Dynamics of inflationary Universe models.
- 4) Quantum particle production and formation of topological defects during phase transitions.

In his research on galaxy and large-scale structure formation he has this year focused on a model in which cosmic strings give the initial density perturbations and in which the dark matter which makes up 90% of the mass of the Universe consists of 25eV neutrinos (called hot dark matter by cosmologists). In collaboration with his student Leandros Perivolaropoulos and with Albert Stebbins (CITA, Toronto), Prof. Brandenberger has studied the formation of structure on large scales in this model[3,7,12]. They discovered that wakes, planar density enhancements which form behind long moving cosmic strings, dominate the structure on these scales (distances larger than about 40Mpc, the comoving horizon at the time of equal matter and radiation). Most of the mass of the universe which condenses into bound objects collapses in wakes. By studying the accretion of neutrinos onto wakes they determined the thickness of the sheets and determined the minimal mass per unit length of the strings in order that any nonlinear objects form by the present mechanism. They concluded that in a cosmic string model with hot dark matter, the large-scale structure will be dominated by planar concentrations of galaxies with length and width of about 40 Mpc and thickness of about 4Mpc. These predictions are in encouraging agreement with the recent redshift surveys which show a Great Wall of galaxies with similar dimensions (J. Huchra and M. Geller, Science 246, 897 (1989)).

Currently, Prof. Brandenberger is continuing the development of the cosmic string model with hot dark matter. James Gerber (a Brown undergraduate) and Prof.

Brandenberger have worked out the topology of large-scale structure by computing the genus statistic which measures the genus of isodensity surfaces as a function of the density. This statistic is a good discriminator between different theoretical models.

The most exciting result of his research on quantum field theoretical effects near cosmic strings has been the discovery of a direct channel by which nonabelian cosmic strings can catalyze proton decay [15]. We noticed that the long range gauge fields of a nonabelian cosmic string can turn a beam of baryons into a mixed beam of baryons and leptons by the Aharonov-Bohm effect. This process is specific to cosmic strings and does not occur for grand unified monopoles. This work was done in collaboration with Leandros Perivolaropoulos, Andrew Matheson (postdoc at Brown, and Anne-Christine Davis (DAMTP, Univ. of Cambridge) who spent the fall of 1989 on sabbatical leave at Brown, supported in part by Task K. They also performed a more detailed analysis of scattering of fermions by cosmic strings and the proton decay catalysis cross sections due to core interactions. They discovered that in spite of the absence of classical long range forces which attract the fermions to the cosmic string, the scattering and catalysis cross sections are in general larger than the geometric cross section if the flux in the string is fractional [20]. They also investigated finite temperature effects on scattering cross sections and discovered that the enhancement is reduced at high temperature [19]. In collaboration with Ruth Gregory (Fermilab), Anne-Christine Davis, Prof. Brandenberger also discussed catalysis using a skyrmion picture for the protons [1]. They were invited to write a review of this work [9].

Related work on quantum field theoretical effects near strings includes a computation of the predicted ultra-high energy neutrino flux from cosmic strings, work performed in collaboration with Jane MacGibbon (Harvard-Smithsonian Center for Astrophysics and Goddard Space Flight Center) [2].

His third main area of research has been the study of the dynamics of inflationary Universe models. He considered models in which a scalar field is responsible for generating inflation. However, in order to obtain inflation, the scalar field must be homogeneous and almost static. Prof. Brandenberger's student Jong Kung and Prof. Brandenberger studied the evolution of scalar field configurations in the early

Universe in order to discover whether generic initial conditions will lead to inflation. They discovered the initial conditions which give chaotic inflation are an attractor in initial condition space [4,18]. This puts chaotic inflation on a much firmer ground. In previous work, his former student Hume Feldman (CITA, Toronto) and himself have shown that chaotic inflation is stable to both matter and metric perturbations [5].

Prof. Brandenberger's fourth main area of research has been a study of the formation of topological defects and of quantum particle production during cosmological phase transitions. With his graduate student Jinwu Y he studied the formation of global and local vortices in an expanding Universe [10,16]. They considered non-equilibrium initial conditions for the fields and discovered that the density of topological defects formed agrees with the predictions based on the Kibble mechanism. Jennie Traschen (Univ. of Massachusetts, Amherst) and Prof. Brandenberger developed techniques to calculate quantum particle production during second order phase transition [11]. They applied the formalism to study reheating in the New Inflationary Universe, and showed that most of the energy produced is transferred by parametric resonance.

Other projects on which they have worked included a study of cosmological implications of dynamical symmetry breaking versus spontaneous symmetry breaking, a more detailed study of gravitational radiation from cosmic strings [14], and a study of how classical density perturbations emerge in the early Universe using methods of quantum cosmology [17].

Prof. Brandenberger has reported on his research as an invited speaker at several conferences [6,8,2]. He also gave lecture series on "Physics of the Very Early Universe" at the Scottish Universities Summer School in Physics [13].

Professor Feldman and Mr. Crombie have been carrying out a study of the group contraction process as applied to quantum field theories. In addition to their examination of the renormalization of an $SU(2)$ to $E(2)$ gauge theory, they have also been considering the renormalization of an $SU(3)$ gauge theory under a group contraction.

In the course of their study of the contraction of gauge groups, they have found

a means of formalizing the contraction process in terms of a geometric perturbation theory in the curvature of the Higgs manifold. Since the Higgs manifold arises as a coset space of the full gauge group with respect to the little group of the vacuum, it is a space of constant curvature, i. e., the curvature tensor of the Higgs manifold reduces to that of a scalar. Hence the fully contracted theory appears as the zeroth-order contribution to an expansion in the scalar curvature of the Higgs manifold.

Professor Feldman and Mr. Crombie have also continued their study of the generation of $E(2)$ chiral fermions under the group contraction process. Starting with isodoublets in an $SU(2)$ invariant theory, one obtains, under a group contraction, a chiral theory. The component of the representation undergoing $E(2)$ translations is projected out, and only the $E(2)$ invariant component of the isodoublet remains after the group contraction. It is expected that this approach will lead to interesting implications when extended to the chirality problem in the context of Kaluzan-Klein theories.

Professor Fried's research during the past year concentrated on four main subjects, as follows. (1) Attempts to formulate a meaningful, analytic "infrared" (R) approximation for $SU(N)$ -(QCD)₄ have progressed to the point where the general form of the sequence of IR approximations is now clear. Informal talks with the group of J. Polony at MIT indicate that the very approximate IR form of the gluon propagator obtained by the IR method has also been found by them, and resemble previous machine work on this subject by Mandula and others. (2) An independent test of the "Loop Bremsstrahlung" (LB) model of sharp e^+e^- production in the Darmstadt heavy-ion scattering experiments has been suggested (HET-744), with the surprising result that LB of e^+e^- pairs appears possible at very low values of atomic number, $Z \geq 2$, while $Z_{min} > 5$ for LB production of $\mu^+\mu^-$ pairs. It is hoped that new experiments now being set up at Argonne to verify the Darmstadt results will be able to test this effect. (3) A very general method of approximating solutions to non-linear differential equations (NLDE) has been developed in conjunction with J-D Fournier, of the Observatoire de Nice (HET-726) and presented in an invited paper at the Kiev "Nonlinear World" meeting in October 1989. Based upon previous IR

approximations described in these reports for the Green's functions of quantum field theory, the method provides a simple, analytic method of extracting the large-scale (low-frequency) properties of solutions to classes of NLDEs. (4) A new way of writing the NLDEs of inviscid fluids has just been devised, whose solutions are "continued functions" (functions of functions of functions...here labeled CF), and which suggest new methods of finding approximate solutions to the extremely NLDEs of fluids. Previous "eikonal" approximations here find a natural and unambiguous description. In particular, the appearance of fractals and bifurcations should be unavoidable in this framework. A first paper deriving these CF equations and presenting some simple (symmetric) solutions is at present under construction. In addition to the above projects, the manuscript of Prof. Fried's new book ("Functional Methods and Eikonal Models") was submitted to its publishers (Editions Frontieres) during the past academic year.

During the last year Prof. Jevicki has concentrated his efforts on string theory and its relationship with large N matrix models. Recently significant progress was achieved in formulating string theory in other than $D=26$ dimensions. This progress came from the lattice approach where surfaces are discretized in terms of flat triangular elements and the integration over the matrix is replaced by the discrete summation over triangulations [26,27,28]. This problem can be then approached numerically and the numerical studies led to initial interesting results. A very elegant analytic approach is given by the dual Feynman diagram picture of matrix models. It was pointed out originally by G't Hooft in 1974 that the $1/N$ expansion of $U(N)$ QCD generates a topological expansion over surfaces with the string coupling given by $1/N^2$. Most recently a renormalized version of the $1/N$ expansion was studied. Using simple matrix models analogous to those of QCD, a double scaling limit ($N \rightarrow \infty, g \rightarrow g_c$) was introduced, leading to an exactly solvable continuum theory. The results for the critical exponents were identical to those of a $D < 1$ string theory; but the matrix model also lead to the exact computation of all correlation functions[29,30,31].

String theory in one dimension is of special interest. It is the limiting case of exactly solvable models at $D < 1$ and represents a point of phase transition to a

possible novel phase of the theory. Here some partial but very interesting results have been obtained, while the theory is subject of recent, concentrated investigations. The ground state energy was computed to all orders in string perturbation theory [30] showing a puzzling infrared divergence. The physical meaning of these terms is not yet clear.

In collaboration with S. Das (Tata Institute), Professor Jevicki has developed a field theoretical approach to the problem of strings (HET-750). It is given by the collective field representation developed earlier by B. Sakita (City College) and Professor Jevicki [31]. One obtains a field theory in two dimensions with the additional dimension arising from the large N color of the matrix model. The spectrum is given by a massless relativistic particle on the half line ($p > 0$). This theory gives a framework for nonperturbative studies and provides a first, workable, closed-strings, field theory.

While visiting the Institute of Physics, University of Tokyo, Professor Jevicki has collaborated with Prof. T. Yoneya. They have written a paper entitled "Action Principle for Strings in Less Than One Dimension" (HET-749). In this paper a possible nonperturbative framework for string theory is outlined. The recently discovered string equations which follows from the critical multi-matrix model have an integrable KdV structure. It was shown by Professor Jevicki and Professor Yoneya that this equation follow from an effective action. This effective action is much like effective actions in field theory. It generates correlation functions and offers a framework for nonperturbative investigations.

During the last year Professor Jevicki has given lectures at the VIth Meeting on Particle Physics, Dubrovnik, Yugoslavia, and at the Meeting on Modern Quantum Field Theory, Tata Institute, Bombay, India. He was invited to visit the University of Tokyo and the University of Kyoto, and the Institute for Theoretical Physics, Santa Barbara where he participated in the workshop "Physics Much Below the Planck Scale".

Prof. Kang has concentrated his research on TeV physics of hadron-hadron interactions, electroweak interactions, axions, and neutrinos. In collaboration with

Dr. Alan R. White of Argonne National Laboratory, he has constructed in HET-743 a simple model of hadron scattering to explain recent collider results from CERN and Fermilab Tevatron on the total cross-section and the real part of the forward elastic amplitude. It was found that there should be a genuine physical threshold just below the CERN energy range, and the authors suggested identifying this threshold with diffractive production of a new particle of mass $30 \text{ GeV}/c^2$ (which may have been seen in mini-centauro and Greminion cosmic ray events). By assuming the existence of hadronic photons this particle can consistently be identified as an axion-like η made of strongly-interacting color sextet quarks, that may very well provide a dynamical origin of the electroweak symmetry breaking. It seems that most of cosmic ray exotic events including Germions, mini-centauro and strongly interacting photons may be attributable to the strongly-interacting color sextet quark sector of QCD. The consequence of this new particle were discussed in HET-754, in connection with the collider anomaly of diffractive cross-sections, and with the often alluded to growth rate of the total cross section based on asymptotic theorems.

The possible existence of the odderon, a Regge singularity in the odd-signatured amplitude that has an intercept of unity in the forward directions, has been with us for almost two decades. Though the odderon can not be ruled out in principle, the evidence for its existence has been scarce except for the UA4 measurement of large real part of the forward $p\bar{p}$ amplitude at the CERN collider. Prof. Kang reviewed in HET-721 the analysis of pp and $p\bar{p}$ elastic scattering at high energies. Consistent fits of all data of total cross sections and the real part of the scattering amplitude at high energies give statistically unfavorable χ^2 -values for the odderon, unless one is willing to ignore certain sets of published data points that may appear to be "out of the trend".

The physics at TeV energy scale definitely promises to be exciting. For example, if the Higgs particle is found to be heavier than $1 \text{ TeV}/c^2$, perturbation theory is no longer valid for the electroweak interactions, and $W^\pm, Z^0$ and Higgs bosons interact strong at the TeV scale. A recent experiment at CDF on the t-quark mass, and four competing LEP experiments on the Z^0 mass and the number of the light

neutrino species have brought several important changes of the parameters in the standard model. It appears that the standard model may have to undergo a number of improvements, as one explores the TeV energy range. Prof. Kang discussed in HET-746 possible new physics at the TeV energy range, based on the wisdom gained by the standard model and newly emerging experimental information from SLC, CDF, CERN SPS and LEP.

The topics of the axions, neutrino oscillations and quark flavor mixing have been Prof. Kang's research topics of interest. He reviewed the axion and neutrino physics learned from the discovery of Supernova 1987A in HET-718 and HET-719. In addition he reviewed in HET-720 the range of the neutrino masses and mixing angles that can be expected from a realistic grand unification model that contains three generations of quark-lepton family with phenomenologically acceptable flavor mixings in the quark sector.

During the past year, Professor Tan has carried out research with the aim of deriving string equations from large- N unitary matrix models. In a discrete approach to a path integral formulation for string theories, one begins by first summing over inequivalent triangulations of the two-dimensional world sheet at a given genus. This procedure leads to a perturbative, topological expansion in terms of the string coupling. It turns out that this discrete approach can be represented by a suitable matrix theory in the large- N limit[22]. Much excitement has been generated by the recent suggestion that a "double-scaling limit", near a critical point of a large- N matrix model in which one sums over contributions from all genera, could provide a nonperturbative framework for studying string theories and two-dimensional gravity[24]. This nonperturbative sum can be characterized by a differential equation. For instance, in the case of pure 2D gravity, the Hermitian one-matrix model leads to a specific heat which satisfies the Painleve-I equation[24]. In spite of these dramatic advances, many questions, both technical and conceptual, remain unanswered. Topological expansions resulting from Hermitian matrix models have a natural interpretation in terms of two-dimensional orientable surfaces. Since a unitary matrix is related to a Hermitian matrix by exponentiation one suspects that a unitary matrix

model and a Hermitian matrix model should possess the same physical constants, at least in the weak-field limit. Surprisingly, in collaboration with K. Demeterfi (HET-753), Prof. Tan has shown that a unitary matrix model contains a much richer scaling structure than the corresponding Hermitian matrix model. They emphasize that, due to the compactness of the $U(N)$ group, the partition function is always well defined, a feature not always shared by the corresponding Hermitian model; this approach could prove useful in resolving ambiguities involving boundary conditions for the string equations.

Prof. Tan has also carried out research on various aspects of nonperturbative aspects of QCD and on their ramifications at collider energies. (HET-722) A concrete realization of the large- N expansion for QCD is the dual parton model (DPM) which was introduced by Prof. Tan, in collaboration with Drs. A. Capella, U. Sukhatme, and J. Tran Thanh Van. The model has provided a rather complete quantitative description of low- p_T multiparticle production in high energy collisions. [Ref: C-I Tan et al, in "Hadronic Multiparticle Production", ed. P. A. Carruthers (World Scientific 1988).] A comprehensive review of the model is being prepared as a Physics Report volume.

Prof. Tan and Dr. Jain, in collaboration with Dr. Nivedita Deo, have carried out an on-going program to study the statistical mechanics of strings at high energy densities. Building upon the work in ref. 22, where singularities of the canonical partition function of an ideal gas of strings and their consequences for the microcanonical density of states were obtained, a formalism was developed to obtain some physically relevant information about the string gas (refs. 23,24). It was found that these distributions did not depend upon details of the particular string model but only on the number d of noncompact dimensions of the space in which the gas lives. For $d \geq 3$ the string gas at energy densities above the Hagedorn energy density is dominated by a single string which captures most of the energy of the gas. For $d = 0$ the energy is distributed equally among strings in various energy range. The inclusion of conservation laws into the microcanonical ensemble does not alter this qualitative picture. The effect of the expansion of a compact universe containing a gas of strings at high

energy densities was studied. Also the unusual relationship between the canonical and microcanonical ensembles for a string gas was clarified (ref 25).

In addition to the above, Dr. Jain has been engaged in studying aspects of 2-d quantum gravity and non-critical strings both from the viewpoint of matrix models and of topological field theory.

In the past year most of Dr. Matheson's work has been in the field of cosmology, concentrating on the behavior of particle physics models at very high energies and their implications for the subsequent evolution of the universe. Borrowing from formalism developed originally for QCD, Dr. Richard Ball of the the Niels Bohr Institute and he modeled dynamical symmetry breaking in gauge theories (ref.32) to investigate if inflation is realizable in such transitions. They found that realistic inflationary models could be built in scalar field-free theories, provided that there was a transition at a high-enough energy to a gauge-condensate phase. This conclusion was changed quantitatively, but not qualitatively, by the inclusion of matter fields.

Working with Leandros Perivolaropoulos and Prof. Brandenberger of Brown University, and Warren Perkins and Dr. A. C. Davis of Cambridge University, they continued a study of the interaction of cosmic strings with fermions. They found a realistic model (ref.33) in which such interactions could lead to a significant destruction of a primordially-generated baryon excess. They also showed (ref.34) that the various competing baryon number-violating string- fermion interactions gave the same order-of-magnitude effect at the most important scale, that of string formation.

Finally (ref.35), Prof. D. Upton of Harvard University and Dr. Matheson proposed a novel means of solving the monopole problem, whereby cosmic string loops accrete monopoles to them to form black holes. The black holes carry a small (or zero) magnetic charge, and if they evaporate at a sufficiently high temperature the final monopole-to- entropy ratio can be reduced to an acceptably low level.

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31. A. Jevicki and B. Sakita, Nucl. Phys. B765, 511 (1980).
32. R. D. Ball and A. M. Matheson, "Dynamical Inflation", BROWN-HET-738.
33. L. Perivolaropoulos, A. C. Davis, R. H. Brandenberger and A. M. Matheson,
"Nonabelian Aharonov-Bohm Baryon Decay Catalysis", BROWN-HET-739.
34. R. H. Brandenberger, A. C. Davis, L. Perivolaropoulos, W. Perkins and A. M. Matheson,
"Catalysis of Proton Decay by Cosmic Strings at Finite Temperatures", BROWN-HET-747.
35. D. M. Upton and A. M. Matheson, "Monopole Accretion by Cosmic Strings",
Modern Physics Letters A, to appear.

III. Theoretical Papers Published during the Preceding Year and Papers in Press

HET-716 Progress Report - Task A (1989)

TA-425

HET-717 Progress Report - Task K (1989)

TA-426

HET-718 "What Have We Learned from Supernova 1987A?" K. Kang.

TA-427 (Presented at the 10th Workshop on Grand Unification,
Chapel Hill, North Carolina, April 20-22, 1989.)

HET-719 "Axion Emissions from Supernova 1987A," K. Kang.

TA-428 (Presented at the 12th Intl. Workshop on Weak
Interactions and Neutrinos, Ginosar, Israel, April 1989).

HET-720 "Neutrino Oscillations from Realistic $SO(10)$," K. Kang.

TA-429 (Presented at the 12th Intl. Workshop on Weak Interactions
and Neutrinos, Ginosar, Israel, April 1989).

HET-721 "Elastic Scattering With and Without the Odderon," K. Kang.

TA-430 (Presented at the Third Intl. Conf. on Elastic and Diffractive
Scattering, Northwestern University, Evanston, IL, 2-6 May, 1989).

HET-722 "Dual Parton Model for Soft Hadronic Collisions," U. Sukhatme,

TA-431 C-I Tan, A. Capella, J. Tran Thanh Van.
(Proc. of IX High Energy Physics Symposium, Madras, India).

HET-723 "Enforcing the Wheeler-DeWitt Constraint the Easy Way," R. Woodard.

HET-724 "Large-Scale Structure and Galaxy Formation with Hot Dark Matter and

TA-432 Cosmic Strings," R. H. Brandenberger.
(Invited Lecture presented at the "Symposium on the Formation and
Evolution of Cosmic Strings," Cambridge, July 2-7, 1989; to be published
in the proceedings (Cambridge Univ. Press, 1989)).

- HET-725 "Cosmic Strings and Baryon Decay Catalysis," R. Gregory, W. B.
 TA-443 Perkins, A.-C. Davis, and R. H. Brandenberger. (Based on talks
 presented by R. Gregory and W. Perkins at the "Symposium on the
 Formation and Evolution of Cosmic Strings,"
 Cambridge, July 2-7, 1989.)
- HET-726 "Large-Scale Time-Dependent Approximations to Non- Linear
 TA-444 Differential Equations," J-D. Fournier and H. M. Fried.
 (Presented at the Workshop "Wavelets and Their
 Applications," Marseille, France, 29 May - 2 June 1989.)
- HET-727 "The Kaon B Parameter from Lattice QCD," G. Kilcup, S. Sharpe,
 R. Gupta, and A. Patel.
- HET-728 "On the Stability of the Chiral Vacuum," A-C. Davis and A. M. Matheson.
- HET-729 "Topological Field Theories," A. Jevicki.
 TA-445 (Lectures given at the VIth Adriatic Meeting on Particle
 Physics, Dubrovnik, Yugoslavia, June 12-22, 1989.)
- HET-730 "Formation and Evolution of Vortices in an Expanding
 Background," J. Ye and R. H. Brandenberger.
- HET-731 "Particle Production During Out-of-Equilibrium Phase Transitions,"
 J. Traschen, R. H. Brandenberger, and J. Frieman.
- HET-732 "Cosmic Strings, Hot Dark Matter and the Large- Scale
 Structure of the Universe," R. H. Brandenberger.
- HET-733 "Aspects of String Statistical Mechanics at High Energy Densities,"
 TA-446 N. Deo, S. Jain, and C-I Tan. (Talk presented at
 University of Cambridge, "Symposium on the Formation
 and Evolution of Cosmic Strings," July, 1989.)
- HET-734 "Energy Distributions for a String Gas in Compact and Noncompact
 TA-447 Spaces," N. Deo, S. Jain, and C-I Tan. (Lectures given
 at the VIth Adriatic Meeting on Particle Physics,
 Dubrovnik, Yugoslavia, June 12-22, 1989.)

- HET-735 "Lectures on Inflationary Universe Models and Cosmic Strings,"
 TA-448 R. H. Brandenberger. (Lectures given at the Scottish
 Universities Summer School in Physics, 1989.)
- HET-736 "Comments on Gravitational Radiation from Cosmic Strings," J. Kung
 TA-449 and R. H. Brandenberger. (To be published in "Symposium on
 the Formation and Evolution of Cosmic Strings".)
- HET-737 "Kaon Decay Amplitudes with Staggered Fermions," G. Kilcup.
 TA-450 (Talk presented at the International Workshop, Lattice '89,
 Isola di Capri, Italy, September 18-21, 1989.)
- HET-738 "Dynamical Inflation," R. D. Ball and A. M. Matheson.
- HET-739 "Nonabelian Aharonov-Bohm Baryon Decay Catalysis," L.
 Perivolaropoulos, A.-C. Davis, A. Matheson and R. Brandenberger.
- HET-740 "The Formation and Evolution of U(1) Gauged Vortices in an
 Expanding Universe," J. Ye and R. Brandenberger.
- HET-741 "Classical Perturbations from Decoherence of Quantum
 Fluctuations in Inflationary Universe," R. Brandenberger,
 R. LaFlamme and M. Mijic.
- HET-742 "Cosmic Strings on the Monopole Problem," A. M. Matheson,
 D. M. Upton.
- HET-743 "A Collider Diffractive Threshold, Hadronic Photons and Sextet
 Quarks", K. Kang and A.R. White.
- HET-744 "An Independent Test of Loop Bremsstrahlung", H. M. Fried.
- HET-745 "Chaotic Inflation as an Attractor in Initial Condition Space",
 J. H. Kung and R. Brandenberger.
- HET-746 "New Physics at TeV", K. Kang.
 TA-451

- HET-747 "Catalyst of Proton Decay by Cosmic Strings at Finite Temperature", A. Matheson, L. Perivolaropoulos, W. Perkins, A. C. Davis, and R. Brandenberger.
- HET-748 "Large Scale Time - Shape Non linear analysis", J-D Fournier and H. M. Fried.
- HET-749 "Action Principle for Strings in Less than one Dimension", A. Jevicki and T. Yoneya.
- HET-750 "String Field Theory and Physical Interpretation of D=1 Strings, S. R. Das and A. Jevicki.
- HET-751 "Scattering of Fermions from a Cosmic String"
- HET-752 "Effective Actions", A. Jevicki and T. Yoneya.
- HET-753 "String Equations from Unitary Matrix Models, K. Demeterfi and C-I. Tan.
- HET-754 "Have We Passed a New Strong Interaction Threshold?",
- TA-452 K. Kang and A. R. White. (Presented at the XXVth Rencontres de Moriond, High Energy Hadronic Interactions, March 11-17, 1990, Les Arcs, Savoie, France.)
- HET-755 "Cosmic Strings and Large-Scale Structure: A Comparative Review", R. H. Brandenberger.
- HET-756 "Cosmology as a Probe of (Almost) Plank Scale Physics", R. H. Brandenberger.
- HET-757 "Black Holes in Periodic Universe", A. Bogojevic, S. Garcia and L. Perivolaropoulos.

**IV. Scientific Personnel Associated with the Theoretical Program: 1
January - 31 December 1990**

D. Feldman - Professor

H. M. Fried - Professor

K. Kang - Professor

C-I. Tan - Professor

A. Jevicki - Professor

R. Brandenberger - Assistant Professor

S. Jain - Research Associate

A. Matheson - Research Associate

W. Crombie - Graduate Research Assistant

J. W. Kung - Graduate Research Assistant

K. Demeterfi - Graduate Research Assistant

L. Perivolaropoulos - Graduate Research Assistant

T. Prokopec - Graduate Research Assistant

A. D'Abba - Visiting Professor (Research)

N. Deo - Visiting Research Associate