EXPERIMENTAL INVESTIGATIONS OF STRONG INTERACTION IN
NON-PERTURBATIVE QCD REGION

PROGRESS REPORT

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EXPERIMENTAL INVESTIGATION OF STRONG INTERACTIONS IN THE NON-PERTURBATIVE
QCD REGION INCLUDING GLUEBALLS, EXOTICS, QUARK-GLUON PLASMA
AND OTHER POSSIBLY NEW PHENOMENA

Annual Progress Report

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City College of New York

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Annual Progress Report for DOE Contract DE-FG02-92ER40698 for the period January 16, 1993 through January 15, 1994

by S.J. Lindenbaum, P.I.

Title: Experimental Investigation of Strong Interactions in the Non-Perturbative QCD Region

ABSTRACT

In order to critically investigate non-perturbative QCD we have been engaged in investigating: 1) Glueballs, 2) search for a Quark Gluon Plasma (QGP), and 3) search for strangelets.

In this past year in the glueball area we have been analyzing the data obtained (E-881) at 8 GeV/c for $\pi^- + p \rightarrow \phi\phi n$ (OZI forbidden), $\phi K^+ K^- n$ (OZI allowed), $K^- p \rightarrow \phi\phi(\frac{\Lambda}{\Sigma})$ (OZI allowed), and $\bar{p} p \rightarrow \phi\phi\pi^0$ (OZI forbidden), $\phi K^+ K^- \pi^0$ (OZI allowed). By comparing the OZI forbidden (glueball filter reactions) with the OZI allowed and our previous 22 GeV/c $\pi^- p \rightarrow \phi\phi n$ or $\phi K^+ K^- n$ data we hope to further critically test our so far unsuccessfully challenged hypothesis that our $g_T(2010)$, $g_T(2300)$ and $g_T(2340)$ all with $I^{GJPC} = 0^+ 2^{++}$ are produced by 1-3 2^{++} glueballs.

In our QGP search with a large solid angle TPC a good Ξ^- signal was observed. The ratio of Ξ^- to single strange quark particles such as Λ is a better indication of strangeness enhancement in QGP formation. Our data

indicates enhancement by a factor ≈ 2 over cascade model corrected to observed strangeness) predictions is observed but it is definitely far from conclusive at this stage since the result is model dependent. We have found double Λ topologies of the type needed to discover light strangelets in the nanosecond lifetime region and therefore are looking forward to our approved Au on Au experiment, E-891, which is expected to have a much better chance of producing strangelets and finding evidence for a QGP if it is produced.

INTRODUCTION

The standard model is generally considered by many as the bedrock foundation of modern high energy theory. Although the electroweak part has had striking successes and the perturbative parts of QCD have been checked to a reasonable degree (~15%) the non-perturbative region is not even qualitatively established in several important aspects. Therefore we have been investigating experimentally and phenomenologically the weakest links in the establishment of non-perturbative QCD.

1. The establishment of more or less universally accepted glueballs (multi-gluon color singlets) which are predicted¹ and directly demonstrate in the most dramatic fashion the non-abelian nature of $SU(3)_{\text{color}}$ and the predicted strong coupling of gluons to each other at low enough energy. We are also searching for exotic glueballs, and possibly exotic hybrids and exotic multi-quark states.

2. The establishment of a Quark-Gluon Plasma which is predicted by Lattice Gauge and phenomenological models to occur at high enough temperatures and pressures.²

3. We are also searching for strangelets with lifetimes around the nanosecond region. This will complement other searches for longer lived strangelets.

Progress in the Period Beginning January 16, 1992

1. Glueballs and Exotic Hybrid Research

The Principal Investigator (S.J. Lindenbaum) is Spokesman of E-881, an experiment whose major objective is to use the powerful $\phi\phi$ spectroscopy to compare the OZI forbidden (i.e. Zweig disconnected diagram) $\pi^-p \rightarrow \phi\phi n$ with the $K^-p \rightarrow \phi\phi \left(\frac{\Lambda}{\Sigma} \right)$ OZI allowed (Zweig connected diagram) and investigate the $\bar{p}p \rightarrow \phi\phi\pi^0$ OZI forbidden (Zweig disconnected diagram) provided the unknown cross section of the latter is large enough. The experimental group was the BNL/CCNY/RPI collaboration. However CCNY was the largest and most active group in the collaboration. The first run took place May-July (92). The running conditions were poor and sporadic due to the first time commissioning of the AGS booster for protons during this run and some other AGS difficulties. Nevertheless we obtained several hundred tapes of data in the 8 GeV/c Medium Energy Separated Beam (MESB) for which analysis is being pursued. We have made significant progress in the analysis this year, and this analysis work will be continued.

The MESB had (at the MPS) about 1.5% negative kaons, $\sim 1\%$ $\bar{p}$ and the remainder being negative pions. When one or both of the ϕ 's is replaced by a K^+K^- pair (not coming from a ϕ) all diagrams are OZI allowed, and we study these also. We simultaneously triggered on all three incident particles interacting with a hydrogen target. By comparing the various OZI allowed and forbidden channels we hope to strengthen the already strong evidence for the case that the $g_T(2010)$, $g_T'(2300)$, and $g_T''(2340)$ which were discovered in $\pi^-p \rightarrow \phi\phi n$ are

produced by 1-3 $J^{PC} = 2^{++}$ glueballs.^{3,4} They are listed with all quantum numbers established in the Particle Data Group Summary Table.⁵

It should be noted that for over a decade all alternative explanations of our g_T states have been shown to be theoretically incorrect, do not fit the data, irrelevant, or two or three of the above.⁶⁻¹⁰

A big problem in the data analysis is inadequate computer power to analyze the data. Therefore it would be of great value to us to receive sufficient funds to purchase a new powerful computer workstation. The data analysis will continue through the next year continuation period being requested.

2. Phenomenological Analysis

The Principal Investigator has continued to investigate the experimental and phenomenological status of glueballs as shown in (ref. 11 attached) only our glueball candidates the $I^{GJ^{PC}} = 0^{+2^{++}} g_T(2010)$, $g_T(2300)$ and $g_T(2040)$ have no viable alternative explanation⁽⁶⁻¹⁰⁾ to date except our explanation that they are produced by 1-3 $0^{+2^{++}}$ glueballs.

3. The Search for a Quark-Gluon Plasma

The BNL/CCNY/Johns Hopkins/Rice Collaboration has since 1988 been searching for evidence for a Quark-Gluon Plasma using the 14.5 GeV/c per nucleon Si ion beam. We have in a number of runs used a novel detector which consists of a Time Projection Chamber (TPC) system designed so that its three-dimensional point readout and especially designed high resolution allow us to track essentially all of the many charged particles emitted in the forward half hemisphere in nucleon-nucleon cms system of the Si ions colliding with various targets ranging from Si to Pb. The TPC system sits in the 5 KG MPS magnet so that the momentum as well production angles of all charged particles are determined.¹²⁻²²

A unique feature of this system is that it allows us to detect Λ^0 and K_S^0 particles and we have observed up to three Λ 's and three K_S^0 events and one case of a candidate for a 5Λ event.

This year we have concentrated on:

1) A search for Ξ^- production which has been successful. Figure 1a shows the $\Xi^- \rightarrow \Lambda\pi^-$ effective mass spectrum with a well-defined Ξ^- peak. Figure 1b shows the acceptance corrected data compared to the known lifetime dependence. The agreement is excellent showing clearly that we have detected Ξ^- and that our acceptance corrections are reasonably correct. The acceptance corrected rapidity distribution of Ξ^- is shown in Fig. 2 and comments on its significance are made in the caption.

The ratio of Ξ^- (2 s quarks) to single strange quark particles such as Λ is a better indication of strangeness enhancement in the QGP formation than an increase in singly strange particles. This is so since it is possible to more or less explain the increase in singly strange particle production by secondary interactions as we have done.²¹⁻²³

On the other hand the increase in doubly strange particles such as Ξ^- is much less sensitive to secondary interactions. We seem to have ~ a factor of two increase in the ratio Ξ^-/Λ produced by $14.5 \text{ GeV/c} \times A$ Si ions incident on Pb compared to that expected from cascade models (eg. AGS HIJET, RQMD, etc.) corrected for their deficiency in observed Λ production. However this is far from conclusive at this stage since it is model dependent. Nevertheless it is indicative that further experiments with Au on Au (our approved E-891) etc.) in which formation of a QGP is much more likely may lead to more definitive evidence.

2) We have obtained the results of "central production" of 817 K_S^0 produced from a $14.5 \times A \text{ GeV/c}$ Si on a Si target rapidities $\sim 2.0 < y < 3.5$. We have

also obtained the results for "central production" of 1122 Λ 's from the Silicon target. For Si on a Pb target we have obtained 2241 K_S^0 and 3060 Λ 's with rapidities $1.7 < y < 3.5$ and $1.4 < y < 3.4$ respectively. Due to reflection symmetry this covers nearly all of the rapidity range available at AGS.

These results are shown in Figs. 3 (K_S^0) and 4. They are compared to two cascade models our developed AGS HIJET + N^* ²² and the ARC Model.²⁴

The integrated K_S^0 yields^{21,22} agree well with both the predictions of AGS HIJET + N^* and ARC. The Λ yields are predicted well by ARC but underestimated by AGS HIJET + N^* by about a factor of 2. The integrated Λ yields in the rapidity $1.7 < y < 3.2$ are the same within errors from both Si and Pb targets but the rapidity distributions (shown in Fig. 3) differ markedly. They are obviously larger than the naive assumption $28 \times pp$.

AGS HIJET + N^* seems to do a reasonable job of predicting the K_S^0 rapidity distributions for the Si and Pb targets especially at the higher rapidities whereas ARC predicts a yield which is too large by about a factor of 2 at high rapidities. The authors of ARC plan to modify the p-p data input which at present achieves the correct overall level of strangeness production with too wide a rapidity distributions. They believe this will remedy this problem (private communication).

In Fig. 4 we plot the rapidity distributions of Λ 's from Si and Pb targets. The ARC predictions are in excellent agreement with the data for both the Si and Pb targets. AGS HIJET + N^* underestimates the yields for both targets.

In Fig. 5 and Fig. 6 we present the results of the m_T inverse slopes (commonly called "temperature") for K_S^0 and Λ .

We compare with AGS HIJET + N^* only since ARC results are not available. We find that our cascade model cannot explain the rise in temperature from the ~ 100 MeV at high rapidity to ~ 200 MeV at midrapidity.

What we call a global fit contains a "fireball" component term $b \cosh(y - y_0)$ and fits the data well. We conclude that it is very likely that no cascade model will fit the data without adding a fireball in the central region unless one does what we have done in the so-called Random model which allows enough collisions (which are an adjustable parameter) to effectively dynamically make the equivalent of a "fireball."

Thus we conclude from our data that a fireball of temperature ~ 200 MeV is produced at AGS with incident 14.5 GeV/c Si ions for both The Si and Pb targets.

Again this raises the interest in what our E-891 will find for $11.7 \times A$ GeV/c Au on a Au target collisions which are expected to lead to even higher temperatures.

Strangelet Search

We have found events with topologies consistent with a light strangelet decay²³ of strangeness 2 baryon number and charge of one. This strangelet $\rightarrow \Lambda\Lambda p$. We have made a search of over $\sim 10,000$ central Si-Pb events and our results for double Vees are shown in Figs. 7a-d. Although we obtain a peak at the $\Lambda\Lambda$ threshold we do not have evidence yet for any mass below the $\Lambda\Lambda$ threshold. It is difficult for technical reasons to find evidence for a neutral strangelet,²³ however for a charged strangelet which decays to $\Lambda\Lambda p$ the situation is much easier. Figure 7d shows the effective mass spectrum for the $\Lambda\Lambda p$ candidates. Here again we do not yet find evidence for a peak below threshold. We can place a limit of $< 2 \times 10^{-2}$ for the $H_{\Lambda\Lambda}^3$ strangelet per central event at (90% C.L.) if it had a lifetime around 3 nanoseconds and decayed only into the above channel.

In our forthcoming Au on Au approved experiment (E-891) we believe the chances of discovering strangelets will be much better.

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10. Lindenbaum, S.J. The Status of Glueballs. Proc. of Future Directions in Nuclear and Particle Physics at Multi-GeV Hadron Beam Facilities, Brookhaven National Laboratory, March 4-6, 1993, (to be published).
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Fig. 1: (a) Effective mass plot of $\Lambda\pi^-$ hypothesis for the intersection of a negative track with the projection of the Λ decay vertices from Pb target. (b) The Ξ^- decay distribution from central events in the Pb target. The dashed curve is the known measured value $e^{-ct/4.92}$.

Fig. 2 Rapidity distribution of E^- 's (Pb target), acceptance corrected with the fireball model. The asterisks are $1/8$ of the Λ yield. The dashed curve is the global fit, the dotted curve is eight times the prediction of AGSHIJET+N* model. Allowing for a possible deficiency of a factor of 2 in single strange quark production (from comparison with Λ data) we still find an excess ~ 2 in this ratio.

Fig. 3: (a) Rapidity distribution for K_s^0 's from the *Si* target. The solid points above a rapidity of 1.7 are our measurements. Errors shown are statistical only. The open circles below rapidity of 1.7 are our measurements reflected about 1.7. The open squares represent the measurements of Ref. 8 scaled up by 28. The solid curve is the prediction of the ARC model. The dashed curve is the prediction of the HIJET with N^* 's included in the model. (b) Rapidity distribution for K_s^0 's from the *Pb* target.

Fig. 4: (a) Rapidity distribution for Λ 's from the *Si* target. The solid points above a rapidity of 1.7 are our measurements. Errors shown are statistical only. The open squares represent the measurements of Ref. 8 scaled up by 28. The solid curve is the prediction of the ARC model. The dashed curve is the prediction of the AGSHIJET+N* model. (b) Rapidity distribution for Λ 's from the *Pb* target.

Fig. 5: (a) Inverse exponential slopes for K_S^0 's from the *Si* target. The points are fits to an exponential in each rapidity bin. The solid curve is the result of our global fit, not a fit to the points. The statistical error on the curve representation is similar to that shown on the individual points. The dashed curve is the prediction of AGSHIJET+N*. (b) Inverse exponential slopes for K_S^0 's from the *Pb* target.

Fig. 6: (a) Inverse exponential slopes for Λ 's from the *Si* target. The points are fits to an exponential in m_T for each rapidity bin. The solid curve is the result of our global fit, not a fit to the points. The statistical error on the curve representation is approximately as shown on the individual points. The dashed curve is the prediction of AGSHIJET+N*. (b) Inverse exponential slopes for Λ 's from the *Pb* target.

Fig. 7: (a) The effective mass of the double V 's from Monte Carlo generated $Si Pb$ central events. (b) The effective mass of the double V 's from our $Si Pb$ central events. (c) the effective mass of the double V 's with an added proton from Monte Carlo generated central $Si Pb$ events. (d) the effective mass of the double V 's with an added proton from our central $Si Pb$ events.

Progress Report

This report summarizes work accomplished during the last twelve months. This research was supported in part by the United States Department of Energy. Research has been accomplished in three main areas: (A) bosonic technicolor and strings, (B) buckminsterfullerene C_{60} and (C) neutrino oscillations in a dense neutrino gas. In addition, a section on (D) other activities is included.

A. Bosonic Technicolor and Strings

Most postulated fundamental theories involve unification at a high energy scale. Two noteworthy examples are grand unified theories and superstrings. In contrast, electroweak breaking occurs at a low energy scale of ~ 100 GeV. The disparity of these two scales is the hierarchy problem. In particular, it is unnatural for the mass of the Higgs field to be much less than the scale of unification. Supersymmetry and technicolor are two competing proposals to deal with this problem. Both have some phenomenological difficulties. These difficulties arise because one tries to use one mechanism for two purposes, namely, electroweak breaking leading to W and Z masses and chiral symmetry breaking leading to quark and lepton masses.

Bosonic technicolor uses both supersymmetry and technicolor to address these issues. A fundamental Higgs field produces quark and lepton masses and a technicolor sector breaks $SU_c(3) \times SU_L(2) \times U_Y(1)$ to $SU_c(3) \times U_{EM}(1)$. Although bosonic technicolor involves extensive theoretical structure, it avoids the phenomenological problems of a purely supersymmetric theory or a purely technicolor theory. The one drawback about bosonic technicolor is its unaesthetic use of both supersymmetry and technicolor. There is little, if any, evidence in nature for either of these structures. However, in certain string theories, it is possible to have both supersymmetry and technicolor in such a manner that a bosonic technicolor structure emerges. This was shown in

1. *Bosonic Technicolor in Strings*, (co-author A. Kagan), Phys. Letts. **B284** (1992) 289.

Alex Kagan and I demonstrated, using the fermion formulation of string model building, that some four-dimensional strings have bosonic technicolor. These strings have gauge groups large enough to include $SU_c(3) \times SU_L(2) \times U_Y(1)$ and a technicolor group and they are supersymmetric. In addition to ordinary quarks and leptons, they contain technicolor matter and Higgs particles. The Higgs fields couple to standard model fermions as well as technicolor matter in precisely the manner prescribed by bosonic technicolor. String provide some motivation for the extensive theoretical structure of bosonic technicolor.

B. The Molecule C_{60}

Several years ago, I developed the idea of a group lattice. Given a discrete group, one forms a one-to-one correspondence between group

elements and the sites of a lattice. Nearest neighbors are determined by specifying a subset of elements of the group. Group lattices appear more random than a regular lattice but more regular than a random lattice. Enough structure is provided by the group to permit an exact solution of the propagation of bosons or fermions on the lattice. It turns out that the carbon atoms of C_{60} are located at the sites of a group lattice. The group is A_5 , the alternating group on 5 elements. Under some reasonable approximations, one can compute the electron structure of C_{60} using group lattice methods. This was carried out in

2. *On the Electronic Structure of C_{60}* , CCNY-HEP-92/5, to appear in the Intl. J. Mod. Phys. B.

Included in this work, is an analysis of the experimental situation. The agreement between theory and experiment is satisfactory. At talk on this research was given at the conference *The XIX International Colloquium on Group Theoretical Methods in Physics*, Salamanca, Spain, (1992) and is published in the proceedings:

3. *Group Lattices with Applications to the Molecule C_{60}* , in the proceedings of the XIX International Colloquium on "Group Theoretical Methods in Physics", Salamanca, Spain, *Anales de Física, Monografías*, eds. M. A. del Olmo, M. Santander and J. Mateos Guilarte, Vol.II, p394, (CIEMAT/RSEF, Madrid, 1993).

I have been able to solve the Ising model on the truncated icosahedron lattice of C_{60} using a series of tricks. The high-temperature series expansion for the partition function was computed exactly. Also computed were the average energy and specific heat. This work is published in

4. The Solution of the Ising Model on the Truncated Icosahedron Lattice of C_{60} , *J. Math. Phys.* **34** (1993).

A short talk on this subject was given at the 67th *Statistical Mechanics Meeting* at Rutgers University, Brunswick, New Jersey, (1992).

C. Neutrino Oscillations in a Dense Neutrino Gas

In the recent work

5. Neutrino Oscillations in Dense Neutrino Gases, *Phys. Rev.* **D48** (1993) 1462,

I considered neutrino oscillations for a situation in which the neutrino density was sufficiently large that neutrino-neutrino interactions could not be neglected. This situation arises in the early universe, in supernova explosions and in neutron stars. Since the concept of a neutrino gas is general, there may be other applications.

Previous attempts to handle the dense neutrino gas have either failed or made incorrect assumptions. The system is quite complicated. If the flavor content of the background neutrino gas is known, one can compute the oscillation behavior of a single neutrino. If the oscillation behavior of

each neutrino in the gas is known, one can obtain the flavor content of the background. Hence, one is in a kind of "catch 22" situation. We have obtained a formalism for analyzing neutrino oscillations for a dense self-interacting neutrino gas. The procedure is as follows. We assumed that the background neutrino currents and densities are known. We then derived the correct equation governing the behavior of oscillations for a single neutrino propagating through the gas. Lastly we used individual solutions to obtain the background. A self-consistency condition requires that the initially inputted background agree with the final background as determined by individual solutions. The approach is very similar to the Hartree-Fock method. We have succeeded in obtaining a formalism to treat the highly non-linear system.

One important realization is that the physics depends on certain statistical distributions characteristic of and specific to the gas. One cannot begin an analysis until neutrino energy distributions, density fluctuations, initial flavor states, etc. are specified. As a consequence, general conclusions cannot be drawn; each type of gas must be analyzed separately.

We performed numerical simulations to gain insight into the physics of dense neutrino gases. We treated the homogeneous gas and restricted ourselves to the two-flavor case. Computer simulations revealed the non-linear system gas to exhibit a rich array of phenomena. Four generic behaviors were observed.

(1) The neutrinos oscillate more or less as they would in a vacuum. Such a behavior usually occurs when the gas is not too dense so that the effect of neutrino-neutrino interactions is minimal.

(2) In some cases, we observed a self-induced MSW effect. A gas initially consisting of electron neutrinos converted itself into a gas consisting mostly of muon neutrinos.

(3) For one type of gas in which the neutrino density was relatively small, a parametric resonance occurred. After many many oscillation times most of the electron neutrinos were converted into muon neutrinos. The reasons why such a resonance can arise is that the background oscillated in phase with individual neutrinos.

(4) Finally, for another type of gas, self-maintained coherence occurred. This was a somewhat surprising behavior. One expects statistical fluctuations to cause individual neutrinos to have different oscillation times causing them to be out of phase for sufficiently large times scales. As a consequence, the average background neutrino currents should approach smooth constant asymptotic values. Instead, the neutrino-neutrino interactions caused the oscillations to occur in phase and decoherence did not occur. With hindsight, we were able to understand intuitively why this phenomenon arose. It took place for a relatively dense system and was a result of the non-linear nature of the problem.

Our formalism can be applied to a number of physically interesting systems. In future research projects we intend to carry out this endeavor. It will be interesting to see which if any of the above behaviors are realized.

D. Other Activities

I attended the conference *Neutrino '92*, Granada, Spain, in order to obtain a better understanding of the developments in the area of neutrino physics. I also participated in the workshop (*The NATO ASI - XXIII GIFT Seminar on Recent Problems in Mathematical Physics*, Salamanca, Spain, and the conference (*The XIX International Colloquium on Group Theoretical Methods in Physics*, Salamanca, Spain, on mathematical physics. The purpose was to get updated in the new developments concerning quantum groups, conformal field theory, anyons, and quantum gravity in two- and three-dimensions. Finally, I spoke at the UCLA Conference on Low Energy Signals from the Planck Scale, (Los Angeles, California, October, 1992). The title of the talk was

6. *Experimental Constraints on Compactified Dimensions*, (to be published in the proceedings).

The subject was an update of the work *Experimental Constraints on Extra Dimensions* written with A. Kostelecký and published in *Phys. Letts. B270* (1991) 21.

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