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**PROGRESS REPORT OF A RESEARCH PROGRAM
IN EXPERIMENTAL AND THEORETICAL
HIGH ENERGY PHYSICS**

Robert Brandenberger

David Cutts - Contact Person

Herbert M. Fried

Gerald Guralnik

Antal Jevicki

Kyungsik Kang

Robert E. Lanou

Richard Partridge

Chung-I Tan

Mildred Widgoff

Principal Investigators

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**Department of Physics
Brown University
Providence, RI 02912, USA**

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I. INTRODUCTION

This report covers the work accomplished during the preceeding twelve month period in the high energy physics program in the Department of Physics at Brown University.

The program is organized into several Tasks. Two of the Tasks are in theoretical physics (*A* and *D*) and two are in experimental physics (*B* and *C*). There is an Outstanding Junior Investigator Award in experiment (*J*). At the end of the period covered by this report, Task *J* merged with Task *C*. A final Task *S* comprises the technical support for the experimental tasks. (There is also a Task *E* which is for an SSC sub-system but is not supported by this office).

II. PROGRAM IN THEORETICAL PHYSICS

A. TASK A

Progress Report for a Research Program in Theoretical High-Energy Physics

The High-Energy Theory Group (Task A) of Brown University has been carrying out a research program in theoretical high energy physics with the support of DOE. Currently, Professors Robert Brandenberger, Herbert M. Fried, Antal Jevicki, Kyungsik Kang and Chung-I Tan are Principal Investigators of the Theory Group (with Kyungsik Kang serving as the Person-in-Charge from July 1992 to June 1993). The Group includes, in addition, one Assistant Professor (Research), one Research Associate, Graduate Research Assistants and Visiting Research Faculty. This report serves to summarize the progress which has been made during the past year. The report for Task A is divided into three sections.

1. Individual Physics Research Contributions
2. Theoretical Papers Issued Since 30 June 1992
3. Scientific Personnel Associated with the Theoretical Program

The research activities of the high energy theory group at Brown University continue to cover a broad spectrum of topics in the theory of elementary particles and quantum fields, commensurate with the research specialties of its personnel. The Group has continued to produce a significant output of important papers with new ideas and calculational techniques in topics of high current interest. All of our regular staff have continued to actively work in a variety of research projects of interest and importance, with considerable impact on their evolution and development.

1. Individual Physics Research Contributions

Over the past year, the main topics of Prof. Brandenberger's research has been Electroweak Baryogenesis, Topological Defect Models of Structure Formation, Theory of Cosmological Perturbations and the Construction of a Nonsingular Theory of Space-Time.

Recently, there has been much interest in the possibility that the observed baryon to entropy ratio of the Universe is generated at the electroweak scale rather than at the scale of grand unification. All mechanisms put forwards so far have relied on the electroweak phase transition being first order. In Refs. 1 and 2, we have shown that mechanisms for electroweak baryogenesis exist which work also if the phase transition is second order. Currently, A-C Davis, Mark Trodden and Prof. Brandenberger are investigating whether the mechanisms for electroweak baryogenesis also are effective if the electroweak symmetry is dynamically (rather than spontaneously) broken. In particular, they are studying possible origins of extra CP violation in these theories. In this context, it is important to calculate the formation probability of defects during cosmological phase transitions. They have developed a new approach to this problem in Ref. 3.

With the discovery of anisotropies in the cosmic microwave background (CMB) announced in 1992, the need for more quantitative analyses of the present models of structure formation has become urgent. In Ref. 4, T. Prokopec, A. Sornborger and Prof. Brandenberger have presented a detailed analysis of the dynamics of global textures with the aim of calculating the critical winding number which in turn determined the number of hot and cold spots in the microwave sky predicted by the texture model. Currently, graduate student, R. Moessner and Prof. Brandenberger (in collaboration with Dr. L. Perivolaropoulos from Harvard) are performing a detailed analysis of the statistics of CMB anisotropis in topological defect models. They are using a statistical analysis to calculate the reliability with which current and future CMB anisotropy experiments can detect or rule out these models. They have also investigated possible signatures for cosmic strings in the gamma ray region [5]. In particular, they have studied the possibility that recently discovered isotropic distribution of gamma ray bursts might be due to cosmic strings [6]. In collaboration with

undergraduate students, Prof. Brandenberger has also been developing new statistics for large-scale structure with which the different models for the origin of structure, can be distinguished.

Almost all of Prof. Fried's research activities this past year have been devoted to the implementation of a new, analytic, strong-coupling approach to QCD. Published at the end of 1992, this first method [7] for performing dimensional transmutation (DT) in the gluon sectors of four-dimensional QCD has been under active development since then, with particular emphasis on introducing quarks into this framework. The successes already found (DT, an expected form of the Meissner effect, finite gluonic condensates) are now, with visiting Prof. Y. Gabellini of the Université de Nice, under study for quark sectors where chiral symmetry breaking is automatic. In addition, some new work has been reported [8] describing an application of these techniques to quark binding in the formation of hadrons.

Other work has continued in the study of infrared approximations to non-linear differential equations; and to a new application (and derivation) of an old formalism in Navier-Stokes fluids, which suggests [9] how chaos and turbulence can simultaneously appear; and which also suggests an "eikonal" mechanism for the construction of coherent effects (even in the most turbulent of backgrounds).

A participant and speaker at the March'93 Rencontre de Moriond, Prof. Fried was Co-Director of the Workshop on QCD Vacuum Structure, June '92, Paris, France.

During the last year Professor Jevicki has continued with investigations in string theory and matrix models. The main direction of the research is to use gauge theories and matrix models for studying and formulating string theory. In turn the relationship between the two seemingly different type of theories is likely to lead to a nonperturbative (stringy) solution of QCD.

Two major projects were pursued by Professor Jevicki and his collaborators. Working with Jean Avan, Professor Jevicki has formulated an interacting theory of topological and collective fields in [10]. The theory is derived from nontrivial bosonization of nonrelativistic fermions and is based on the large W_∞ symmetry

previously discovered by Avan and Jevicki [11,12]. In addition to the well-known bosonic scalar field, a series of higher spin fields is introduced. These turned out to be of topological origin, and interact with a unique cubic coupling.

Collaborating with Joao Rodrigues and Andre van Tonder (Univ. of Witwatersrand, S. Africa), Professor Jevicki has given a novel derivation of 2D string scattering amplitudes from the matrix model [HET-874]. In addition the special role played by the W_∞ symmetry was investigated and a comparison was made with similar studies performed by Klebanov [13], Witten and Zweibach [14], and others [6] who use the conformal approach.

Professor Jevicki has given summaries of the above work at invited talks at various conferences and international meetings: The Yakawa - Nishinomiya Symposium, November 1992 [HET-894]; The Coral Gables Conference on Unified Symmetry in the Large and in the Small, January, 1993 [HET-900]; The SUSY-93 Conference [HET-906] and the Strings 93' meeting. He was an invited lecturer at the TRIESTE Spring School on String Theory and Quantum Gravity (ICTP), April 19-27, 1993.

Professor Kyungsik Kang has continued to study dynamical electroweak symmetry breaking by a chiral condensate of color sextet quarks, in collaboration with Dr. A. R. White of Argonne National Laboratory. The minimal sextet-quark condensation model [15], which was originally constructed in connection with the elastic and diffractive scattering in the TeV energy range, has a number of attractive features including the special aspects of QCD providing the role of a "walking technicolor" group, and of the strong CP resolution via a "heavy axion", the η_6 , that should be looked for instead of the Higgs. In HET-872 and HET-885, they have pointed out the tantalizing possibility that the η_6 may have already been seen experimentally; i.e., the η_6 is expected to have a major two-photon decay mode and thus is an excellent candidate for the 60 GeV resonance which decays into two-photon pairs, as seen in $Z^0 \rightarrow \ell^+ \ell^- \gamma \gamma$ events at LEP [16]. It is also expected to decay into high multiplicity hadrons, as in the mini-Centauros experiment; and a small bump in the hadronic cross section seen [17] at TRISTAN, at just this energy, may be interpreted as due to the η_6 . This possibility has led TRISTAN to repeat the measurements [18] of hadronic cross section and of 2γ production. The results are compatible in order of

magnitude with what can be expected from $\eta_8 \rightarrow \gamma\gamma$ and $\eta_8 \rightarrow \ell^+\ell^-$ given by loop diagrams with a $\eta_8 \alpha^\mu W_\mu^+ \alpha^\nu W_\nu^-$ vertex of a CP-violating type, as suggested by the color sextet quark condensation model, although the error bars on the data prevent such a definite conclusion. Also, Professor Kang has been studying with Dr. P. Valin (Universite de Montréal) high-energy elastic and diffractive models in order to account for the total cross section and the real part of the elastic $p\bar{p}$ scattering as observed by E710, CDF and UA4.2 at CERN. F. has reported on a model of Pomeron, odderon and threshold fits in two invited talks [19] and emphasized the possibility of discovering a new physical effect beyond the standard model in high energy elastic and non-perturbative QCD process.

Prof. Chung-I Tan has been actively involved in three main areas of research: (1) **Ideal Gas of Strings and QCD at Hadronic Scales:** Prof. Tan has begun applying lessons learned in the studies of fundamental strings to practical problems of hadron collisions at high energy densities. He has shown that non-perturbative features of QCD can be inferred from future heavy ion collisions experiments even if deconfinement density is not reached [HET-879]. (2) **Non-Critical Strings and Random Surfaces:** Prof. Tan has actively engaged in clarifying aspects of large-N matrix models for the formulation of non-critical string theories, which potentially could make contact with non-perturbative string realization of QCD. In particular, he has concentrated on understanding the nature of critical behavior involving matrix models with degenerate minima [HET-863]. Further development have also been carried out together with his student, Kostas Orginos. (3) **Hadronic Physics at Fermilab Energies:** Prof. Tan has also been interested in the question of how confinement in QCD might manifest itself through topological structure in particle production at high energies. Together with E.M. Levin, (formerly St. Petersburg and currently FNAL), they have been successful in incorporating both aspects of perturbative and non-perturbative high energy scattering in QCD by introducing the concept of a Heterotic Pomeron [HET-889], which was presented by Prof. Tan at the March '93 Rencontre de Moriond, France.

Dr. Jean Avan's work consisted in constructing and studying – in collabora-

tion with Antal Jevicki – a generalization of the 2– dimensional string field theory including tachyon continuous modes, together with relevant discrete states. This was achieved by a conjectured bosonization of the free fermion $W_{1+\infty}$ algebra and leads to interesting comparisons with topological theories and 3–dimensional Toda theory. (Brown HET 879).

He also studied the algebraic structures (R-matrices and algebra of observables) for the related Calogero–Moser model. Preliminary results were described in PAR-LPTHE 92) (with M. Talon), and a more fundamental approach is currently devised (with O. Babelon and M. Talon). Relations between the algebraic structures of the Calogero and string field theory models have been classified recently (J. Avan, in preparation).

Current work with A. Jevicki, under a CNRS-NSF Exchange Program, includes a study of the relations between the x^2 -potential and the zero-potential eigenstates of the collective string field theory, from various approaches (algebraic and analytic).

Prof. Mende's recent research has involved investigating string theory (short-distance properties and non-perturbative effects) and quantum chromodynamics (the heavy quark limit of QCD). Research on these fields will continue during the coming year.

Prof. Mende has demonstrated how string theory predicts qualitatively new gravitational effects which appear as deviations from the principle of equivalence that underlies classical gravitational theory [20]. String theory has been under intensive study during the last decade but has yet to be tested experimentally. It is hoped that the study of these effects make it possible to identify low-energy effects which carry the signature of string physics.

Point particles fall freely along geodesics; strings do not. In string theory all probes of spacetime structure, including photons, are extended objects and therefore always subject to tidal forces. It was shown how string theory modifies the behavior of light in weak gravitational fields and limits the applicability of the principle of equivalence. This gives in principle a window on the short-distance structure of geometry in quantum gravity where one can see in a model-independent way how

some of its predictions differ from those of classical gravity. This complements the picture of short-distance string interactions which arises in high-energy scattering.

In other research on non-perturbative string interactions, Prof. Mende and Julian Lee, a Brown graduate student, found instanton solutions in the semiclassical limit of non-critical 1+1 dimensional string theory [21]. These are likely to be important in making contact with the eigenvalue behavior of the matrix model approach, in understanding non-perturbative symmetry breaking, and perhaps in elucidating the physics of black hole solutions which have been mostly viewed in the conformal field theory approach.

The large mass limit of QCD is important both experimentally and theoretically. Heavy mesons play a prominent role in understanding fundamental processes: one can extract fundamental electroweak parameters from their weak decays, while their rare decays are sensitive to the presence of new fundamental forces. In this limit of very heavy bottom and charm quark masses, moreover, symmetries emerge which are not present in the QCD lagrangian. The heavy quark effective field theory formalism is one powerful approach to make these approximate symmetries explicit and thereby overcome some of the practical difficulties imposed by the strong interactions in finding a straightforward interpretation of the measured lifetimes and branching ratios. It is clearly vital to determine the accuracy of the large-mass approximation since in reality the charm and bottom quark masses are both only factors a few times larger than, for example, the ρ -meson mass. This issue involves non-perturbative matrix elements and therefore requires directly confronting challenging strong-interaction dynamics.

In collaboration, Dr. Benjamin Grinstein (SSC) and Prof. Mende have been investigating these issues using two-dimensional QCD in the $1/N$ expansion as a model of the strong interactions. Their goals have been to first test the validity of approximations that can be applied to higher dimensions in the setting of a solvable model; and second, to develop a general description of those non-perturbative dynamical properties which have so far been proven conclusively only in this model. In earlier work of Prof. Mende and R.L. Jaffe (MIT), it was shown in detail how the transition from hadron to quark effective-field theories takes place in QCD with a single flavor in the large-mass limit, and shown that this two dimensional dynamics in fact

provides an excellent guide to such behavior of four-dimensional theories. Recently the dynamics which underlies this transition was shown by Grinstein and Mende to have crucial consequences for attempts to derive model-independent properties of heavy-meson form factors[22]. They found earlier that the large-mass approximation is good for form factors, even at the charm mass, although it breaks down for the pseudoscalar decay constant. This is significant because the latter had been proposed as a diagnostic for the breakdown of the expansion.

In the past eight months or so, the research interests of Dr. Li have focused on the field of low-dimensional string theories, especially two dimensional string theory. This theory has been the most well-studied string theory of the past decade, and therefore provides a good toy model for understanding various issues pertaining to any string theory. For example, what is the complete description of the entire string theory, in addition to accounting for some lowest modes, such as the graviton and dilaton? Ideas from matrix models have enabled us to achieve a complete understanding of the the tachyon in 2D string theory. This mode is massless in two dimensions. Studies by various means showed that there must be an infinite tower of higher excited modes, most notably the graviton and dilaton. In two dimensions, these modes are nonpropagating, or in other words, topological. It is obvious that the theory for tachyons is an effective theory in which those topological modes are integrated out. This can be easily seen from the non-locality of the effective theory for tachyons [23]. A complete theory for both tachyon and topological fields is still out of reach, although there have been several proposals. From our experience in study of gauge theories in two dimensions, it is believed that those topological fields must be gauge fields, precisely because they are topological. Based upon this motivation, Dr. Li proposed a gauge theory for topological modes in 2D string theory [24], by utilizing the W_∞ gauge symmetry.

Another interesting aspect of the 2D string theory is that it allows for a black hole solution. This feature is particularly interesting, in view of the paradox which has existed for some time in reconciling quantum mechanics and gravitation, namely the information problem. Since one believes that the 2D string is exactly solvable, this suggests that this model may provide a solution to this paradox. A complete theory of

the 2D string will certainly allow a thorough investigation of this issue. On the other hand, it is helpful to study physics in the fixed, black-hole background. There have been two models for such a background. One is the original model of Witten, based on the coset model $SL(2, R)/U(1)$ (the euclidean version) on the world sheet. Another was due to Mukhi and Vafa. These authors proposed to mix world sheet ghosts with world sheet matter, in order to have a no-ghost theorem. These two models are different in many aspects. One of these is that the exact metric and dilaton are different, as shown by Dr. Li in [25]. Amusingly, the exact metric in Mukhi-Vafa model is the solution of the theory in [24]. It remains to see which model is correct, or if both models can co-exist.

References

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4. T. Prokopec, A. Sornborger and R. Brandenberger, "Texture Collapse", *Phys. Rev. D***45**, 1971 (1992).
5. J. MacGibbon and R. Brandenberger, "High Energy Gamma Ray Bursts from Ordinary Cosmic Strings", *Phys. Rev. D***47**, 2283 (1993).
6. R. Brandenberger, A. Sornborger and M. Trodden, "Gamma Ray Bursts from Ordinary Cosmic Strings", Brown preprint BROWN-HET-896 (February 1993), *Phys. Rev. D*, in press (1993).
7. H. M. Fried, "Transversally Confined, Noncausal Gluons", *Phys. Rev. D***46**, 5574 (1992).
8. H. M. Fried, "Singular, Sourceless Gluon Fields of Finite Energy", BROWN-HET-878, Proceedings of the Rencontre de Moriond, Les Arcs, France, March 1993. (To appear).
9. H. M. Fried, "Integral Maps for Eulerian Flows", BROWN-HET-870, 1993. (Submitted).
10. J. Avan and A. Jevicki, "Interacting Theory of Topological and Collective Fields in 2-Dimensions" BROWN-HET-869 (to appear in *Nucl. Phys. B*).
11. J. Avan and A. Jevicki, "Classical Integrability and Higher Symmetries of Collective String Field Theory, *Phys. Lett. B***266**, 35 (1991).

12. J. Avan and A. Jevicki, "String Field Actions from W_∞ ", *Mod. Phys. Lett.* **A7** 357 (1992).
13. I. Klebanov, "Ward Identities in 2D STring Theory", *Mod. Phys. Lett.* **A7** (1992) 52.
14. E. Witten and B. Zweibach, *Nucl. Phys.* **B377** (1992) 55.
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21. P. Mende, "String Theory at Short Distance and the Principle of Equivalence", BROWN-HET-875 (1993).
22. J. Lee and P. Mende "Semiclassical Tunneling in 1+1 Dimensional String Theory", *Phys. Lett.* **B** (1993) in press.
23. M. Li, "Some remarks on tachyon action in 2D string theory", BROWN- HET- 887, submitted to *Mod. Phys. Lett.* **A**.
24. M. Li, "A proposal on the topological sector of 2D string", BROWN-HET- 888, submitted to *Mod. Phys. Lett.* **A**.
25. M. Li, "Matter-ghost mixing and the exact 2D black hole metric", BROWN-HET-903.

2. Theoretical Papers Issued since 30 June 1992

HET BROWN PREPRINTS June 1, 1992 - May 31, 1993

- HET-859 "Nonequilibrium Entropy of the Stochastic Gravitational Field",
R. Brandenberger and V. Mukhanov. (*Phys.Rev.Lett.*
69, 3606 (1992).
- HET-860 "Gauge Invariant Cosmological Perturbations: Theory and Applications",
R. Brandenberger, H. Feldman, V. Mukhanov and T. Prokopec.
- TA-478 Invited lecture at Pont d'Oye Meeting (April 26-May 2, 1992),
to be published in the Proceedings.
- HET-861 "Entropy of the Squeezed Vacuum", T. Prokopec.
- HET-862 "Electroweak Baryogenesis with Electroweak Strings", R.
Brandenberger and A. C. Davis. (*Phys. Rev. Lett.* b in press (1993).
- HET-863 "Multiple Two-Cut Solutions in Hermitian Matrix Models",
R. Brower, N. Deo, S. Jain and C-I Tan. (*Nucl. Phys.*)
- HET-864 "Local Screening and Softening of Lipatov Pomeron",
E. M. Levin and C-I Tan.
- HET-865 "Electroweak Baryogenesis with a Second Order Phase Transition",
R. H. Brandenberger, and A-C. Davis.
- TA-479 Conf. Proceedings - Yale Workshop on Electroweak Baryogenesis
to be published in proceedings.
- HET-866 "Modified Aharonov-Bohm Scattering from Electroweak Strings", N. Ganoulis.
- HET-867 "Transversally Confined, Acausal Guonons", H. Fried.
(*Phys. Rev.D*46 (1992) 5574).
- HET-868 "Physics with and Beyond the Standard Model", K. Kang and P. Valin.
- TA-497 INS Report 92-62, Univ. J. Fournier, Grenoble, 1992.
- HET-869 "Interacting Theory of Collective and Topological Fields in 2 Dimensions",
J. Avan and A. Jevicki (*Nucl. Phys. B*.
- TA-480 Proceedings XIX International Colloquium on Group Theoretical
Published in the Proceedings of the XIX International
Colloquium on Group Theoretical Methods in Physics
Anales de Fisica, Monografias, Vols 1 , page 225.
Salamanca, June 29-July 4, 1992
- HET-870 "Integral Maps for Eulerian Flows", H. M. Fried.
- HET-871 "Two-Dimensional Quantum Gravity, Matrix Models and String Theory",
K. Demeterfi.(Submitted to IMJP)
- HET-872 "The η , at LEP and TRISTAN, K. Kang , I. G. Knowles
and A. R. White, *Mod. Phys. Lett. A* (in press).

- HET-873 "Color-Sextet Quark Condensation in QCD", K. Kang and A. R. White.
- TA-498 Invited talk at the Workshop on QCD Vacuum Structure
American University in Paris, June 1992.
- HET-874 "States, Scattering and Symmetries in the Matrix Model and
Two-Dimensional String Theory", A. Jevicki,
J. Rodrigues and A. J van Tonder. (Nuclear Phys. B)
- HET-875 "String Theory at Short Distance and the Principle of Equivalence",
P. Mende.
- TA-482 Published in the International Workshop on
Theoretical Physics: 6th session, String Quantum Gravity
and Physics at the Planck Energy Scale, N.Sanchez
editor, World Scientific (1992).
- HET-876 "A Non-Singular Universe", R. Brandenberger.
invited lecture at the International School of Astrophysics
D.Chalonge, 6-13 Sept. 1992, to be published in proceedings.
- HET-877 "Are There Evidences for the Color-Sextet
Condensation?", K. Kang and A. R. White.
- TA-481 (Proceedings XIX International Colloquium on Group
Theoretical Methods in Physics - Salamanca
June 29-July 4.1992
- HET-878 "Singular, Sourceless Gluon Fields of
Finite Energy", H.M. Fried.
- TA-497 Proceedings of the Rencontre de Moriond,
Les Arcs, France, March 1993. (To appear)
- HET-879 "Ideal Gas of Strings and QCD at Hadronic
Scales", C.-I Tan".
- TA-483 Invited talk at Workshop on QCD Vacuum Structure, Paris, June 1992.
- HET-880 "Semiclassical Tunneling in 1+1 Dimensional String Theory",
J. Lee and P. Mende. *Phys. Lett. B* (1993) in press.
- HET-881 "Topological Defect Models of Structure Formation After
the Cobe Discovery of CMB Anisotropies". R. H. Brandenberger.
- TA-484 Invited lectures at the International School of Astrophysics
"D. Chalonge," 2nd course 6-13 Sept., 1992, Erice, Italy, to be
published in the proceedings (World Scientific, Singapore, 1992).
- HET-882 "On the Constraints on Heavy Meson Form Factor", B. Grinstein
and P. F. Mende. *Phys. Lett. B* 299 (1993) 127.
- HET-883 "Color Sextet Quarks and New High-Energy Interactions",
K. Kang and A. White.
- TA-485 Presented at VIIth International Symposium
on Very High Energy Cosmic Ray Interactions,
Anabor, Michigan, June 21-27, 1992.
- HET-884 "Tunneling in Anisotropic Cosmological Models",
R. Mansouri and M. Mohazzab.

- HET-885 "The η_6 and Massive Photon Pairs at LEP", K. Kang,
I. G. Knowles and A. White .
- TA-486 Invited talk at DPF'92 (ANL-HEP-CP-92-117), Fermilab, Nov. 1992.
- HET-886 "Color-Sextet Quark Condensation in QCD", K. Kang and A. White.
- TA-487 Invited talk at DPF'92, Fermilab, Nov. 1992.
- HET-887 "Some Remarks on Tachyon Action in 2D-String", M. Li.
(Submitted to Mod. Phys. Lett. A).
- HET-888 "A Proposal on Topological Sector of 2D-String", M. Li
Submitted to Mod. Phys. Lett. A).
- HET-889 "Heterotic Pomeron: A Unified Treatment of High Energy
Hadronic Collisions in QCD", G. Levin, C-I Tan.
- TA-488 Presented at XXII Int. Symposium on Multiparticle Dynamics,
Santiago, Spain, July, 1992.
- TA-489 Presented at Workshop on Small x Physics at Fermilab, September 1992.
- HET-890 "Towards a Nonsingular Universe", R. H. Brandenberger.
- TA-490 Presented Texas Pascos Meeting, December 12-18, 1992.
- HET-891 "A Cosmological Theory Without Singularities", R. Brandenberger,
V. Mukhanov and A. Sornborger. (subm. to Phys. Rev. D.
- HET-892 "Gamma-Ray Bursts from Cosmic Strings (cups)?",
R. H. Brandenberger and M. Mohazzab.(subm. to IJMPA)
- HET-893 "Lectures on Modern Cosmology and Structure Formation",
R. Brandenberger.
- TA-491 Invited Lecture at the 7th Swieca Summer School in Particles
and Fields, Campos do Jordao, Brazil, January 10-23 1993, to be publ.
in the proceedings, etc. O. Eboli and V. Ribelles (Worlds
Scientific, Singapore, 1992).
- HET-894 "Fields and Symmetries of 2D Strings", A. Jevicki.
- TA-492 Invited Talk at the Yukawa-Nishinomiya Symposium,
Japan, November 1992. (to be published in proceedings)
- HET-895 "A Semi Analytical Study of Texture Collapse", A. Sornborger.
(Phys. Rev. D in press (1993))
- HET-896 "Gamma Ray Bursts From Ordinary Cosmic Strings",
R. H. Brandenberger, A. T. Sornborger, M. Trodden.
(Phys. Rev.D, in press (1993).
- HET-897 "Cobe vs Cosmic Strings: An Analytical Model", L. Perivolaropoulos.
Phy. Lett. B, 298, 305 (93).
- HET-898 "On the Statistics of CMB Fluctuations Induced by Topological Defects",
L. Perivolaropoulos. (Submitted Phy. Rev. D in press)
- HET-899 "Perturbation Theory in Two Dimensional String Field Theory", B. Urosevic.
- HET-900 "Symmetries of 2-Dimensional Strings", A. Jevicki
- TA- 493 Invited talk at Conference on Unified Symmetry
in the Small and in the Large, Coral Gables,
Florida, January 25-27, 1993 to be published in the

- Proceedings (Nova Science Publ. In., New York, 1993).
- HET-901 "Towards a Nonsingular Universe", R. Brandenberger.
- TA-494 "Invited talk at the 1993 Coral Gables Meeting
"Unified Symmetry in the Small and in the Large",
Jan. 25-27, 1993, Coral Gables to be published in the Proceedings
(Nova Science Publ. In., New York, 1993).
- HET902 "Formation of Topological Defects in First and Second
Order Phase Transitions", M. Hindmarsh, A-C. Davis and
R. Brandenberger, (to be subm. to Nucl. Phys. B).
- HET903 "Matter-ghost Mixing and the Exact 2d Black Hole
Metric, "M. Li. (Submitted to Phys. Lett. B).
- HET-904 "Black Holes from Matrix Models", A. Jevicki
and T. Yoneya.
(subm. to *Nuclear Physics B* (1993)).
- HET-905 "Theory of Topological and Collective Fields in 2 Dimensions,
A. Jevicki
- TA-495 Proceedings of the PASCOS Symposium, Northeastern University,
Boston, MA, April, 1993. (to be published in proceedings)
- HET-906 "Topological Defects and Structure Formation", R. Brandenberger
- TA-496 Lecture Given at the Troisieme Cycle de al Siusse
Romande, Lausanne, Switzerland, April 22 - May 23, 1993.
- HET-907 "A Nonsingular 2-Dimensional Black Hole", M. Trodden, V.
F. Mukhanov and R. Brandenberger. (to be subm. to Phys. Rev. D.)
- HET-908 "A New Approach to Numerical Quantum Field
Theory", S. Garcia, G. Guralnik and J. Lawson.

3. Scientific Personnel Associated with the Theoretical Program: 1 June 92 – 31 May 1993

H. M. Fried – Professor

A. Jevicki – Professor

K. Kang – Professor

C-I Tan – Professor

R. Brandenberger – Associate Professor

P. Mende – Assistant Professor (Research)

J. Avan – Research Associate

M. Li – Assistant Professor (Research) – As of 1 September 1992

K. Demeterfi – Graduate Research Assistant – Until 31 August 1992

J. Lee – Graduate Research Assistant

T. Prokopec – Graduate Research Assistant – Until 31 August 1992

A. Scrnborger – Graduate Research Assistant

B. Urosevic – Graduate Research Assistant

K. Orginos – Graduate Research Assistant – As of 1 September 1992

L. Perivolaropoulos – Visiting Scientist

K. Itoh – Visiting Research Associate – 31 January 1993 – 2 April 1993

A. vanTonder – Visiting Assistant Professor (Research) – 2 August 1992 – 2 February 1993

S. Mukhanov – Visiting Assistant Professor (Research) – Long-term Collaborator

I. Gabellini – Visiting – 1 February 1992 – 30 June 1993.

M. Mohazzab - Visiting Scholar – 1 June 1992 – 31 May 1993.

B. TASK D

1. Progress Report for a Research Program in Computational Physics

Task D's research has concentrated on the development of the source Galerkin method of numerical quantum field theory. This method, discovered by Guralnik, is dramatically different from Monte Carlo based methods in concept and application. The build up time has been long as is usually the case for numerically based methods. We are now able to calculate with small amounts of computer time systems that required vast amounts of time using conventional methods. Over the last year we have learn how to calculate non-trivial systems in two or four dimensions to potentially very high accuracy. The results obtained to date are sensationally accurate where it is possible to make comparisons. On the basis of work done thus far Santiago Garcia was able to finish his PhD dissertation this year. He is now supported as a postdoctoral fellow at Brown using a combination of Brown, DOE and NSF funds. The NSF money was granted to hire Garcia into this position so as to continue this very promising work.

Monte Carlo methods resulted in thrilling initial successes in calculating some parameters associated with quantum field theories. They work by generating and combining sets of configurations of fields with values on sites or links of a space time lattice. The Green's Functions of a theory are calculated by inverting matrices associated with these field configurations. A large lattice for even a simple self interacting scalar field theory requires a huge amount of calculation. Despite great strides in refining and modifying algorithms and enormous increases in computer power, it is arguable that Monte Carlo methods have not given much more detail than that which was obtained with the initial calculations. This is understandable through simple arguments and operation counts. These confirm that detailed evaluations of systems with dynamical quarks with low masses require computing times well beyond our current capabilities.

In part, the problem with the Monte Carlo methods occurs because of their statistical nature and great generality. They make no use of any of our knowledge of the systems studied. In particular, symmetry which is the primary mold for all theories is never invoked. We have formulated a deterministic numerical evaluation scheme for Lattice quantum field theory which has a relatively symmetric treatment of boson and fermion fields. It makes full use of the space time symmetry of quantum field theory as well as the internal symmetry. It has become apparent over the last few months, that we can also insert much of our knowledge about the spectral form of the final results to productively speed our calculations. The ideas involved are straightforward.

We will briefly describe these methods in their simplest form. The details are given in reference [1] A source for every field is placed in the action of the quantum field theory being studied. Then, either using the operator equations of motion, or equivalently the path integral representation on a lattice, equations are derived for the vacuum-vacuum matrix element Z . The result is a set of coupled linear differential equations in the discretized sources. Differentiation with respect to the sources produces the lattice Green's function equations. These, of course, have the same "problem" as the continuum equations in that no finite subset of them closes. An N point Greens function is associated with Green's functions of more as well as fewer than N points. Except for their large number, the equations for Z , in themselves are nothing at all unusual mathematically. We must solve them as any other set of linear differential equations is solved. They must be made manageable through some expansion scheme. The fact that at the end of the calculation the sources are set to zero suggests that Z be expanded in a Taylor series (or other set of complete functions that favor small source values) in these sources. We make the assumption that the series is sufficiently well behaved so that for small values of the sources only some finite number of terms need be retained to obtain the desired accuracy in Z . In other words, we approximate by truncating the expansion of Z in powers of the sources. This means that we set all Green's functions involving more than some set number of points equal to zero. By doing this we obtain a finite set of linear equations accurate within the limits of the approximation. Note that it is in general possible to choose sources so as to make this truncation appropriately respect any symmetries the theory

might have.

The truncation has nothing to do with the space time structure which is entirely specified by the initial choice of the lattice. We can, however, use this structure to great advantage in constructing solutions. The resulting equations must have a high degree of symmetry because of the translational invariance of the underlying periodic lattice as well as reflection symmetries associated with this structure. This greatly reduces the number of equations to be considered. If the vastly reduced number of equations resulting from exploitation of space time symmetries are treated as given algebraic equations in the usual sense they are, not surprisingly, usually inconsistent. This problem is an artifact of the approximation. There are many ways to deal with it. One particularly elegant method is to use a technique that requires that a weighted average of the truncated equations be true. A clever choice of weight functions will speed the convergence of the truncated equations to the exact solutions. Methods of this sort have been used for examining differential equations associated with engineering problems and are called Galerkin methods. Since our expansions and weighting functions depend on the external sources we have introduced we call this method "the Source Galerkin method". It is very different from any technique that we know to have been used to solve quantum field theory in the past. It is dramatically different from Monte Carlo. As a practical matter, one of the most important differences is that Fermions and Bosons are treated in a similar manner. It is not necessary to solve an exact (or near exact) fermion problem for every boson configuration. Consequently, useful solutions of dynamical fermion problems are possible with existing computers. In the case of free fields, it is easy to see that this method is a variational technique for an effective action in the sources. However, for interaction the method is explicitly not a variational technique.

There are some beautiful subtleties of boundary conditions which turn out to work automatically in a truncation expansion. These insure that the solutions obtained from the differential equations correspond to the evaluation of the path integral formulation of the theory. These boundary conditions might not be the ones of physical interest but to our knowledge are the ones always used in physics. Since the differential equations we begin with originate from the restrictions of canonical quantization, they are more general than the path integral solutions. Nevertheless, they are consis-

tent with the basic postulates of quantum field theory and should not be dismissed. In the last year we have studied (non truncated) Source Galerkin solutions to these equations which do not meet path integral boundary conditions. So far our studies have been limited to lower dimensions. The results are interesting and could turn out to be relevant.

Source Galerkin can be utilized with many classes of expansion functions. To date we have examined polynomial and exponential classes in quartic scalar and fermionic field theory with extremely good results. We have extensive results in two dimensions. We have some very good results in four dimensions and expect to produce extensive results using our spectral expansions. Publications are in preparation. In general our observations are that a very large amount of computer algebra and group theory must be performed to set up the appropriate classes of functions. This work is identical for interacting or free theories so the known free field results always stand as a guidepost. The integrations (trivial) and the solution of the linear equations are done in fortran. The matrices to be inverted become very large but, unlike in the case of Monte Carlo, we only have to do the inversion once for any given set of parameters.

This year has seen a number of major developments which will make it possible for us to calculate non-trivial and four dimensional systems. The most striking development is that we have managed to eliminate huge amounts of numerical noise by working with the differential equations for $\ln(Z)$ instead of Z . This is impossible to do with Monte Carlo and we have avoided it in the past because it requires working with non-linear differential equations. It turns out that the effort is possible and worthwhile. The second major result is that we have managed to incorporate spectral analysis directly into our computational scheme. The result is a set of expansion functions which are very similar to the ones that we must use to fit the numerical data to physical results. Source Galerkin is really working. It appears that we will be able to move beyond existing Monte Carlo results in the next year with even a minimal amount of good luck.

Reference

1. S. Garcia, G. Guralnik and J. Lawson, " A New Approach to Numerical Quantum Field Theory", BROWN-HET-908 (1993).

III. PROGRAM IN EXPERIMENTAL PHYSICS

A. INTERACTIONS OF LEPTONS AND HADRONS FROM ACCELERATOR AND ASTROPHYSICAL SOURCES TASK B

1. Experiments and Data Analysis in Progress

1.1. THE LARGE VOLUME DETECTOR AT GRAN SASSO

The first of the five towers of LVD was completed and data acquisition was begun during the winter and spring of 1992. Since that time the detector has been running continuously, except for a shut down of about one month (December 1992) to change the gas in the tracking system counters (LSTs) to a non-flammable mixture. Meanwhile, construction of modules for the second tower has proceeded, and Tower 2 is now about half finished.

Even a single tower is a very substantial detector. Table I shows the physical particulars of the full LVD; one tower is about 13m high by 12m wide by 6m deep, and consists of 38 modules. An end view of the detector is shown in Fig. 1, and Fig. 2 shows an overall view of the LVD, as well as the individual module structure, consisting of six $1m \times 1m \times 1.5m$ liquid scintillation counters each viewed by three photomultipliers, in a portatank covered on two sides by an L-shaped tracking detector made up of two double layers of LSTs.

The hardware trigger calls for detection of energy greater than 7 MeV deposited in at least one scintillator tank, or a majority of four planes of the tracking system – a very low bias trigger. Various software triggers are then applied, appropriate to any physics study. In the following we will briefly describe the data obtained thus far on three subjects: (1) muon multiplicity and angular distributions, from the tracking system, (2) energy deposited in scintillation counters along reconstructed tracks, in a search for particles of fractional charge, and (3) search for neutrinos from supernovae.

Table 1.	
Main Characteristics of LVD	
Detector Properties	
Size	$13.135 \times 39.304 \times 11.96 \text{ m}^3$
Volume	6174 m^3
Geometric Acceptance	7184 m^2 - steradian
Mass	3.6 kilotons (metric)
Scintillator Elements:	
Size	$0.992 \times 1.492 \times .992 \text{ m}^3$
Number	1520
Total Volume	2232 m^3
Total Mass	1.8 kilotons (metric)
Acceptance ($\geq 0 \text{ MeV}$)	$6089 \pm 158 \text{ m}^2$ - steradian
Acceptance ($\geq 3 \text{ MeV}$)	$5983 \pm 157 \text{ m}^2$ - steradian
ΔE	$20\% / \sqrt{E(\text{MeV})}$
$E_{\text{threshold}}$	7 MeV (outer layer)
	5 MeV (inner layers)
	0.8 MeV (within gate)
Tracking Chambers:	
Gas Cell Size	$0.9 \times 614.6 \times 0.97 \text{ cm}^3$
Total Cells	109,440
Total Volume	58.72 m^2
Sense Strip Width	4 cm
Number	155,040
$\Delta\Theta$	1 mrad (≥ 3 plane-pairs)
	2 mrad (2 plane pairs)
	67 mrad (1 plane-pair)

(1) Muon Studies

To a sample of about 6×10^6 raw triggers, we apply a software trigger requiring at least one scintillation counter signal (energy > 7 MeV) and counts in at least 2 legs of the tracking system, a leg being one side of the L bordering the portatank. About 5.8×10^5 muon tracks have been reconstructed. Fig. 3a) shows an example of a reconstructed track – the tracking plane hits are shown; and the numbers in the squares representing the scintillation counters are related to the energy deposited in the counter.

Fig. 3b) is included to show that tracks from events of quite high multiplicity can be reconstructed in our system. Fig. 4 is a plot of the muon multiplicity distribution, while Fig. 5 shows muon angular distributions in θ and φ . The distributions agree with expectations from Monte Carlo calculations; the peaks in the φ distribution correspond to dips in the mountain itself – where the absorbing material is not so thick, the flux of muons is of course greater. Figures 6 a) and b) respectively show the slant depth and minimum surface energy distributions of the muons.

Muon studies will constitute the basis of Asoka De Silva's thesis, which will be further described in the Proposal.

(2) An Investigation of the Energy Deposited in LVD by Vertical Muons: Search for Fractionally ($2/3$ e) Charged Particles.

Tracks are reconstructed from the tracking detector independent of the scintillator data. The length of each track in each scintillation counter traversed was calculated from the geometry, and the charge per unit length, Q/L , was then obtained for each track, using the photomultiplier output in pC. By comparing the peak of the Q/L distribution for many tracks in each counter with the theoretical dE/dx for a high energy muon, 1.6 MeV/cm, a calibration factor was determined for each counter. These calibration factors have been found to remain essentially constant over time. After this calibration, the dE/dx distributions of the individual counters can be summed together: this summed distribution for all tracks with $L > 95$ cm in the counters is shown in Fig. 7a), where the theoretical Landau distribution is shown for comparison.

In the search for weakly interacting fractionally charged particles, we used this subset of the data in which the track length inside the scintillator was at least 95 cm,

at a distance of at least 10cm from the wall of the counter. For a particle with charge equal to $2/3 e$, since dE/dx varies as the square of the charge, we expect most of the such particles to give a measured $dE/dx < 1 \text{ MeV/cm}$. In a data set of 210,000 muons (188 data-taking days) which fired at least 3 double layers of streamer tubes plus one scintillation counter, with the track length in the SC fulfilling the criteria stated above, 503 tracks were found with $dE/dx < 1.0 \text{ MeV/cm}$. This portion of the dE/dx distribution is shown in Fig. 7b). Each of these candidates was studied separately, and they were found to be mostly due to showers, or low energy muons with very bent tracks, or small geometrical errors.

No weakly interacting fractionally charged particles were found. Knowing the acceptance of the detector from Monte Carlo studies, we set an upper limit on the flux of $2/3 e$ charged particles at $1.6 \times 10^{-14} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$. This limit is compared in Table 2 with results from other experiments. When the second tower is completed, this experiment will very quickly pass the limit set by Kamiokande II.

Table 2.
Underground Search for Fractionally
Charged Particles ($2/3 e$)

Experiment	Nr. of Events	Duration of Run (Days)	Upper Limit of Flux ($\text{cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$, 90% C.L.)
Kamiokande-II	4.9×10^6	1009	2.3×10^{-15}
LVD	2.1×10^5	188	1.6×10^{-14}
LSD	4947	2097	3.1×10^{-13}
Tokyo	2.7×10^6	217	9.8×10^{-13}

(3) LVD as a Stellar Collapse Monitor

The full LVD will have 1800 tons of liquid scintillator, and Tower 1 alone is already the largest scintillation detector of neutrinos from stellar collapse in the world. The principal mode of detection is via the interaction

$$\bar{\nu}_e + p \rightarrow n + e^+,$$

of which approximately 150 would be expected in Tower 1 of LVD, operating at energy threshold $E_{th} = 7 \text{ MeV}$, from a stellar collapse at the galactic center. The signature of this interaction is the 2.2 MeV γ ray emitted when the neutron is captured, with the characteristic neutron capture time distribution. The method of search is first to trigger on a signal of energy greater than about 7 MeV in any scintillation counter (SC) – this is the high threshold trigger. When this threshold is exceeded, the struck SC and all other SC's in the local quarter tower have their thresholds lowered to about 0.7 MeV for 100 ms – the low threshold gate. The scintillation readout is done after the 100 ms gate and the time distribution of the pulses is recorded. The background in the first tower is about $3 \times 10^{-2} \text{ Hz}$ from muons, and from radioactivity it is about $1.1 \times 10^{-1} \text{ Hz}$ at $E_{th} = 7 \text{ MeV}$, about $2 \times 10^2 \text{ Hz/counter}$ at $E_{th} \sim 1 \text{ MeV}$.

Each sequence of m events, regarded as a cluster of multiplicity m , with m ranging from 2 to 150, within a time interval $t_m - t_1 \leq 600 \text{ sec}$, is compared on line with the Poisson distribution of counts for the measured rate. Off line, the energy and angular distributions are studied, and the presence of the signature delayed low-energy signals from the $\bar{\nu}_e p$ interactions is checked.

Two main features are precise absolute timing (G.S.N.L. $100\mu \text{ sec}$) and fast event recognition with the on-line SN monitor.

Needless to say, no SN has been observed during the brief time LVD has been on watch, but the detector is well prepared for events to come.

1.2. GEM COLLABORATION AT SSC

The GEM Collaboration has submitted its Technical Design Report to the SSC, and it now awaits consideration and discussion. The Collaboration decided in favor of cathode strip chambers (CSCs) for the muon system. Although this was not our original recommendation, we expect to be part of the group that produces the muon detector, once the TDR is accepted.

1.3. RESEARCH AND DEVELOPMENT ON RESISTIVE PLATE COUNTERS.

A small subgroup of GEM, including MIT, LLNL, Tennessee, Indiana and Brown, engaged in an R and D project to evaluate Resistive Plate Counters (RPCs) for use as muon detectors. The Texas National Research Laboratory Commission provided partial support for equipment for the test facility we proposed to build at MIT. The development work on this type of detector is considered to be of great general interest and value, even though that it will not be used in GEM.

Two RPC's, one made of bakelite and the other of two glass backed wall mirrors, were completed with a view to determining the operating characteristics as a function of the resistivity of the chamber wall material and the style of construction. Figure 8 shows a diagram of a generic RPC, which is very similar to our bakelite version

The Bakelite RPC has a resistivity of 10^{11} Ω -cm, while the Glass RPC resistivity was measured to be about 5×10^{12} Ω -cm. To achieve low noise and high efficiency, the Bakelite surfaces facing the gas were polished and painted with a linseed-oil-based semi-conducting paint. The Glass RPC was built out of two mirrors ($1.35\text{m} \times .4\text{m}$) purchased from a local hardware store; no care has been taken to control the glass composition or surface irregularities. The gas gap for both RPCs is 2mm and the wall thicknesses differ by 1 mm. Also, the electrical properties of the metallic coating could not be as finely controlled in the Glass RPC as in the Bakelite RPC.

The high voltage and ground for the Bakelite RPC are provided by graphite paint on the outside surfaces of the Bakelite, to which the electrical connections are made. The high voltage and ground for the Glass RPC are provided by the metallic reflective coating of the mirrors, to which electrical connection was made using copper

tape. The signal readout for the Bakelite RPC is achieved by using aluminum strips, isolated from high voltage and ground by a thin insulating film. For the Glass RPC, the readout is achieved by segmenting the metallic coating on the ground side into strips that run along the length of the mirror. Approximately 1 mm of the reflective coating was removed between adjacent strips, thus electrically isolating them from one another. Table 3 shows a summary comparison of the construction of the two chambers. The major significant quantitative difference appears to be the resistivity.

Both RPCs were studied using the same experimental setup, i.e. the same gas system, the same high voltage supply, the same electronic components and in the case of efficiency and time jitter measurements, the same scintillator telescopes. A summary of the various measured parameters for the Bakelite and Glass RPCs is collected together in Table 4. Among the most interesting findings are the following:

- (i) Pulse characteristics were found to be very similar, in spite of the differences in the materials and construction.
- (ii) Efficiency measurements were made using cosmic rays with a scintillation counter trigger. The Bakelite RPC has a counting efficiency of about 95%, compared to 70% for the Glass RPC.
- (iii) The Bakelite chamber had superior time resolution (jitter) as well – the measured resolution for the Bakelite RPC was 1.25 ns at 8 KV, while the glass RPC resolution was about 7 ns.

Details of this investigation are given in Report SSC GEM NOTE 1 (92- 1). Briefly, to summarize, we find that the high resistivity of the Glass RPC degrades the rate handling capability of the counter, and prevents the achievement of high efficiency. The time jitter is also worse for the Glass RPC. On the other hand, the two RPCs agree remarkably well in such pulse characteristics as pulse height, pulse width, rise time and pulse velocity along a strip.

We are continuing RPC studies, including spatial resolution, with support from the SSC laboratory.

DETAILS OF CONSTRUCTION

PARAMETERS	BAKELITE RPC	GLASS (MIRROR) RPC
MATERIAL OF CHAMBER	BAKELITE (Phenolic Polymer)	GLASS
SIZE	2 m x 1 m	1.35 m x 0.4 m
WALL THICKNESS	2 mm	3 mm
VOLUME RESISTIVITY	$10^{11} \Omega\text{-cm}$	$5 \times 10^{12} \Omega\text{-cm}$
GAS GAP	2 mm	2 mm
INTERNAL SPACERS	YES	NO
HIGH VOLTAGE SUPPLY SURFACE	GRAPHITE PAINT ON BAKELITE	REFLECTING SURFACE OF MIRROR
READOUT STRIPS	ALUMINUM	STRIPS CUT OUT ON REFLECTING SURFACE
STRIP IMPEDANCE	50 OHM	50 OHM
STRIP WIDTH	3 cm	3 cm
GAS COMPOSITION	64% ARGON, 4% F13B1 30% ISOBUTANE	65% ARGON, 4% F13B1 30% ISOBUTANE

Table 3

PERFORMANCE CHARACTERISTICS

PARAMETERS	BAKELITE RPC	GLASS (MIRROR) RPC
PULSE HEIGHT	0.3 - 0.6 VOLTS	0.2 - 0.5 VOLTS
PULSE WIDTH	~ 10 ns	~ 20 ns
PULSE RISE TIME	~ 3 ns	~ 3 ns
PULSE VELOCITY along strip	> 0.5 (< 6.6 ns / meter)	> 0.5 (< 6.6 ns / meter)
EFFICIENCY	> 95%	~ 70%
PLATEAU KNEE	~ 7 KVOLTS	~ 7 KVOLTS
PLATEAU WIDTH	~ 2000 VOLTS	~ 2000 VOLTS
CURRENT DRAWN	~ 25 microAmp @ 8 KV	~ 2 microAmp @ 8 KV
COUNTING RATE at 8 Kvolts (@ two thresholds)	0.3 Hz / sqcm @ 0.016v 0.1 Hz / sqcm @ 0.100v	0.2 Hz / sqcm @ 0.032v 0.1 Hz / sqcm @ 0.100v
SOURCE TEST RATE / CM ² ("medical source")	~ 543 Hz / sqcm @ 0.016v	~ 48 Hz / sqcm @ 0.016v
TIME RESOLUTION (JITTER)	~ 1.1 ns	~ 7 ns

Table 4

End View of LVD, Showing Tracking Planes
(Rectangles are End Views of Scintillator Portatanks)

FIGURE 1

a) GENERAL VIEW OF LVD

b) DETAIL OF LVD ASSEMBLY SYSTEM

FIGURE 2

MULTIPLICITY FROM PIPR

[PIPR IS THE TRACK RECONSTRUCTION PROGRAM]

FIGURE 4

Muon Angular Distributions

FIGURE 5

a) Distribution in Slant Depth

b) Distribution in Minimum Surface Energy

FIGURE 6

a) All Tracks with Length > 95 cm in Scintillator

b) Detail for $E/L < 1$ MeV/cm

$E/L = dE/dx$ in Scintillator

FIGURE 7

Sketch of a Generic RPC

FIGURE 8

2. Associated Matters

Asoka De Silva will do his Ph.D thesis on the muon data collected in LVD during the operation of Tower 1 since Spring 1992. He will return to Brown in June 1993 to concentrate on data analysis and writing after a stay of about three years at Gran Sasso. He has been a most valuable contributor to both the hardware and data acquisition of Tower 1, the construction (in progress) of Tower 2 and the planning of Tower 3.

During the past year we were told that the Amdahl computer at Fermilab was to be taken out of general use. We have depended on this machine for analysis of the Fermilab neutrino and muon data of Experiments E745 and E782. We want to express our appreciation to Mukunda Aryal, our former colleague, now at Ohio State University, for his help in saving programs, files, data, so analysis can, we hope, be continued elsewhere.

3. Scientific Personnel Associated With Task B

Mildred Widgoff – Professor of Physics, Principal Investigator

Asoka De Silva – Graduate Research Assistant

David Rossi – Senior Research Technician, part-time, through Support Task S which was inaugurated in January, 1991.

4. Papers and Reports Published and in Preparation

- *445. "Study of Intermittency in Hadron-Hadron Collisions at $\sqrt{s} = 16.7$ GeV", M. Widgoff with IHSC (International Hybrid Spectrometer Consortium), *Nuovo Cimento* **105A**, 883 (1992).
- 447. "Large Volume Detector at Gran Sasso Laboratory", A. De Silva and M. Widgoff, LVD Collaboration, LVD Analysis Note 92-1, July 1992 (Presented at VULCANO 92 Conference, L. Votano).
- 448. "The Status of the LVD Experiment at Gran Sasso Laboratory", A. De Silva and M. Widgoff, LVD Collaboration, LVD Analysis Note 92-2, August 1992 (Presented at ICHEP Conference at Dallas, I. A. Pless).
- 449. "LVD: The Stellar Collapse Monitor:", A. De Silva and M. Widgoff, LVD Collaboration, LVD Analysis Note 92-3, August 1992 (Presented at ECRS '92, CERN, W. Fulgione).
- 450. "Status of the Large Volume Detector at Gran Sasso", A. De Silva and M. Widgoff, LVD Collaboration, LVD Analysis Note 92-4, September 1992 (Presented at Wein 1992 Conference, Dubna, O. Ryazhskaya).
- 451. "Status of the LVD Experiment at Gran Sasso Laboratory", A. De Silva and M. Widgoff, LVD Collaboration, LVD Analysis Note 92-5, November 1992 (Invited Paper at Southeastern Section of American Physical Society, Oak Ridge, E. Hafen).
- 452. "Status of the Large Volume Detector at Gran Sasso", A. De Silva and M. Widgoff, LVD Collaboration, LVD Analysis Note 92-6, November 1992 (Presented at Meeting of the Division of Particles and Fields, American Physical Society, Fermilab, P. Haridas).
- 453. "The Most Powerful Scintillator Supernova Detector: LVD", A. De Silva and M. Widgoff, LVD Collaboration, *Nuovo Cimento* **105A**, 1790 (1992).

* Previously Listed as in Preparation

- 454. "First Observation of High Energy Cosmic Ray Events Obtained in Coincidence Between EAS-TOP and LVD at Gran Sasso", A. De Silva and M. Widgoff, LVD Collaboration, *Nuovo Cimento* **105A**, 1815 (1992).
- 455. "Status of the LVD Experiment at Gran Sasso Laboratory, A. De Silva and M. Widgoff, LVD Collaboration, *B.A.P.S.* **38**, 1020 (1993).
- 456. "Angular Distributions Observed in the LVD Particle Astrophysics Experiment at Gran Sasso Laboratory", LVD Collaboration, *B.A.P.S.* **38**, 1020 (1993).
- 457. "An Investigation of the Energy Deposited by Vertical Muons in the LVD Detector", M. Widgoff and A. De Silva, LVD Collaboration, *B.A.P.S.* **38**, 1020 (1993).
- 458. "Progress Report of a Program in Experimental High Energy Physics - Task B", M. Widgoff, May 1993, Doc-FG-02-41ER-4068-B2.

B. HADRON COLLIDER AND NEUTRINO PHYSICS (TASKS C AND J)

1. Task C

The major emphasis of Task C at present is the $D\bar{0}$ ("D-ZERO") experiment at Fermilab's TeVatron Accelerator, which has just completed a nearly year-long collider run. In this report, we will discuss the commissioning of the $D\bar{0}$ detector and its operation during this run, ending May 31, 1993, for which over 25 pb^{-1} of integrated luminosity was delivered to the experiment.

An additional project involving Task C personnel builds upon our earlier neutrino program at BNL by developing and testing new cryogenic methods for neutrino physics. We will discuss recent progress in this effort.

1.1. THE $D\bar{0}$ EXPERIMENT

The $D\bar{0}$ experiment has been the principal focus of this Task since the completion of the neutrino program (E734) at Brookhaven. We have been part of the $D\bar{0}$ collaboration from its inception, and have carried as a principal responsibility the design, development, and installation of the Level-2/data acquisition system, together with expert support for its operation and its ongoing improvement. This work is coordinated by Professor Cutts, and will be described below. Professor Partridge is responsible for $D\bar{0}$'s Level-0/interaction trigger system; this work is described in the accompanying Task J report.

The $D\bar{0}$ Detector

The $D\bar{0}$ Detector is the premier new facility in high energy physics. Just completing its first period of operation at the world's highest energy accelerator, $D\bar{0}$ provides a next generation detector to enhance the physics potential of the Fermilab 2 TeV Collider. Important features of $D\bar{0}$ include excellent identification and measurement of leptons and jets, based on tracking (including a TRD), fine-grained uranium-liquid

argon calorimetry, and full muon chamber coverage, over nearly the entire solid angle. Data bearing on a wide range of important and exciting physics are now available; some major areas of interest are top searches, electroweak, W/Z, and QCD studies as well as searches for exotics like SUSY- or techni-particles.

There has been enormous progress in the DØ Experiment since the last Task C Progress Report. During the period of the present Report, Fermilab has operated the Tevatron for Collider Run Ia, from June 1, 1992 to May 31, 1993. Rolled in to the DØ collision hall in February 1992, the DØ Detector was operational in time for the first collisions in June, although the accelerator performance was such that serious luminosities were not encountered until August 1992. It has been a tremendous period of excitement, for the whole collaboration, mixed with satisfaction (and relief) as our efforts designing, constructing, installing and commissioning this superb new instrument have been rewarded with a massive collection of world-class data. In the late summer and fall, typical initial luminosities were $10^{30} \text{cm}^{-2} \text{sec}^{-1}$, but this increased in several periods of activity such that stores were commonly $6 - 8 \times 10^{30}$ in April and May 1993, with normal store times upwards of 20 hours. The total luminosity delivered to DØ, by accelerator reckoning, was over 25pb^{-1} , while we collected to tape effectively 15pb^{-1} . This efficiency, nearly 60 percent, is outstanding (especially for a first run) when one considers that DØ must gate out nearly 25% of live-time due to backgrounds associated with beam in the main ring. [The main ring presently runs through the top of the DØ detector, about 2m above the Tevatron ring.] All sections of the apparatus performed well and truly reliably; there are no significant portions of the collected luminosity that were taken without all calorimeter, tracking and muon detectors online. For its first ever collider run which some competitors expected to be mainly "engineering," the DØ Detector has made the Collaboration proud.

DØ Physics

With a nearly fourfold increase in collider data over that available (to CDF) from previous runs, DØ has available a gold mine of data that should produce a large number of exciting physics results. The physics analysis effort is divided into five physics groups: top search, QCD studies, b-quark physics, new particle search, and

W/Z measurements. Preliminary analysis of the data has confirmed the high quality of the data and the excellent performance of the detector. Numerous conference reports have been presented showing preliminary results from a large variety of physics analyses. A small selection of these results are shown below to give a flavor of the physics coming from DØ.

One of the outstanding features of DØ is its excellent calorimetry. This is demonstrated in Figure 1.1, which shows the missing transverse energy resolution to be $\approx 2\%$ of the total transverse energy in the event. This good resolution allows us to accurately measure the transverse energy of neutrinos (or photinos in SUSY searches). Figure 1.2 shows the transverse mass distribution for the $W \rightarrow e\nu$ events. The sharpness of the high-mass edge of this distribution is directly attributable to our excellent calorimeter resolution and is related to our ability to accurately measure the mass of the W boson. During this run, we were able to collect over 12,000 W and 1,000 Z candidates in the electron channel. A measurement of R , the ratio of the W/Z cross section times branching ratio, has led to a measurement of the width of the W with $\approx 10\%$ uncertainty.

DØ has reported preliminary results from a variety of QCD studies, including the inclusive jet cross section, di-jet angular distributions, direct photon cross sections, and the first evidence for rapidity gaps. We have observed b-quark production through semi-leptonic and J/ψ decays. This work has also led to the measurement of direct J/ψ and Υ decays. The new particle group has made progress in looking for a wide variety of potentially exciting new physics, including supersymmetric particles, leptoquarks, techni-particles, and massive stable particles.

Perhaps the most exciting physics prospect for DØ is the search for the top quark. We are looking in many different decay modes and applying a wide variety of analysis techniques in an effort to discover the top quark. One very interesting top-quark candidate has been found in the $e\mu$ channel. A display of this event is shown in Figure 1.3. The kinematics of this event include a very high E_T electron and muon, two jets, and a large missing energy. While it is not possible to claim top discovery on the basis of a single interesting event, we are hard at work to uncover further events in our data sample and to expand our search to include all top decay channels.

DØ Level-2/Data Acquisition

As mentioned above, the Level-2/data acquisition system for DØ is the responsibility of Brown's Task C. This system encompasses the hardware and associated control software for the complete data path - from buffer boards in the 81 VME crates which accept the raw data that has been digitized, through to a special high speed link to the host cluster. The heart of the data acquisition system is a farm of 50 VAXstations (currently model VS4000/60s), each of which receives a complete event, performs a software filter, and transmits accepted events to the host.

Figure 1.4 shows a diagram of the data acquisition system, including the eight parallel datapaths into the Level-2 farm of filter nodes and the output datapath to the host. Figure 1.5 is a diagram showing the layout of a specific Level-2 node. The general operation of this system has been described in previous Reports and most recently at the Annecy Conference. We discuss in this Progress Report some work on the Level-2/data acquisition system which has been particularly important for DØ during the last year.

The readout from the digitizing crates into the Level-2 farm is controlled by two systems, the Supervisor and Sequencer. The Level-1 trigger interrupts the Supervisor with the trigger-pattern and event number, at the time it passes an event, and then initiates full digitization. After selecting a node appropriate to the trigger, the Supervisor interrupts the Sequencer system via a special high speed bus. The Sequencer system includes custom readout sequencing hardware, one per each of the eight separate high speed datapaths corresponding to separate groups of VME digitizing crates. The Sequencer creates a 32-bit token for each readout board, which routes it repeatedly through the digitizing crates on its data cable. (The token includes both the crate numbers to be read out plus the event number, used to insure synchronization of data blocks). A custom VME buffer board collects blocks within each crate and outputs on its data cable in response to an appropriate token.

The event rate into the Level-2 system is determined by both the ability of data to flow through the digitizing electronics and through the readout paths together with the control time needed to respond for the Level-2 system to the Level-1 triggers and initiate readout, as described above. The initial version of the readout control

sequencers were operated via software in an attached MicroVAX, which involved a delay of 3.5 milliseconds at each event in forming the appropriate readout tokens and responding to the multiple interrupts as the tokens were circulated. During the summer, before the significant running period started, we upgraded the sequencer boards and associated hardware and software to reduce this time by an order of magnitude. This new system utilizes an intelligent list processor to perform a fast lookup and derive from the trigger word, the pattern of crates needed to be readout. With this system the response to the interrupt signalling the Level-1 trigger, the formation of the readout tokens, their circulation, and the completion of the readout, is all managed at the low level, principally in hardware, and without intervention (except for error situations) from the control processor. Following this upgrade the maximum event rate into the Level-2 system was limited not by the data acquisition readout capabilities but by elements of the triggering and digitizing hardware - which improved gradually during the fall from 50 to 100 Hz.

Because the collider luminosity started at a low level, the initial running did not require all planned Level-2 nodes. In June, the 16 Level-2 systems were more than adequate for handling the filtering required for the low event rate. Physically, the 16 systems formed a unit of three 7-ft racks, with a central rack containing 16 VAXstation processors flanked on each side by a rack with VME crates containing the custom multiport memory boards and other modules (see Fig. 1.2). At this time the datapaths were prepared for another triplet of racks (16 nodes) along the same row. In late summer, the 2nd group was installed, during a time when the accelerator was down briefly. At this time we also added modifications in the control software, to streamline the communication links needed between the Supervisor and the Level-2 nodes. Again, the number of nodes available at this time were fully able to cope with the filtering requirements, given the event rate, event size and type, and complexity of the filter algorithms. A further group of 16 nodes was available but not actually installed until a two-week shutdown, which occurred in January. The final 2 nodes, in a special rack, have been at DØ since spring but are not yet connected to the datacables.

As the average TeVatron luminosity increased during the year-long run, the datataking requirements became more secure, due both to the number of events and

the average event size. As the luminosity increased we changed the mix of hardware triggers, in order to prescale events of high rate (such as QCD jet triggers) and not impact triggers of rare phenomena (such as Top events). In fact, during the typical 20-hr period of a store we would modify the trigger prescales as the luminosity fell. During the run we did not at any point find that the number of available Level-2 nodes for filtering was less than adequate. There were limitations on the datataking capability, however; the ability to digitize and input data to the Level-2 nodes and the rate at which events could be sent to the host. After the sequencer-related improvement mentioned above, the limitation in the input rate came from the digitizing electronics. Gradual improvements in these systems brought us to operating levels of around 100 Hz. [We defined these levels as rates for which the front-end crates were 10 percent front-end busy.] At this point we were led by modelling studies (described in Section 1.3) to expect that an improvement in the control time related to the Supervisor operations in response to the event trigger, would be significant. We upgraded the Supervisor from a MicroVAX-III to a VAXstation 4000/60, connecting from the VAXstation to the Supervisor's Q-BUS modules through a new interface. After this change our operating level rose to 120 Hz, where again it was constrained within the digitizing crates.

The output bandwidth also received considerable attention. Initially we were able to send about 440 KBytes/sec from the Level-2 nodes to the host, via ethernet. At the start of the run this corresponded to about 1.5 events/second; but as the luminosity increased so did the average event size, due both to the increased number of multiple interactions and to the changing selectivity of the hardware trigger for more complex events. In the fall a modification of the ethernet (splitting the output via a multiple FDDI adaptor) brought the bandwidth to 700 KBytes/sec. During the winter break we installed the components of a high speed output path, described in the following paragraph. We maintained the ethernet link, and worked on the software and hardware between collider stores, during January and into February when the link became the standard output datapath. With this link we were able to send roughly 1.2-1.3 MBytes/sec, or 2.0-2.5 (larger-sized) events/sec. Further upgrades to both the input and output datataking capabilities are described in the accompanying Renewal Proposal.

The Level-2 high speed output datapath is very similar to the input datapath from a group of VME digitizing crates into the Level-2 system. As shown in Figures 1.4 and 1.5, each Level-2 node has an output buffer board (a "VBD-2"), in its associated VME crate. Events that pass the Level-2 filter analysis are moved to the VBD-2 from the multiport memories. (This is the first time that the event data is transferred from the multiports.) A new readout-control processor ("DØSNTY"), is interfaced both to a sequencer (which circulates a readout token to all the VBD-2's) and to a multiport memory board (which receives the event from the output data cable connected to a 40 MByte/sec port). In the same crate with the multiport memory is a DEC VME interface which provides a memory-mapped connection to one of the computers in the host cluster. Upon receipt of an event in the multiport, DØSNTY signals the DEC interface which transfers it to the host.

In addition to the major upgrades to the Level-2/data acquisition system, we made a major effort to enhance its operational behavior. Another processor node, the "Surveyor," monitored the status of the Level-2 nodes as well as the control systems, making possible the system status display shown in Figure 1.6. We installed numerous additional features in the Level-2 control systems and in the Level-2 node's filter framework, both to increase reliability and provide additional capabilities.

At the beginning of the run, hardware reliability was of concern, especially with an unacceptably high (10 percent) loss of events due to transmission errors on the input data cables. The original specification for the cables had called for a maximum length of 20 feet; typical runs from the counting house to the Level-2 system were 250 feet, and the first attempt at installing repeaters was not a complete success. The problem was that the 32 datalines and the data strobe pulse would skew with respect to each other such that a multiport memory at the far end would see the data strobe out-of-time with the proper state of every data line. Parity checking implemented in hardware (as well as checksumming) maintained data integrity, but the loss of events was unacceptable. In the summer we installed a new generation of data cable repeaters which resynchronized the signals; this together with the replacement of some faulty cables eliminated the problem. (Currently parity errors occur at less than $1/10^6$ events or $2/10^{12}$ bytes of data transferred.) A less serious problem was related to the VME hardware in the Level-2 node, or more specifically the low-level driver for

the multiport memories. A bug related to interrupt handling would cause a node to crash, with a mean time of 50 hours of continuous operation. In practice this meant that the number of Level-2 nodes available during a run would gradually decline (not a real problem as there was generally a surplus, and a crashed node could be restarted on-the-fly). We finally came to grips with this problem and eliminated it this spring.

Task C personnel have been heavily involved in the operation of the DØ detector during the run just completed. Some of this work was associated with the hardware and software improvements which are described above. Actually, we have emphasized the upgrades but should stress that the Level-2/data acquisition operated very successfully. We were able to manage the support without a 24-hr presence; the resident expert, David Cullen-Vidal, carried a pager but after last summer he was very rarely bothered for emergency help. Because the Level-2 served as the crucial component between the digitizing of the data and its recording, we needed to interact with others frequently as aspects of the complex datataking operation evolved. By being continuously aware of changes and able to contribute our components, or to initiate improvements to the overall system and coordinate system upgrades, we played an important part in supporting the run. Further, all Task C personnel on DØ participated heavily in shift-taking during the run; this was important as it helped us stay close to the actual behavior of the detector during collider data taking. More than that, however, being in the control room could be very exciting; and, after working on DØ for as long as ten years it was a real pleasure to see it all operating so well.

DØ Physics Analysis

In addition to supporting datataking, we have participated in initial analysis efforts in several areas. This work is preliminary and will be mentioned only briefly. Of the five physics groups formed within DØ (see earlier discussion of physics analysis), Task C personnel are working within three groups : W/Z, New Phenomena, and QCD. Task J's involvement with the Top Physics group is mentioned in a later section.

Our involvement with W/Z events is motivated by a particular interest in WZ pair production, for its own physics and as a potential signature for technicolor. We have made analysis filters to look for events with three leptons and substantial missing transverse energy, and are presently studying the data taken in this run. We have

generated at Brown sizeable Monte Carlo data sets involving WZ pair production to use in this work. This study also relates to the New Phenomena group as an enhancement in WZ pair production could be caused by a technicolor particle like a techni-rho.

Many models of new physics predict massive stable particles (MSPs). We have begun a search for such events. Our current filter selects events with two or more tracks penetrating through the iron torroid and thus tagged as muons. We eliminate cosmic rays through a back-to-back cut and examine energy deposited along the track in the calorimeter and the tracking chambers. We are currently studying data from the last run along with Monte Carlo events generated for pairs of MSPs of several masses.

We are also involved in QCD studies. David Cullen-Vidal has focused his analysis efforts on studying the jet energy scale, using models to extrapolate from test beam measurements of particle energy deposits to that produced by jets in the DØ detector. Understanding the energy scale in the DØ calorimeters is a serious task for many aspects of DØ physics. For a thesis topic David is pursuing studies of color coherence effects in three-jet events.

1.2. NEUTRINO CALORIMETRY

Introduction

We report here on a research project to develop a novel cryogenic technique utilizing superfluid helium; the project is supported by the Nuclear Physics Division but faculty from this Task are participating in it and there is substantial connection with our previous work by this Task on neutrino physics. No person on this Task receives funds from cryogenic project. Progress has been made on several fronts in this ten-month period since our last Report. We briefly touch on several areas and emphasize a particularly interesting discovery concerning the generation of rotons in liquid helium by charged particles, a discovery which holds promise of providing a means of the determining the direction of the particle track.

The principal aim of the project is to develop a method for the measurement of the spectrum of very low energy neutrinos from the sun – the neutrinos generated by the

p-p and ${}^7\text{Be}$ reactions. (The method has other applications for dark matter, neutrino moments and scattering.) The detection of these neutrinos and the measurement of their energies is important for several reasons. The flux expected for the p-p neutrinos is highly constrained by the optical luminosity and depends only slightly on the astrophysical model of the sun. The ${}^7\text{Be}$ neutrinos constitute a line spectrum and have a dependence on solar temperature quite different from that of the p-p as well as from that of the high energy ${}^8\text{B}$ neutrinos. Taken together, measurements of the total (i.e., all neutrino types) fluxes and spectra from all three major reactions would provide all the data essential to a full resolution of the “solar neutrino problem” (SNP); and if it is established that the cause of the problem is due to the properties of the neutrino, this would represent the first evidence for new physics beyond the “standard model” of nuclear and particle physics.

Given the existing experiments there still remains the important challenge of measuring the neutrino flux from the primary p-p reaction in the sun in real time, with sensitivity to the neutral current and with energy resolution.

Such a measurement is important for several reasons, among them the fact that it is the least dependent on solar models. Also, the ratio of the ν_e flux to the overall neutrino flux must be known for all three major reactions before an over-determined solution is established. Should the solution to the SNP be related to the neutrino mass, then the ambiguities in masses and mixing parameters are likely to require as many details of each of the three reactions as can be measured. Because relative flux comparisons among the three reactions are key ingredients in seeking an understanding, it is also valuable to measure more than one reaction in the same experiment so that systematic effects can be minimized.

It is a challenge to measure the p-p reaction because, although it has a copious flux ($6 \times 10^{10} \text{ cm}^2 \text{ sec}$ at the earth), the energies are very low ($< 420 \text{ keV}$). The gallium radiochemical experiments have established beautifully the ν_e flux for p-p solar neutrinos. To go further and to measure the flux of all neutrinos and to do it in real time is the next necessary step. It implies a need for exceptional radioactive purity of target and control of backgrounds. The techniques to do this have not existed, and it is to achieve this goal that we have been developing the superfluid

helium detection method. If successful it will allow the simultaneous measurement of these quantities for both the p-p and ${}^7\text{Be}$ reactions in one experiment.

The principles of our novel method to use superfluid helium as the neutrino target and as the medium for energy deposition have been described in detail in several of our publications and reports.

In this Progress Report we describe our new experiments, including the intriguing discovery of effects which may lead to determining the original direction of the recoiling particle.

Helium Results

As discussed in our last Progress Report, we have completed a re-configuration of the interior of our test cell. The interior diameter of the cell has been increased to 15 cm so that 3 liters of helium are contained in the volume below the wafers. We now have provision for placing a number of wafers in the cell and reading as many as 4 of them simultaneously. Also tiny superconducting stepping motors are mounted inside the cell to permit studies with a movable radioactive source as well as with other test pieces. These modifications have given us the ability to study 1) discrimination of signals from background by coincidence measurements, 2) angular dependence of quantum evaporation and 3) reflection of rotons from solid surfaces.

In investigating the physical processes important in the functioning of a detector of solar neutrinos, we have studied the dependence of quantum evaporation on the incident angle of the excitations at the surface using both α particles and a resistance heater as sources. From these measurements using the α source we can make an estimate of the efficiency of evaporation.

The two sources are located 1.5 cm below the liquid surface and can be moved laterally through a distance of 12 cm by a superconducting stepping motor. The quantum evaporation signal measured by 1 cm² wafer/calorimeter for a 1 μJ heat pulse into the heater is shown in Figure 1.7. The horizontal axis represents the lateral distance of the heater from the center of the wafer. For a given size of heat pulse and orientation the amplitude of the signal is constant to within a few percent. As expected the maximum amplitude as a function of position occurs with the source directly below the wafer, and the signal decreases rapidly with angle.

To understand this result we note that the track of a 5.5 MeV α particle is only 200 μm in helium, and the average range of the secondary electrons is much shorter, on the order of 10 nm. Thus, something in excess of 10^9 excitations are created in a cylindrical volume of 10^{-13} cm^3 . Since the roton-roton scattering cross-section is the order of 10^{-14} cm^2 , a dense, strongly interacting gas of excitations is produced along the α track. Before propagating away from the α track the excitations will undergo mutual scattering, and thermalization within the initial, dense cloud is likely. This process will cause a narrowing of the initial distribution of excitations to a region in the vicinity of the minimum, which is consistent with our data.

It is possible from the measured size of the signal detected by the wafer to make an estimate of the product of the efficiency of generation of excitations by an α particle and the efficiency of evaporation. We use the simulation with thermalization of the rotons and compare the detected energy to the α energy. The comparison also must include parameters associated with helium atoms on the wafer surface such as sticking probability (~ 0.7) and binding energy ($\sim 100 \text{ K}$). We can conclude that as a lower bound the probability is 0.3 that a roton, incident on the surface at less than the critical angle, will evaporate a helium atom. This lower bound uses the limiting assumption that all of the energy of the α is converted into elementary excitations of the liquid.

We now return to the statement that the size of the detected signal may depend on the orientation of the α particle track. The rotons are created as a dense, interacting cylindrical cloud. They thermalize before propagating away. Simple geometrical considerations suggest that the number propagating away from the region of interaction in a direction perpendicular to the axis of the cylinder will be greater than the number propagating parallel to the axis. Instead of a "fireball" we have a "fire-cylinder" from which thermal radiation is anisotropic.

Background Study for a Helium Detector

We have completed our first detailed studies of potential backgrounds for a full scale (ten ton) superfluid helium detector. These studies have two components: a) Monte Carlo simulations of radioactive backgrounds to any apparent signal and the nature of potential cuts to reduce them and b) consideration of materials to be used

as absorbers/shielding from potential sources of radioactivity and the purity of those materials themselves.

We have used the GEANT Monte Carlo program from CERN (suitably modified to account for very low energy deposition) as the principal vehicle for these calculations. We have used as a model detector a cube of helium contained in a copper cryostat the outer dimensions of which were 5.6 meters on an edge. Typically, a fiducial volume of 4.0 meters on an edge was defined for signal cuts (~ 22 neutrino events/day for the full p-p and ${}^7\text{Be}$ flux). The region between the cryostat and fiducial volume was then filled with varying amounts of active helium and inactive moderator; the moderator served two purposes: to absorb/attenuate some of the γ flux and to shift the spectrum in such a way as to increase the probability of multiple interactions in the helium of the emerging γ 's.

The helium and most of the moderator materials considered in the calculations were of light nuclei and the γ interactions are overwhelmingly Compton scatters with little or no photoelectric or pair production occurring ($< 0.03\%$ in helium). Calculations were performed for two classes of moderator materials in varying thicknesses. These were polyethylene and several cryogenic gases (including nitrogen, carbon dioxide, argon and neon).

For purposes of illustration, it is useful to look at the kind of features for signal-to-noise which result from the use of 50 cm of carbon dioxide lining the copper cryostat and the helium volume outlined above. In Figure 1.8 is shown a LEGO plot of a single typical 300 keV background γ ray event; it is typical in that the median number of Comptons per event for the observed spectrum is 5 and that they have a mean length for the "shower" of about 40 cm in helium. A neutrino signal event will, of course, consist of a single recoil electron with a range less than 1 cm. This suggests an algorithm for cuts to enhance signal-to-noise which we have implemented as follows: a) only one visible deposition per event, b) conversion point of deposition < 200 cm radial distance from center of fiducial volume, c) energy of deposition < 800 keV. In Figure 1.9 is a histogram in which the results of a simulated 10 day run are plotted - 260 neutrino events from p-p (black) and ${}^7\text{Be}$ (hatch) as well as 373 background gamma events (white). This first cut gives a signal-to-noise ratio of 0.7. However, because the mean free path for the γ spectrum is 59 cm and that for the

neutrinos approaches infinity in helium, we can make a subtraction of the position-dependent background from the uniformly-distributed neutrino signal. The observed distribution of 462 events in the live helium volume between 200 cm and 230 cm is extrapolated into the fiducial volume. The distribution of events with the singularity and energy cuts applied is plotted in Figure 1.10 for a 10-day run. Performing the extrapolation and subtraction on a bin-by-bin basis produces the result of Figure 1.11 and signal-to-noise of $0.9 \pm 10\%$; for purposes here the residual background has been taken to be the size of the quadratically compounded errors of the subtraction.

If we take a 70% operational duty factor for the detector and the full p-p and ${}^7\text{Be}$ neutrino fluxes of the "standard model," about 5000 signal events would be expected in a year, assuming the flux is entirely of electron-type neutrinos. Should oscillations occur such that neutrinos having only neutral current interactions compose a fraction, F , of that flux then the number of events would be less; $5000 \times (1 - 0.83 \times F)$. The neutral current cross section for those neutrinos being roughly 1/6 of that for electron-type neutrinos.

These are very encouraging results. It continues to appear that there are as yet no technical obstacles to a solar neutrino experiment of the type envisioned. As details are gathered from our other experiments, we shall continue to refine and make more specific our Monte Carlo studies of backgrounds.

1.3. SSC PARTICIPATION

Tasks C and J have been members of the SDC collaboration since its founding. Our principal area of activity has been the architectural modelling of the high bandwidth data acquisition (DAQ) systems needed for the SSC. This involvement builds on our experience and success in developing the $D\bar{0}$ data acquisition system.

Brown has previously completed data acquisition modelling studies that analyze the throughput and deadtime associated with generic SSC architectures. These results indicated that non-blocking architectures with adequate buffering exhibited scaling behavior that could be predicted analytically.

We have applied these techniques to the $D\bar{0}$ data acquisition system to test the validity of these modelling procedures and help us better understand the performance

of the DØ DAQ system. Based on our model of the DØ DAQ system, we determined the throughput could be significantly improved by decreasing the overhead time required by the supervisor computer to setup a transfer between the VME electronics crates and the Level 2 processor farm. An analytical model developed at Fermilab suggested that little improvement would be seen from reducing the supervisor overhead, so we had the opportunity to test the predictive powers of the various models. Following the installation of new hardware to reduce the supervisor overhead, a substantial increase in throughput was observed as predicted by our model. While the increased DAQ bandwidth was extremely helpful in meeting the trigger needs of DØ, it also demonstrated that such models can make useful contributions to the design and improvement of an experiment.

1.4. OTHER MATTERS

Professor Partridge was promoted to Associate Professor of Physics with tenure effective July 1, 1993; accordingly, Task J will be merged into Task C. During the period of this Progress Report, Professor Lanou was on sabbatical leave at the Center for Particle Astrophysics, University of California, Berkeley, having completed a six year term as Physics Department Chair. Professor Cutts became Chair of the Fermilab Users Executive Committee and has been active in this role. In September he gave an invited talk at the CHEP92 conference in Annecy, France.

At the 1993 Spring Meeting of the American Physical Society held in Washington, D.C. (April 12-15), an invited paper was presented by Professor Lanou on progress in neutrino calorimetry. to a special Joint Session of the Division of Nuclear Physics and the Division of Fundamental Constants and Precision Measurements. Additional requests for seminars and colloquia on this novel technique and its goals have continued throughout the year. A feature article by the English physicist, P. McClintock, describing this work, appeared recently in *Physics World*, the journal equivalent to *Physics Today* in Great Britain.

1.5. PUBLICATIONS AND REPORTS DURING THE REPORTING PERIOD

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3. J. Bantly et. al., "Global Monitoring Notes and Documentation", DØ Notes 1652 and 1652A, 4/93.
4. J. Bantly et. al., "Multiple Interaction Tool", DØ Note 1691, 4/93
5. S. Abachi et al., Beam Tests of the DØ Liquid Argon End Calorimeters, NIM **A324**, 53 (1993).
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9. F. S. Porter, S. R. Bandler, C. Enss, R. E. Lanou, H. J. Maris, T. More, and G. M. Seidel, "Calorimetric Detection of 5.5 MeV Alpha Particles in Superfluid Helium-4", *Proceedings of 7th International Conference on Phonon Scattering*, edited by R. Pohl, Springer-Verlag, in press.
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11. C. Enss, S. R. Bandler, F. S. Porter, R. E. Lanou, H. J. Maris, T. More and G. M. Seidel, "Quantum Evaporation of Helium-4: Angular Dependence and Efficiency", *Proceedings of the 20th International Conference on Low Temperature Physics*, Eugene, Oregon (1993), *Physica* (to be published).

1.6. SCIENTIFIC PERSONNEL IN TASK C

David Cutts	Professor of Physics
Robert E. Lanou	Professor of Physics
Richard A. Partridge*	Assistant Professor of Physics
Jan S. Hoftun	Research Assistant Professor of Physics
Dusan Nesic	Research Associate
Rushdy Ahmed	Graduate Research Assistant
David Cullen-Vidal	Graduate Research Assistant
Thomas Fahland	Graduate Research Assistant
Freedy Nang	Graduate Research Assistant
Haowei Xu	Graduate Research Assistant

* Also on Task J

DØ preliminary

Figure 1.1: Missing transverse energy resolution versus transverse energy in the event.

Figure 1.2: Transverse mass distribution for $W \rightarrow e\nu$ candidate events.

Figure 1.3: Event display for a top candidate event in the $e\mu + 2$ jets channel.

Figure 1.4: Diagram of the DØ Data Acquisition System

Layout of Level-2 Node

Figure 1.5: Layout of a DØ Level-2 Node

Figure 1.6: Status Display of the DØ Level-2 System

Figure 1.7: Evaporation signal as a function of the position of the pulsed heater. The maxima of the simulations are normalized to the maximum of the data.

Figure 1.8: Horizontal Distribution (x-y) of a 300 keV gamma ray interaction in liquid Helium. Each "tower" is a single Compton scatter and its height is proportional to the recoiling electron energy. Each bin is 2x2 cm. The event is contained in an area 100x60 cm (Monte Carlo).

Figure 1.9: Monte Carlo result for 10 day run in 10 tons of liquid helium.

Figure 1.10: Radial distribution of Compton scatters in liquid helium. The events at sites larger than 230 cm arise because of the square nature of the cryostat in this Monte Carlo model.

Figure 1.11: Monte Carlo of background subtracted 10 day run in 10 tons of liquid helium. The white bins are to indicate the error in the subtracted background.

2. Task J: Outstanding Junior Investigator Award in Experimental Particle Physics

Task J is an Outstanding Junior Investigator Award to Richard Partridge for a program in experimental particle physics. The principal activities supported during the past year have been the commissioning of the Level 0 trigger for the $D\bar{D}$ experiment at Fermilab and preliminary physics analysis of data from $D\bar{D}$'s first run. This section summarizes the progress in these areas during the past year.

2.1. THE LEVEL 0 TRIGGER

The Level 0 trigger is the first level in a multi-level trigger scheme developed for $D\bar{D}$. It is responsible for identifying interactions, determining the location of the primary interaction vertex, detecting multiple interactions in a single beam crossing, and measuring the luminosity of the collider. During the past year, the Level 0 trigger was brought into operation following several years of design, construction, and testing. Performance has generally been consistent with the design goals and is described below.

The Level 0 trigger consists of two arrays of scintillation counters placed near the collider beam pipe on opposite ends of the detector. Figure 2.1 shows the layout of the Level 0 counters, with each array consisting of 20 short counters with single PMT readout and 8 long counters with PMT readout on both ends of the counters. Good time resolution for the counters allows the vertex position to be measured by making time-of-flight measurements on the particles in the beam jets. Every physics trigger in $D\bar{D}$ requires that the Level 0 trigger find a coincidence between scintillator planes and reconstruct a vertex position in the range $|z_v| < 100$ cm.

The efficiency of the Level 0 trigger in detecting non-diffractive inelastic collisions was measured during a special run where the trigger conditions were altered to take those events failing the Level 0 trigger conditions. From this run, it was determined that the efficiency of the Level 0 trigger is 97.2%, in good agreement with our expectation of 1% loss from particles missing Level 0, 1% loss for vertices outside the cut, and 1% loss from vetoing beam halo crossings.

The time resolution for Level 0 counters was determined by comparing the time measured by a single counter with the average time from the entire set of counters. Figure 2.2 shows that good time resolution is obtained for the short counters, $\sigma_t \approx 240$ ps, while the long counters exhibit somewhat poorer time resolution, $\sigma_t \approx 500$ ps. The poorer time resolution of the long counters is likely due to multiple charged particles hitting the counters causing the time averaging algorithm to incorrectly measure the time of a hit.

The longitudinal extent of the Tevatron luminous region ($\sigma_z = 30$ cm) would produce significant uncertainty in the measurement of transverse energies if not corrected for. The excellent time resolution of the Level 0 counters is used to determine the position of the primary interaction vertex for use by the other trigger levels. Two measurements of the vertex position are made: a fast measurement used by the Level 1 calorimeter trigger to correct calorimeter energies for the vertex position (FASTZ) and a more precise measurement completed just prior to the time of the Level 1 trigger decision (SLOWZ) that is used by Level 1 and Level 2 triggers. The vertex position resolutions for FASTZ and SLOWZ are determined by comparing the vertex position measured by Level 0 with the more accurate determination made by the tracking system. Figure 2.3 shows the difference in vertex position measurements for events with a single $\bar{p}p$ interaction, yielding a resolution of $\sigma_z = 16$ cm for FASTZ and $\sigma_z = 4$ cm for SLOWZ. The vertex position measurements were used during DØ's first run to provide corrected E_T measurements in Level 2, select triggers coming from $|z_v| < 10$ cm for the QCD group, select beam-beam interactions while providing a veto for crossings with beam-halo interactions, and monitor the location of the nominal beam crossing point.

When more than one $\bar{p}p$ interaction takes place during a single beam crossing, particles will strike the Level 0 counters at more than one time and it is no longer possible to accurately reconstruct the position of the primary interaction vertex. Multiple interactions can be detected in Level 0 by measuring the RMS deviation in arrival times for the Level 0 counters. The RMS deviation is calculated by the Level 0 hardware and is available for use in both Level 1 and Level 2 decisions. Figure 2.4 shows that events with a large RMS deviation have a poorly measured vertex position. A single interaction requirement was used in certain triggers as a way to select clean

events at high luminosity.

An important task for Level 0 is monitoring the luminosity and halo backgrounds for the Tevatron. The luminosity is determined by measuring the rate for Level 0 coincidences with $|z_v| < 96.5$ cm, as determined by the FASTZ module. Corrections for multiple interactions are applied by assuming the number of interactions/crossing has a Poisson distribution. At present, the uncertainty in luminosity is 12%. Beam halo is monitored by measuring Level 0 coincidences with timing consistent with particles passing through the detector. Both luminosity and halo rates are sent to the accelerator control system and are used to monitor the operation of the accelerator. The data is also logged for use in determining the luminosity of the accelerator.

2.2. ANALYSIS OF $D\bar{0}$ DATA

Preliminary analysis efforts have begun in a number of areas. These efforts are generally at a very preliminary stage and will only be discussed in general terms. A discussion of selected $D\bar{0}$ physics results is provided in the Task C section of the progress report.

The discovery of the top quark is a major goal for the $D\bar{0}$ experiment. Since the number of top quark events we expect to produce is small, it is important to distinguish top quark events from possible backgrounds. Several efforts are underway to identify ways to differentiate top signals from background.

Kinematic fitting has been used in high energy physics for over 30 years to identify signals. We have explored using kinematic fitting to help identify top quark signals and backgrounds. One goal is to identify $Z^0 \rightarrow \tau\tau$ decays, which are a background for the dilepton channel of the top search. By using the approximation $M_\tau \approx 0$, it is possible to reconstruct the kinematics of the τ pair and check for consistency with the mass of the Z^0 . A Monte Carlo study shows this to be quite promising. Another goal is to separate QCD W +Jet background from top quark events in the lepton+jets channel of the top search. We are currently adapting the SQUAW kinematic fitting program to do a 2C fit for these events.

We have also studied using a likelihood method to test the kinematic distributions for the presence of top quark events. While this method shows promise, further work

is needed to properly model all possible backgrounds. Also, since we only have one top quark candidate at present, the data is presently too sparse to take full advantage of this technique.

Task J has also supervised two graduate students supported by Task C in thesis research. Haowei Xu is working on tagging b-quark decays by identifying muons from semi-leptonic decays of b quarks. He will use this to help reduce backgrounds in the lepton+jets channel of the top search. Freedy Nang is working on a measurement of the QCD double differential jet cross section, $d^2\sigma/d\eta_1 d\eta_2$. This cross section can be used to study the proton structure functions.

2.3. PUBLICATIONS AND REPORTS DURING THE REPORTING PERIOD

1. R. Partridge, Search for the Top Quark in Dilepton Events with $D\bar{0}$, to be published in *Proceedings of 7th Meeting of the American Physical Society Division of Particles and Fields*, (Fermilab, IL, 1992).
2. R. Partridge, Kinematics of $Z^0 \rightarrow \tau\tau$, $D\bar{0}$ Note 1610 (February, 1993).
3. S. Abachi et al., Beam Tests of the $D\bar{0}$ Liquid Argon End Calorimeters, *NIM A324*, 53 (1993).

Figure 2.1: Layout of Level 0 Counters (a) one plane; (b) complete array consisting of two orthogonal planes.

Figure 2.2: Level 0 time resolution for (a) short counters; (b) long counters.

Figure 2.3: Level 0 vertex position resolution for (a) FASTZ; (b) SLOWZ.

Figure 2.4: Level 0 vertex position resolution (SLOWZ) for events identified as being from multiple interactions. The absence of a narrow peak indicates that we can identify events which are poorly measured due to multiple interactions.

3. Task S

This Task's mission is to provide technical support to the experimental Tasks B, C & J. This support is dominantly in the area of electronics and data acquisition support at present.

This year the technical staff (technicians and engineers) has been primarily occupied in work on the DØ project (Tasks C & J) with lesser effort devoted to LVD (Task B) and SSC (Task E) projects.

The details of each of these projects are contained in the sections of this Report related to Tasks B, C & J.

3.1. PERSONNEL IN TASK S

David Rossi	Senior Electronic Technician
Jack Fowler	Electronic Technician
Richard Hlustick	Electronic Technician
Lang Wang	Electronic Engineer

(P.I.'s: R. Lanou (Contact Person), D. Cutts, R. Partridge, M. Widgoff)

END

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