DOE/ER/40698--1

DE92 041153

EXPERIMENTAL INVESTIGATIONS OF STRONG INTERACTION IN NON-PERTURBATIVE QCD REGION

PROGRESS REPORT

For the Period January 16, 1992 - January 15, 1993

Prepared for

THE U. S. DEPARTMENT OF ENERGY
DE-FG02-92ER40698

August 1992

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September 9, 1992

Annual Progress Report for DOE Contract DE-FG02-92ER40698 for the period January 16, 1992 through January 15, 1993

by S.J. Lindenbaum, P.I.

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

ABSTRACT

We have experimentally investigated the reactions $\pi^- p \to \phi\phi n$ (OZI forbidden), $\phi K^+K^- n$ (OZI allowed), $K^- p \to \phi\phi\begin{pmatrix}\Lambda\\ \Sigma\end{pmatrix}$ (OZI allowed), $\phi K^+K^-\begin{pmatrix}\Lambda\\ \Sigma\end{pmatrix}$ (OZI allowed), and $\bar{p}p \to \phi\phi\pi^0$ (OZI forbidden), $\phi K^+K^-\pi^0$ (OZI allowed).

By comparing the OZI forbidden (glueball filter) reactions with the OZI allowed and taking a global view we hope to critically test our hypothesis that the $g_T(2010)$, $g_{T'}(2300)$, and $g_{T''}(2340)$ all with $I^GJ^{PC} = 0^+2^{++}$ are produced by 1-3 2^{++} glueballs.

We have searched for a Quark-Gluon Plasma by using 14.6 GeV/c × A Si ions incident on Au, Cu and Si. The novel detector used was a large solid angle TPC system. Although we found considerable strangeness enhancement this is explainable by conventional cascade physics including N^* production. We have been engaged in phenomenological analyses in both glueball and heavy ion work. We have found that the $\theta(1720)$ is the same as

the 0^{++} $f_0(1720)$ we discovered earlier. Furthermore that the G(1590) can be explained as a sum of the $f_0(1400)$ and $f_0(1720)$ and does not require a new resonant state. We have also found that the strangeness enhancement discovered in heavy ion collisions so far is explainable by conventional physics. We are in the STAR Collaboration at RHIC which uses a large TPC system to search for a Quark-Gluon Plasma.

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 predicted[1] and directly demonstrate in the most dramatic fashion the non-abelian nature of $SU(3)_{color}$ 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]

Progress in the Period Beginning January 16, 1992

1. Glueballs and Exotic Hybrid Research

The Principal Investigator (S.J. Lindenbaum) proposed and as Spokesman successfully defended and obtained (in September 1991) approval 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) $\pi^- p \to \phi\phi n$ with the $K^- p \to \phi\phi\begin{pmatrix}\Lambda \\ \Sigma^0\end{pmatrix}$ OZI allowed (Zweig connected diagram) and investigate the $\bar{p}p \to \phi\phi\pi^0$ 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 this 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.

The MESB had (at the MPS) about 1.5% negative kaons, ~ 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 $\pi^- p \to \phi\phi n$ 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]

One of our biggest foreseeable problems in the data analysis is a woefully inadequate computer power to analyze the data. Therefore it would be of great value to us to receive additional funds to purchase the very new powerful computer workstations that have just become available. The data analysis will continue through the next year continuation period being requested.

2. Phenomenological Analysis

The Principal Investigator and a collaborator published a coupled channel analysis of $J^{PC} = 0^{++}$ and 2^{++} isoscalar mesons with masses below 2 GeV.[11] The highly constrained nature of coupled channel analyses allows us to determine which resonances are likely to be real and avoid claiming too many new resonances.

The main conclusions were that the $f_0(1720)$ represents both the first discovered (by BNL/CCNY/Tufts/Vanderbilt) $S^{*\prime}(1720)$[12] and the $\theta(1720)$ both of which have the same quantum numbers (0^{++})[13] and parameters. Furthermore the G(1590)[14] which is the $f_0(1590)$ was found in our solution to be made up of a sum of the $f_0(1400)$ and the $f_0(1720)$, rather than requiring a new resonant state. This work thus drastically changed the glueball candidate landscape below 2 GeV/c.

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.[15-23]

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 events.

Thus we have concentrated on:

1) A search for sufficiently enhanced strangeness in these heavy ion collisions where one might expect formation of a Quark-Gluon Plasma via pressure at the AGS energies. Many believe that sufficiently enhanced strangeness is a signal for a Quark-Gluon Plasma (QGP). A QGP is one of the most important predictions of QCD in the non-perturbative region and it is generally agreed that heavy ion collisions is the best way to search for it.

2) A study of global variables and the stopping characteristics at AGS energies.

3) We have also obtained incident proton data on various nuclear targets to enable us to study the difference between Si and heavy ion collisions and proton plus heavy ion collisions. This is particularly

important to enable us to check the cascade event generators we have developed to simulate non Quark-Gluon Plasma events, via cascade and secondary interactions. These data have not been analyzed yet.

We have also developed a Quark-Gluon Plasma bubble generator (of the Van Hove type).

During this year we have found that single Λ and K_s^0 production can be reasonably accounted for by conventional physics cascade generators which include N^* formation.[24] However we plan next year to investigate whether the multi-Λ and multi-Kaon production we have observed is explainable by the available models or gives evidence for some Quark-Gluon Plasma formation.

During this year we have had published a Physics Letter[25] on transverse momentum distributions of π^- from 14.6 × A GeV/c Silicon ion interactions in copper and gold. The major conclusions were that the transverse momentum spectrum of pions produced in Si ion collisions at the AGS energies has a different shape from the spectrum produced by nucleon-nucleon collisions of approximately the same energy. The shape is well represented by a sum of two exponentials with different slopes and may reasonably be well accounted for by a model that includes resonance production and decay, especially that of the Δ.

We have measured and analyzed the rapidity distributions of charged particles for 14.6 × A GeV/c Si on Au collisions. The data disagreed with a recent postulate[26] of high nuclear transparency at AGS energies, and in fact demonstrated that there was high stopping (as previously thought) at AGS energies.

We have submitted a proposal to study Au on Au interactions at AGS with the same apparatus (P-891 at BNL). We expect this to be approved. Au on Au interactions are generally considered to have a much better chance of producing a Quark-Gluon Plasma than Si on heavy nuclei. It is of interest to note that as part of the STAR Collaboration (provisionally approved) we have been partly engaged in preparing a large solid angle TPC detector for a search for a Quark-Gluon Plasma at RHIC commencing in 1997. No specific funds for this activity have been requested in this grant.

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<u>Papers and Reports (for First Year of Grant)</u>

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Progress Report

This report summarizes the work accomplished during the last eight months. This research was supported in part by the United States Department of Energy. Research has been accomplished in three main areas: (A) the strong CP problem, (B) bosonic technicolor, and (C) group lattices. In addition, a section on (D) other activities is included.

A. The Strong CP Problem

A θ-term can be added to the lagrangian of QCD. Such a term explicitly breaks parity, time-reversal invariance and CP. However in nature little CP violation is observed in the strong interaction sector: the absence of an observed electric dipole moment for the neutron leads to $\theta < 10^{-10}$. This is known as the strong CP problem: it is hard to understand why a parameter in the strong interaction lagrangian is so small.

I have proposed that long-distance effects perhaps solve the strong CP problem naturally. The basic idea is that θ couples to the total topological charge. If vacuum effects or non-perturbative physics require the total topological charge to be zero then θ multiplies a quantity which is zero and θ vacua are equivalent. Such a phenomenon would lead to no θ dependence and no strong CP violation. If there are still fluctuations of topological charge on the scale of a Fermi then the U(1) problem can still be resolved by instanton effects. There is one model in which the above mechanism for eliminating the θ dependence operates: it is the Polyakov model in 2+1 dimensions. For more details about these ideas see

1. *A Possible Solution to the Strong CP Problem*, in the proceedings of *The 15th Johns Hopkins Workshop on Current Problems in Particle Physics*, Baltimore, Maryland, (August, 1991), eds. G. Domokos and S. Kovesi-Domokos, (World Scientific, Singapore, 1992).

2. *Does the Yang-Mills Theory Solve the Strong CP Problem by Itself?*, Mod. Phys. Letts. **A7** (1992) 2007.

A talk on this subject was also given at the *Southern Association for High Energy Physics Theory Meeting: Current Topics in High Energy Theory*, Gulf Shores, Alabama, (January, 1992), although there are no proceedings.

B. Bosonic Technicolor

The hierarchy problem arises when the low energy group $SU_c(3)\times SU_L(2)\times U_{Y_W}(1)$ is embedded in a grand unified theory. It is unnatural for the mass of the Higgs field to be much less than the scale of unification. There have been two main proposals to deal with this problem: supersymmetry and technicolor. Both proposals have some phenomenological drawbacks. In technicolor, one must introduce extended technicolor forces to generate quark and lepton masses. However, these interactions introduce flavor-violating processes above present experimental limits. Technicolor also predicts light techni-meson states below 45 GeV range which have not been observed. In supersymmetry, flavor violation also occurs unless squark and slepton masses have a high degree of degeneracy. No supersymmetric particle states have yet been observed experimentally.

Bosonic technicolor uses both supersymmetry and technicolor to address the hierarchy problem. In bosonic technicolor, a fundamental Higgs field produces quark and lepton masses and a technicolor sector breaks $SU_c(3) \times SU_L(2) \times U_{Y_W}(1)$ to $SU_c(3) \times U_{EM}(1)$. Although technicolor was proposed to avoid fundamental scalar fields, it may happen that nature chooses this combined system. The best support for bosonic technicolor is comes from its phenomenology. The phenomenological benefits are as follows. Technicolor mesons are heavier than in ordinary technicolor theories. Furthermore, the supersymmetry breaking scale, m_{ss}, is at least an order of magnitude larger than in the usual supersymmetric standard models. Since $m_{ss} > 1$ TeV, supersymmetric particles are also heavier. Thus the combined system produces heavier masses for the unseen particles and provides an explanation of why such states have not yet been experimentally detected. The heavier scale also alleviates the flavor problem as explained in the work with Professor Michael Dine and Dr. Alex Kagan, *Naturalness in Supersymmetry, or Raising the Supersymmetry Breaking Scale*, Phys. Lett. **243B** (1990) 250.

Alex Kagan, a postdoctorate at City College, and I have embedded a multi-Higgs system in bosonic technicolor in order to explain the pattern of quark and lepton masses and mixing angles in the context of bosonic technicolor. The Higgs fields which couple to technicolor fields couple to the third generation thereby explaining why these states are the heaviest. A see-saw mechanism involving Higgs fields coupling third and second families explains why the second generation fermions are less massive. Finally, the first generation masses are produced via radiative corrections. When mixing angles are computed in this system, they turn out to be of the right order of magnitude. Bosonic technicolor is crucial in this framework due to the TeV mass scale of the Higgs bosons. A lighter multi-Higgs system would produce flavor-changing neutral currents via Higgs exchange above experimental limits. The above provides a complete framework for physics below 10 TeV which can be tested in the SSC. In

3. *Multi-Higgs Systems in Bosonic Technicolor: A Model for SSC Physics*, Intl. J. Mod. Phys. **A7** (1992) 1123,

Dr. Kagan and I derived the relevant formulas for computing the physics above the 100 GeV scale. This is the first step in obtaining a phenomenology for SSC physics. Our theory, which is a specific way of combining supersymmetry and technicolor, produces the good features of supersymmetry and technicolor while avoiding the difficulties that each has separately. Even if bosonic technicolor is not realized it nature, nature may mimic some of its features. As such, it can be used for a model for discussing SSC physics.

Bosonic technicolor is unaesthetic from a theoretical viewpoint because of its extensive theoretical structure: it uses both supersymmetry and technicolor. There is little, if any, evidence for either of these structures. A natural theoretical framework has been found, however. In

4. *Bosonic Technicolor in Strings, CCNY-HEP-92/2,* (March, 1992), (co-author A. Kagan), to appear in Phys. Letts. B.,

Alex Kagan and I, showed that four-dimensional strings, in the fermion formulation, often have bosonic technicolor structure. These string theories have gauge groups sufficiently large to include $SU_c(3)\times SU_L(2)\times U_{Y_W}(1)$ and a technicolor group, they have ordinary quark and lepton fields as well as technicolor matter, they possess supersymmetry, and there are Higgs fields which couple to standard model fermions as well as technicolor matter in precisely the manner required by bosonic technicolor. In short, strings provide a natural framework for the extensive theoretical structure of bosonic technicolor.

C. Group Lattices and C_{60}

Several years ago, I developed the idea of a group lattice. Roughly speaking, it is more random than a regular lattice but more regular than a random lattice. The structure of the lattice is provided by a discrete group. Free propagation of bosons or fermions on a group lattice is exactly solvable if the irreducible matrix representations of the group are known. One interesting group lattice was analyzed in

5. *The Solution of the Three-Dimensional Twisted Group Lattices,* Intl. J. Mod. Phys. **B6** (1992) 1631.

Another application is forthe molecule C_{60}. With some work, one can show that the truncated icosahedron lattice of C_{60} is a group lattice. The group is A_5, the alternating group on 5 elements. Using group lattice techniques an approximate calculation of the electron structure of C_{60} was obtained in

6. *On the Electronic Structure of C_{60}*. CCNY-HEP-92/5, (May, 1992).

In addition, an analysis of the experimental situation was performed. The theoretical computations in the above work agree well with experiment. This work should be valuable to both theorists and experimentalists working on C_{60}. This research was reported at the conference *The XIX International Colloquium on Group Theoretical Methods in Physics*, Salamanca, Spain, (July, 1992).

I have also considered the Ising model on the truncated icosahedron lattice of C_{60}. By a series of tricks the exact high-temperature series expansion for the partition function was computed. With this in hand, the average energy and specific heat were obtained. For more details, see

7. *The Solution of the Ising Model on the Truncated Icosahedron Lattice of C_{60}*, CCNY-HEP-92/3, (March, 1992).

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

D. Other Activities

I attended the physics conferences *Franklin Symposium in Celebration of the Discovery of the Neutrino*, Philadelphia, PA, (April, 1992) and *Neutrino '92*, Granada, Spain, (June, 1993). The purpose was to obtain a better understanding of the developments in the area of neutrino physics.

I also attended a workshop (*The NATO ASI - XXIII GIFT Seminar on Recent Problems in Mathematical Physics*, Salamanca, Spain, (June, 1992)) and a conference (*The XIX International Colloquium on Group Theoretical Methods in Physics*, Salamanca, Spain, (July, 1992)) 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.

Proposed Research

The proposed research for the coming year has already been presented in the DOE grant DE-FG02-92-ER40698, where is was stated that the project would investigate various aspects of conventional particle physics, field theory, string theory, supersymmetry, extensions of the standard model and related phenomenology.

Further investigations will be carried out on bosonic technicolor. It is a specific combination of supersymmetry and technicolor which can be used as an extension of the standard model. There are interesting phenomenological implications for the SSC and TeV physics which need to be studied. It is important to determine how SSC measurements can verify or rule-out bosonic technicolor.

Not mentioned in the DOE grant DE-FG02-92-ER40698 are the following: I believe the techniques used to solve the Ising model on C_{60} can be extended to the case of C_{70}. If so, one will be able to understand some of the magnetic properties of the C_{70} fullerene. I am also planning to do some research in the area of neutrino physics with the Indiana University theory group. Several members already have expertise in this field.

7. *The Solution of the Ising Model on the Truncated Icosahedron Lattice of C_{60}*, CCNY-HEP-92/3, (March, 1992).

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12 / 1 / 92