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THEORETICAL STUDIES IN MEDIUM-ENERGY NUCLEAR AND HADRONIC PHYSICS

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Annual Technical Progress Report

for April 1, 1991 to March 31, 1992

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CONTENTS

1. Introduction

In the period covered by this report (April 1, 1991 to March 31, 1992), work focused on six main areas:

(a) Relativistic Theories of Nuclear Structure and Saturation

(b) Relativistic Descriptions of Proton–Nucleus and Electron–Nucleus Scattering

(c) Nonrelativistic Theory of Nucleon–Nucleus Reactions

(d) Relativistic Many-Body Theory at Finite Temperature and Density

(e) Neutrino Interactions in Dense Matter

(f) Quark Models of Nuclear and Quark Matter

During 1991, 12 papers were published or accepted for publication under this grant, 6 more were submitted for publication and 7 invited talks were given at conferences or workshops. The pertinent references are given in Section 6 of this report, and the physics on which they are based is described in Section 3. The research described here is part of the program of the Indiana University Nuclear Theory Center, which is located in the Indiana University Cyclotron building.

The current grant covers summer salaries, 3 graduate students, 1 research associate, and minor miscellaneous items. In September of 1991, Tetsuo Matsui joined the group from MIT, as an Associate Professor of Physics. His research on hot, dense matter, ultrarelativistic heavy-ion collisions, and the physics of the quark-gluon plasma significantly extends the group's range of interest.

Our funding for the current year was $233,000 – a base grant of $206,000 ($69,000 per principal investigator) with a supplement of $27,000 in view of the addition of Matsui to the group.

We request continued funding at $313,000 per annum, or about $78,000 per principal investigator. The requested increase reflects the growth of the group and the need to provide support for a larger number of graduate students (6) and research associates (2) consonant with this growth.

2. Scientific Personnel

C. J. Horowitz, Professor of Physics

M. H. Macfarlane, Professor of Physics

T. Matsui, Associate Professor of Physics

B. D. Serot, Professor of Physics

S. Kumano, Research Associate† [from September 1, 1989]

D. Griegel, Research Associate [from September 1, 1991]

W. Unkelbach, Research Associate†† [from October 1, 1991]

M. P. Allendes, Graduate Student [from January 1, 1989]

H.C. Kim, Graduate Student [from May 1,1991]

W. Melendez, Graduate Student [from May 8, 1990]

H. Roh, Graduate Student [to begin Jan. 1, 1992]

R. Roncaglia, Graduate Student [from Jan. 1, 1991]

H. Tang, Graduate Student [from January 1, 1991]

† Approximately 1/3 of Kumano's support is from the present grant; the rest comes from the Londergan–Walker NSF grant.

†† Partial support from the Alexander von Humboldt Foundation and Indiana University. Unkelbach's support from the present grant was limited to $10,000 per annum.

Long-term Visitors Support shared by this grant, Indiana University and the Indiana University Cyclotron Facility.

E. D. Cooper, Ohio State (July to December, 1991)

D. P. Murdock, Tennessee Tech (May to August, 1991)

J. Niskanen, Univ. of Helsinki (August 1991 to July 1992)

Collaborators Scientist in other groups and at other institutions involved in joint publications over the past year and in continuing work.

T. Cohen	Maryland
E. D. Cooper	Ohio State
R. J. Furnstahl	Ohio State
S. Gardner	CEBAF
C. Glashausser	Rutgers
Y. Koike	Maryland
J. Lisanti	Indiana
J. T. Londergan	Indiana
R. E. Mehrem	Indiana
H. O. Meyer	Indiana
D. P. Murdock	Tennessee Tech
H. Nann	Indiana
T. Otafuji	Akita Univ.
J. Piekarewicz	Florida State
J. Speth	KFA Jülich
E. J. Stephenson	Indiana
J. D. Walecka	CEBAF
G. E. Walker	Indiana
J. Wambach	Illinois
K. Wehrberger	IKP Darmstadt

3. Summary of Research Achievements

3.1 Relativistic Theories of Nuclear Structure and Saturation

Relativistic meson-baryon quantum field theories ("quantum hadrodynamics" or QHD) have proven to be useful models of the nuclear many-body problem [1]. They provide a consistent, Lorentz covariant, causal framework for extrapolating known nuclear information to nuclear matter under extreme conditions of density, temperature, and flow velocity. They also predict large relativistic effects in nuclei under normal conditions. The initial successes of QHD have stimulated several new areas of investigation.

The Dynamical Quantum Vacuum

[Allendes, Horowitz, Serot]

The strong scalar potential in nuclear matter shifts the mass of all baryons, including those in the Dirac sea. This changes the vacuum contribution to the energy density as well as the nuclear scalar density. Thus, vacuum fluctuations cannot be neglected in relativistic meson-baryon field theories. Moreover, these fluctuations increase in strength at small distances because existing QHD field theories are not asymptotically free. One consequence of this behavior is that new poles appear in the meson propagators for spacelike momenta. Indeed, it is believed that such poles also exist in quantum electrodynamics, but only at fantastically high momenta.

Furnstahl and Horowitz [2] investigated the stability of uniform nuclear matter in the relativistic Hartree approximation to the Walecka model by calculating the meson propagators in the one-loop approximation.

Nuclear matter was found to be unstable against short-wavelength perturbations (momenta greater than three times the nucleon mass) because of vacuum polarization effects. This instability implies that there will be an imaginary part in the ground-state energy of nuclear matter. The onset of instability is pushed to larger momenta with increasing baryon density, as the nucleon effective mass decreases. The effects of short-range correlations and vertex corrections on these results were not studied.

Because of the important effects introduced when vacuum loops are included in the meson propagators, it is necessary to study nuclear matter in a relativistic random-phase approximation (RPA) that includes these modes. Since these vacuum terms do not enter in the traditional nonrelativistic RPA, the development of relativistic RPA techniques is an important and non-trivial task. Work on this topic was carried out by Lim and Horowitz [3,4] and is still being actively pursued.

As an alternative way to study the nuclear matter instabilities, Serot and Allendes (a graduate student) investigated nuclear matter configurations that have lower energy than the uniform state [5].

Poles in the RPA meson propagators at zero frequency and finite three-momentum imply that periodic structures with a lattice size comparable to the inverse momentum should lower the ground-state energy. A Thomas–Fermi energy functional was used to search for variational wave functions that are uniform in two directions and periodic in one direction, which sometimes have an energy lower than the totally uniform state. We isolated periodic solutions corresponding to the (long-wavelength) liquid-gas instability at low density, but were unable to find similar solutions arising from the short-wavelength vacuum instabilities discussed above. One important question is whether these instabilities actually persist down to very small densities, where the standard RPA analysis may break down.

The vacuum contributions are large in existing QHD calculations because the meson-baryon vertices have been approximated by point vertices. Thus, contributions at large internal loop momenta, which should be reduced due to the finite size of the hadrons, are overestimated.

However, loop corrections in QHD also generate vertex corrections, and an improved approximation to the vacuum terms would include these corrections inside the vacuum loops. In fact, as pointed out recently by Milana [6], in a theory with vector bosons, the proper vertex functions are highly damped at large spacelike momenta due to the contributions from virtual bremsstrahlung summed to all orders. Moreover, this damping arises from the long-range (infrared) structure of the vertex (the relevant loop momenta are on the order of the vector boson mass) and so should be calculable within the QHD framework. Since the QHD theory is renormalizable, the vertex function is expressed in terms of the couplings and masses of the theory, with no additional *ad hoc* parameters.

Allendes and Serot are currently computing the effects of these vertex corrections on the vacuum polarization in the vector meson propagator, which was computed for point-like vertices by Furnstahl and Horowitz [2]. A full calculation is somewhat involved, as one needs to know the off-shell behavior of the vector-baryon vertex at all spacelike momenta, as well as the modification of the vertex in the presence of valence nucleons at finite density. As a first approximation, we replace the off-shell vertex by its on-shell form, which has a simpler matrix structure and is a function of the momentum transfer q only. At large spacelike q^2, the asymptotic analysis shows that the vertex function falls off *faster* than any inverse power of q^2, and a comparison with the lowest-order correction shows that the asymptotic regime begins at $|q| \approx 4M$. This large damping produces a vacuum polarization that is much smaller than that obtained with point-like vertices, and the instability found by Furnstahl and Horowitz *disappears* when the vertex corrections are included, at least in the approximation discussed above. Moreover, the early onset of the asymptotic behavior implies that the results are insensitive to the long-range structure of the vertex. The essential conclusion of this work is that it is not a good approximation to compute vacuum loops in QHD theories without also including corrections at the vertices.

Work is continuing on the full (off-shell) calculation and the inclusion of scalar mesons. The density dependence induced by valence nucleons is also being studied.

Although the inclusion of vertex corrections appears to have a beneficial effect on the vacuum contributions, it is still necessary to develop systematic approximation schemes that maintain various conservation laws when these corrections are included. We are currently studying the work of Baym and Kadanoff [7,8] on "conserving approximations" in nonrelativistic systems and attempting to extend them to systems containing relativistic bosons and fermions. The construction of conserving approximations is also crucial for deriving thermodynamically consistent approximations and for generating Landau–Migdal parameters that respect the appropriate relations and sum rules.

In addition to computing vertex corrections for inclusion in vacuum loops, we are extending these calculations to baryon electromagnetic form factors. The nucleon electromagnetic form factors from various meson loops will be calculated in the nuclear medium at finite density. The medium has two effects. First, some of the virtual intermediate states are Pauli blocked. Second, both the virtual nucleons and antinucleons now have a smaller effective mass because of the mean scalar field.

The focus of this work will be to examine the density dependence of the nucleon substructure. For example, the nucleon anomalous magnetic moment can be calculated in free space from a simple pion loop, as shown more than thirty years ago. How does the anomalous moment change in the medium?

These questions about vertex structure are also important for the consistency of QHD descriptions of nuclear systems. Since it is clear that quark and gluon degrees of freedom become relevant at extremely small distances, one must systematically explore the regime of validity of models based purely on hadronic degrees of freedom. This is particularly important because QHD theories contain hadronic interactions whose strength increases at very short distances, in contradiction to deep-inelastic scattering measurements. Thus, QHD presents a consistent framework for unambiguously identifying quark and gluon effects in nuclear physics; calculation of hadron structure is one of the most promising areas to explore these effects.

The Inclusion of Pions and Chiral Symmetry

[Horowitz, Serot, Tang]

Chiral symmetry produces low-energy pion dynamics that is consistent with experiment. However, chiral models introduce new problems due to the strong nonlinear interactions of scalar (σ) mesons. These nonlinearities can be mitigated by giving the chiral σ meson a large mass, but this eliminates the strong mid-range scalar attraction known to be present in the nucleon-nucleon interaction.

It has been suggested [9] that this attraction is restored by *correlated* exchange of two pions between the nucleons, and Lin and Serot used a chiral Lagrangian to construct a dynamical model of the mid-range attraction through explicit $\pi\pi$ rescattering [10]. Unitarity and dispersion relations were used to calculate the spectral function for the scalar-isoscalar part of the NN interaction, which can be approximated by a light scalar meson with a broadly distributed mass.

Moreover, the mid-range attraction arises in this framework even when the σ mass in the Lagrangian is large, due to the chiral structure of the $\pi\pi$ scattering amplitude. A large chiral σ mass reduces the strength of the nonlinear scalar interactions. The resulting strong NN attraction and small many-nucleon forces qualitatively reproduce the scalar dynamics in the original Walecka model, while the pion dynamics is incorporated in a manner that resembles the nonlinear σ model of Weinberg. These points were discussed more fully in a letter [11] and at a recent conference on many-body theory in a pair of talks given by Serot and Dirk Walecka (CEBAF) [12]. This approach should provide a major advance in relativistic theories of nuclear matter, since it combines chiral symmetry, a strong mid-range scalar attraction, and reasonable (small) scalar nonlinearities in an explicit dynamical model. All of these features are necessary to develop a consistent relativistic framework for pion dynamics in nuclei. For example, it should be possible to compute the modification in the $\pi\pi$ rescattering and resulting NN interaction when the two-pion exchange takes place in the nuclear medium; work is currently underway with Lin (who is now a research associate at the University of Washington) on this topic.

In spite of the advantages to this approach, several important problems remain. First, the vacuum structure is crucial in chiral theories because the nucleon mass is determined by spontaneous symmetry breaking; it is therefore necessary to treat the vacuum dynamics consistently in any given approximation. To our knowledge, there had been no calculations with pion degrees of freedom in vacuum loop integrals, since these lead to unphysical "tachyon" poles when the standard loop expansion is used. As discussed by Weiss [13], however, it is possible to reorganize the loop expansion by summing various classes of fermion loops to all orders. The lowest-order term coincides with the approximation of Matsui and Serot [14], and Wehrberger, Wittman, and Serot extended this approach to the next order [15]. We verified that renormalizability and chiral symmetry are maintained to this order in the reorganized expansion, and also showed that the tachyon poles present in the conventional loop expansion are avoided to a large extent. Unfortunately, there are still unphysical poles from the short-distance behavior of the vacuum discussed above. This leads to large imaginary contributions to the nuclear matter energy, just as in the Walecka model. We are continuing this investigation into chiral theories to study ways to improve the modified loop expansion. In particular, the addition of vector mesons and the implied modifications to the meson–baryon vertices (discussed above) will be examined.

Furthermore, the basic conclusion of the $\pi\pi$ rescattering work is that important (and previously ignored) nonperturbative sums of diagrams must be included to make chiral models consistent with the properties of nuclear matter and the observed nucleon-nucleon force. These summations can be interpreted as generating "effective" degrees of freedom from the "elementary" fields in the chiral Lagrangian. Thus, in a strong-coupling relativistic field theory, there may be resonant structures (such as the σ meson and Δ baryon) that are just as important as the "elementary" fields, and one must decide which variables are the most efficient. Whereas these ideas are plausible, they have not yet been exploited consistently in QHD. We plan to examine approximations that may be particularly relevant to chiral models (with spontaneous symmetry breaking) and to seek consistent calculational schemes in theories with both "elementary" and "composite" degrees of freedom.

For example, Lin and Serot extended the preceding ideas [16] to study the Δ resonance in πN scattering by performing a fully relativistic, dispersion-theoretic calculation modeled after the original work of Chew and Low. We used a scattering amplitude that has the correct threshold behavior and that produces a Δ resonance with a driving term from one-nucleon exchange. Our basic goal was to see if a Δ resonance was present in the linear σ model with its additional chiral scalar meson. We found that with either a very heavy or a light scalar meson, the Δ resonance exists, and thus the resonance is compatible with the pion dynamics needed to generate the appropriate mid-range NN attraction, as discussed above. As we have emphasized, these techniques are important for developing a viable relativistic nuclear dynamics that includes pionic degrees of freedom.

The High-Density and High-Temperature Nuclear Equation of State

[Horowitz, Serot]

In addition to an accurate description of nuclear saturation, which is required for any realistic model of nuclei, it is also essential to develop a consistent relativistic theory of nuclear matter under extreme conditions of density, temperature, and flow velocity. These conditions exist in astrophysical objects, such as neutron stars and supernovae, and may also be achieved in the proposed generation of relativistic heavy-ion colliders like RHIC. Under these extreme conditions, relativistic dynamics is clearly important, and the extrapolation of existing nonrelativistic calculations is questionable. In addition, previous relativistic calculations have focused mainly on equilibrium properties in the mean-field approximation [1], and even these have not fully exploited the covariant aspects of QHD.

In the past year, Furnstahl (now at Ohio State) and Serot completed a major program involving covariant many-body theory at finite temperature and density. We generated the Feynman rules for both real-time, finite-temperature (matrix) Green's functions and the more conventional imaginary-time functions [17,18]. The former are more useful for dynamical calculations of response and nonequilibrium properties, since the times are real and the well-known (and usually difficult) analytic continuation from imaginary time is unnecessary. The imaginary-time results are most efficient for computing equilibrium thermodynamic properties (*i.e.*, the partition function). The new aspect of this work was to show that *both* the real- and imaginary-time results can be written in a covariant fashion, so that calculations can be performed directly in any convenient reference frame. Moreover, a covariant description incorporates information that would be obscured by working in a fixed frame, such as the role of the fluid velocity and momentum density as conjugate thermodynamic parameters, and it also allows for a clear identification of the Lorentz structure and invariant functions contained in n-point amplitudes. These techniques can be combined with studies of improved systematic expansions in QHD to develop a reliable hadronic framework for studying the properties of hot, dense nuclear matter.

The derivation of these covariant Feynman rules using a path-integral (time-path) formalism is discussed in ref. [18]. The basic starting point is a covariant representation of the generating functional for propagators that involves evolution along contours in the complex time plane. Many technical and mathematical issues arise in proceeding from this generating functional to the Feynman rules; these have not been handled correctly in previous treatments and have led to numerous controversies in the literature. Some of these issues are: the definition of the interacting generating functional using propagators that are generalized (singular) functions, the factorization of the generating functional into real-time and imaginary-time pieces, the incorporation of quantization on an arbitrary spacelike hyperplane (which allows imaginary-time rules to be expressed covariantly), and the distinction between the Eulerian and Lagrangian descriptions of the fluid flow, which is determined by whether canonical or grand-canonical Heisenberg-picture fields are used. All of these points are discussed carefully and the controversies are resolved in what we believe is the most complete description of the time-path formulation of relativistic many-body theory. Although the methods are illustrated by working in the original Walecka model of QHD, the techniques can be extended to QED and QCD in a straightforward fashion.

As an application of these Feynman rules, we carried out a manifestly covariant calculation of nuclear matter properties in the Relativistic Hartree Approximation [17]. The covariant real-time Feynman rules were used to derive expressions for the one-loop energy-momentum tensor. Next, the partition function was evaluated at one-loop order, which generates the thermodynamic potential and pressure in covariant form and which verifies the virial theorem. Finally, covariant imaginary-time rules were shown to reproduce the real-time one-loop calculations; to our knowledge, this was the first presentation of imaginary-time Feynman rules in manifestly covariant form. Our results generalized those we had derived earlier [19], when we applied the model in a simple hydrodynamic picture to discuss the phenomenology of heavy-ion collisions and astrophysical systems. Our goal is now to extend this work and apply the formalism to more sophisticated calculations of relativistic heavy-ion collisions at extremely high energies, such as those that will occur at RHIC.

3.2 Relativistic Nuclear Reaction Theory

[Horowitz, J. Piekarewicz (Florida State)]

To support a variety of new experimental facilities in this decade, there is a crucial need for a relativistic theory of reactions. This is because many future experiments will involve momentum transfers greater then the nucleon mass. We have worked on calculations for a number of different systems.

Electromagnetic currents for the 1990s

CEBAF will probe the nucleus with unparalleled precision and directly determine charge and current densities. However, to interpret these one needs an electromagnetic current operator which allows one to calculate currents given nuclear wave functions.

The construction of a current operator in relativistic field theories is very involved. Consistency with the approximations used for the relativistic nuclear structure is crucial. Furthermore, negative-energy states are clearly needed for completeness and gauge invariance.

We have examined the role of negative-energy states for both elastic magnetic [20] and quasi-elastic electron scattering [21,22,23]. We find that the change in vacuum polarization in the nuclear medium reduces the effective charge. This decreases the longitudinal quasielastic response.

Horowitz has given a series of lectures [24] stressing the importance of the current operator and the many complications involved in its construction. Horowitz also helped organize a joint workshop with CEBAF and Florida State on Currents in composite systems.

Relativistic Effects in Proton Scattering

Relativistic effects may be important in a variety of proton-nucleus spin observables. These could have a large influence on the results from the K600 program at IUCF and on similar programs at LAMPF and TRIUMF. In the past we studied elastic proton scattering. Most recently we have been performing relativistic RPA calculations for spin observables in both $(\vec{p},\vec{p}')$ and $(\vec{p},\vec{n})$ quasielastic scattering [25,26]. We find that relativistic effects reduce the analyzing power in $(\vec{p},\vec{p}')$ but not in $(\vec{p},\vec{n})$ scattering, in good agreement with data. This may be the clearest relativistic signature found to date.

These relativistic RPA calculations also provide very interesting results for the isovector response. A simple model of the isovector NN interaction is used which involves pi meson exchange (with pseudovector coupling) and rho exchange (with both vector and tensor couplings). In addition, a contact term is used to include short range correlations.

Relativistic effects from a change in the nucleon spinors in the medium (arising from a smaller effective mass) reduce the strength of the spin longitudinal response. This all most cancels the enhancement arising from the attractive one pion exchange interaction (in an RPA approximation). As a result, the spin longitudinal response is very close to its free value. This is in good agreement with recent NTOF $(\vec{p},\vec{n})$ results for quasielastic scattering at 500 MeV.

3.3 Pion Production Near Threshold

[Horowitz, Macfarlane, H. Meyer (IUCF), H. Nann (IUCF)]

Relativistic and nonrelativistic distorted-wave Born approximation calculations are underway for the $pp \rightarrow pp\pi^0$ reaction very close to threshold. Simple coupled-channel models are also being developed to study possible threshold anomalies in proton-proton and proton-^{3}He pion production. These calculations directly support the experimental program at the IUCF cooler. Because of the unique capabilities of the cooler, this program is dramatically improving the accuracy of near threshold measurements.

A DWIA calculation [27] for $pp \rightarrow pp\pi^0$ reproduced the energy dependence of the measured cross section and allowed a separation of the data into s wave and p wave contributions. However, the calculation underestimated the overall magnitude of the cross section by a factor of five. This indicates the importance of rescattering (where a pion is emitted from one nucleon and scattered by the second) which was not included in the calculation. The data and calculations are remarkable because of the simplicity of the process and the small number of partial waves which can contribute. As a result, one should be able to understand in detail this most fundamental of meson production reactions.

3.4 Neutrino Interactions in Dense Matter

[Horowitz, Wehrberger (Inst. Kernphysik, Germany)]

The interactions of neutrinos in dense matter are very important for the evolution of supernovae and the cooling of neutron stars. We have extended earlier work on relativistic descriptions of strong and electromagnetic reactions to those involving neutrinos. At low densities the system is modeled as a plasma involving nuclei ($\approx {}^{56}$Fe) and extremely relativistic degenerate electrons. At high densities a relativistic mean-field model for neutron matter (including some electrons and protons) is used. Then, the linear response to neutrinos is calculated using a relativistic RPA approximation. Because the astrophysical conditions can be relatively warm we have extended these calculations to finite temperatures using a real-time field theory formalism [28].

The plasma is interesting because all of the interactions are known. [There are QED interactions between the electrons and ions, while the neutrinos interact according to the Wienberg–Salam–Glashow model.] Since the interactions are under control, the system provides an excellent testing ground for relativistic many-body theory. In addition, because the QED coupling is weak, our relativistic RPA calculations should provide essentially exact answers.

We find that the Coulomb screening of weak neutral currents from other electrons reduces neutrino-electron cross sections and greatly reduces neutrino-nucleus elastic scattering. These reductions may have an important impact on neutrino transport in supernovas.

Our plasma results have been published in *Physical Review Letters* [29]. Results for neutral-current neutrino scattering from neutron matter at zero [30] and finite-temperature [28] have been accepted for publication.

3.5 Quark Models of Nuclear Matter

[Horowitz, Melendez, E. D. Cooper (Ohio State), J. Piekarewicz (Florida State), and S. Gardner (CEBAF)]

We are performing a number of Monte Carlo simulations for a quark model of nuclear matter. The model confines quarks into hadrons, allows the hadrons to separate and is symmetric in all of the quark coordinates. Various ground state properties such as the energy and quark correlation function have now been calculated in both one and three dimensions.

The goals of these simulations are threefold. The first is to examine the role of nucleon substructure in nuclear physics. For example, how do hadronic properties such as the nucleon form factor depend on density? Can we find observables that are sensitive to the nucleon substructure?

Second, we are searching for qualitatively new modes of excitation that are not present in either single hadrons or hadronic models of nuclear matter. Conceivably, there could be a "quark giant resonance" involving the collective excitation of quarks from many hadrons. We are calculating the properties of collective modes using a Feynman variational ansatz.

Finally, these calculations are the first step towards developing a "realistic" quark model of nuclear matter. This model will fit both the nucleon spectrum and form factors and the NN phase shifts.

A number of results for the energy, wave function, cluster properties, quark correlation function etc. have now been published for simulations in both one [31] and three dimensions [32]. These results are currently being extended in several directions. First, a more realistic treatment of the color dependence of the force is being developed. Second we are calculating how the many body system will screen external color forces. For example, the potential between the charmed quark and antiquark of a J/Psi meson is being calculated as a function of density. This is directly useful for studies of J/Psi suppression.

Finally, we are preforming molecular dynamics simulations of a classical approximation to our quark model. This will allow a direct determination of the full response function of the system to an electromagnetic probe as a function of excitation energy and momentum transfer. This is interesting because the response contains many different kinds of modes such as nuclear giant resonances, nucleon quasielastic scattering, hadronic excitations (such as the nucleon to delta) and deep inelastic scattering. We will then study how these nucleon like and quark like modes change and mix with increasing density. We may gain insight into when a virtual photon (at CEBAF) couples to a single quark or to a "complete hadron".

3.6 Physics of the Quark-Gluon Plasma and Ultrarelativistic Nucleus-Nucleus Collisions

[Matsui, Roh]

According to the modern theories of the strong interaction based on Quantum Chromodynamics (QCD), hadrons are expected to lose their identity at sufficiently high temperatures and/or at high baryon densities and melt into a uniform matter consisting of their basic constituents: the *quark-gluon plasma*. Understanding the properties of this extreme state of matter and the nature of the transition are among the outstanding problems of modern physics. It is widely believed that the transition from the quark-gluon plasma to the dilute hadron gas occurred at a certain early stage of the evolution of the universe, as early as several microseconds after the big-bang singularity when the temperature of the universe reached the hadronic scale of the order of 100 MeV.

It is expected that similar extreme physical conditions can be created temporarily in the laboratory by very energetic nucleus-nucleus collisions over an extended space-time region. This line of experimental research programs has already started at Brookhaven and CERN with light ions at modestly high energies and is expected to reach its maturity with the relativistic heavy ion collider (RHIC) which is now being constructed at Brookhaven. The interpretation of the outcomes of these experiments and the identification of the signals of new physics are among the greatest challenges for contemporary nuclear theory.

There are a number of important physics issues to be studied theoretically, such as: the energy-deposition mechanism; kinetics of pre-equilibrium evolution of matter; manifestation of collective plasma behavior (dynamical screening and collective plasma oscillation) in the deconfining plasma phase; hadronization mechanisms; dynamical aspects of possible phase transition(s) (nucleation/phase separation or critical fluctuations); hydrodynamic collective flow; chemical reactions in expanding matter; freeze-out kinetics etc. Our research objectives are to deepen physical understanding of each aspect of these rather broad physics issues, to synthesize it into a coherent and realistic description of the complex reaction process, and to make reliable and useful predictions for various observables which can be tested experimentally. In the following we discuss three specific topics which we plan to study on this program.

Flux-Tube Model for Ultrarelativistic Nucleus-Nucleus Collisions

This model has been proposed [33] to describe the high energy nuclear collision process based on the Low-Nussinov picture of hadronic interactions.[34] In this reaction picture it is assumed that high energy nuclear collisions lead to formation of a strong color field due to random color exchange between two colliding nuclei. The decay of such a strong color field due to the Schwinger mechanism (pair creation in external background field) [35] and the subsequent formation and evolution of a quark-gluon plasma has been described in terms of generalized relativistic Boltzmann-Vlasov kinetic theory.[36,37] In the previous works we focused on the baryon-free central rapidity region employing the symmetry of Lorentz-boost invariance along the collision axis, and we have studied various problems in this model such as transverse expansion of the plasma [37], hadronization mechanism [38], spontaneous excitation of collective plasma oscillation and dilepton production.[39]

There are still many important problems remaining to be examined in this direction. Here are some of the outstanding ones:

a. Inclusion of nuclear fragmentation regions.

b. Fluctuation in the color field.

c. Quantum kinetic theory for spontaneous pair creation.

The first problem requires implementation of the correct boundary conditions at the longitudinal edges of the system, removing the simplifying assumption of Lorentz boost symmetry, and incorporations of baryon-number conservation. These are relatively straightforward extensions of the earlier works although it requires considerablly more extensive numerical labor to carry out the computation in realistic three-dimensional geometry. Less understood is the extent of the initial fluctuations in the color field due to random color exchange process and its impact on the later evolution of the system. This problem is relevant to achieving an understanding of (large) observed non-statistical fluctuations, in the transverse energy distribution in nuclear collisions.[40] The microscopic derivation of a kinetic equation with spontaneous pair creation from a background field is a difficult and still-unsolved problem. In our previous studies, we have used a semiclassical kinetic equation with a particle source term which has been constructed by transcribing Schwinger's result for uniform constant electric field in the spirit of the Thomas-Fermi approximation. Our recent study of non-equilibrium dilepton production [39] showed that dilepton spectrum in the intermediate mass region ($1 < M < 3$ GeV) is sensitive to the form of the particle source term, indicating the importance of a better understanding of the particle production mechanism. There has been progress by others in extending Schwinger's result to include finite-size effects [41] and in formulating and solving the pair-creation problem as a initial value problem in quantum mechanics [42]. We plan to continue to work on this problem in light of these new insights.

Charmonium Suppression by the Quark-Gluon Plasma Formation

One of the proposed signals of quark-gluon plasma formation is a suppression of charmonium production due to plasma screening of the $c\bar{c}$ binding force.[43] This predicted effect has been observed by one of the first experiments at SPS (NA38 collaboration) [44] and their data has been interpreted successfully by us [45] and others [46] in terms of a simple semiclassical model of the charmonium formation taking into account finite space-time extension of the plasma produced in the collision. Encouraged with qualitative success of such interpretations, further theoretical work has been directed toward refining theoretical understanding of the plasma suppression mechanism. This includes the study of the dynamic screening for the $c\bar{c}$ pair traversing the plasma medium [47] and the fully quantum-mechanical formulation of charmonium formation and of the suppression problem.[48] These more detailed studies reveal, however, that some prominent features, such as strong p_T dependence and threshold effects, once thought of as characteristic of plasma suppression in contrast to various other non-plasma suppression mechanisms [49], are weakened considerably. More realistic calculations are now underway in order to make a more quantitative prediction for the J/ψ suppression by plasma formation by incorporating the various plasma effects such as dynamic screening [47] and energy loss of $Q\bar{Q}$ pair in the plasma.[50]

Strangeness Production and Freeze-out Kinetics

Particle composition is a potentially very important probe of the matter produced in the collision. Although enhanced strangeness production was originally proposed as a characteristic signal of the early quark-gluon plasma phase [51], later dynamical studies [52] showed that the strangeness content of the final particle composition may be very sensitive to the later evolution of the system, especially at the hadronization and freeze-out stages. All previous estimates of these effects relied, however, on rather simplifying description of matter expansion based on Bjorken's one-dimensional scaling solution [53] which is adequate, at best, only for the very early stages of expansion. We propose to refine previous calculations by more realistic treatment of the expansion dynamics and the chemical kinetics at the freeze-out stage. Work along this line is now in progress based on the vector meson dominance model for hadronic rate equations [54]

3.7 Nucleon Propagation in Nuclear Matter

[David Griegel, T. Cohen (Univ. Maryland), R. Furnstahl (Ohio State Univ.)]

One of the fundamental interests in nuclear physics today is the medium modification of hadronic properties. The key issue is the extent to which the substructure of the hadrons is influenced by the presence of the nuclear medium. It is possible that the effective masses, sizes, and coupling constants of hadrons in the nuclear medium differ significantly from the corresponding free-space values. The theoretical exploration of these possibilities is of increasing importance, given that one of the dominant experimental goals of the next decade is the study of matter under extreme conditions of temperature and density at RHIC.

Previous studies suggest that the medium-modification of hadronic properties could explain numerous phenomenological puzzles. For example, the reduction of the vector meson masses in the nuclear medium could possibly explain "anomalies" in K^+-nucleus scattering data [55], the suppression of the electromagnetic longitudinal response functions in electron-scattering experiments [56], and the enhancement of the ρNN tensor coupling in the nuclear medium [57]. Although these studies are somewhat schematic, they do suggest that the study of medium modifications is potentially fruitful.

We base our study of in-medium hadronic properties on QCD sum rules. In free space, QCD sum rules have provided a useful framework on which to study the spectral properties of hadrons [58]. We have extended these sum rules to finite density in order to study the propagation of nucleons in the nuclear medium [59]. Other researchers have used in-medium QCD sum rules to study the effective masses of vector mesons in the nuclear medium [60], and aspects of nuclear-structure physics such as nuclear matter saturation [61] and the Nolen–Schiffer anomaly [62].

The properties of hadrons are determined by the properties of the medium in which they propagate, whether it is the vacuum or nuclear matter. The fundamental physical assumption of the QCD sum-rule approach is that the spectral properties of hadrons (e.g., masses and self-energies) are primarily determined by a few coarse properties of the ground state of this medium, which, at the simplest level, can be parameterized by the non-perturbative quark and gluon condensates, $\langle\overline{q}q\rangle$ and $\langle(\alpha_s/\pi)G^a_{\mu\nu}G^{a\mu\nu}\rangle$. Thus

QCD sum-rule techniques are used to relate the spectral properties of hadrons to the quark and gluon condensates.

In the QCD sum rules, one studies the hadron corresponding to the lowest-mass state with a given set of quantum numbers. One then considers a time-ordered correlation function of interpolating fields, built from quark fields, that carry these quantum numbers. By applying an operator product expansion (OPE) for large spacelike momentum transfer, the correlator can be expressed as a sum of coefficient functions, calculated in QCD perturbation theory, that multiply expectation values of composite operators. These expectation values are the non-perturbative quark and gluon condensates. On the other hand, a spectral decompostion shows that the corrlator describes the propagation of the lowest-mass state in the spectrum as well as higher-mass states with the same quantum numbers. QCD sum rules equate these two representations of the correlator; then, after assuming a simple phenomenological ansatz for the spectral density, spectral parameters of low-lying resonances can be extracted in terms of QCD Lagrangian parameters and the condensates. A Borel transform improves the overlap of the two descriptions: on the QCD side, it improves the convergence of the OPE by suppressing the contributions of higher-dimensional operators, while on the phenomenological side, it emphasizes the contribution from the lowest-mass state.

The application of QCD sum rules to the study of hadrons in the nuclear medium depends on knowledge of the in-medium quark and gluon condensates, and this issue must be addressed first. Given the in-medium condensates, we use QCD sum rules to relate changes in these condensates at finite nucleon density to the in-medium spectral properties of nucleons.

In-medium quark and gluon condensates

The in-medium quark condensate can be calculated in a model-independent manner up to first order in the nucleon density. The calculation is based on an application of the Hellmann–Feynman theorem. One finds that the in-medium quark condensate at nuclear matter saturation density is roughly 25–50% smaller than the vacuum value, with the scale of the change being set by the nucleon σ term. It is important to study corrections from terms that are of higher order in the nucleon density. Estimates of these corrections based on simple models suggest that the corrections are numerically small [63]. In general, the higher-order corrections depend on the quark-mass derivative of the nuclear matter interaction energy density; thus an accurate determination of these corrections depends not only on a realistic model of nuclear matter, but on knowledge of the quark-mass derivatives of all hadronic masses, couplings, form factors, etc. It is possible that estimates of some of these quark-mass derivatives can be obtained from QCD sum rules, given an estimate of the quark-mass derivatives of the quark and gluon condensates. We intend to pursue this matter further (see below).

The in-medium gluon condensate can be calculated from the trace anomaly. As with the quark condensate, the in-medium gluon condensate can be determined in a model-independent manner up to first order in the nucleon density. We find only a modest change in the gluon condensate at nuclear matter saturation density; thus corrections from terms that are of higher order in the nucleon density are not of great concern [63]. Nevertheless, we intend to study the in-medium gluon condensate further: We intend to study the effects of higher-order α_s contributions to the trace anomaly. There are also questions concerning the renormalization-group invariance of the gluon condensate that we intend to pursue.

Other questions regarding in-medium condensates that we intend to study are the density dependence of higher-dimensional condensates and non-local condensates. In free space, higher-dimensional condensates are parameterized in terms of the simple quark and gluon condensates through the vacuum saturation hypothesis, which is justified in the vacuum by large-N_c QCD arguments (where N_c is the number of quark colors). Non-local condensates are expanded in terms of local condensates. It is not obvious that these approximations are reliable in the nuclear medium.

Nucleon self-energies from QCD sum rules

In relativistic treatments of nuclear physics, nucleon propagation in the nuclear medium is described by a Dirac equation with an optical potential featuring large (several-hundred MeV) and cancelling Lorentz scalar and vector components. These optical potentials are equivalent to the in-medium nucleon self-enegies. In the Dirac phenomenology of proton-nucleus scattering, these self-energies are determined so as to fit empirical free-space p-p and p-n scattering amplitudes. In studies of nuclear matter saturation with quantum hadrodynamics (QHD), the nucleon self-energies are determined so as to fit saturation properties such as the saturation density and binding energy. It is obviously desirable to have a QCD-based estimate of these self-energies. In a preliminary calculation, we have used QCD sum rules to study the properties of nucleons in nuclear matter. From these studies, we have shown how large scalar and vector self-energies arise naturally in QCD due to changes in the scalar and vector quark condensates, $\langle\bar{q}q\rangle$ and $\langle q^{\dagger}q\rangle$, in nuclear matter. The self-energies obtained are similar in magnitude to the self-energies of Dirac phenomenology and QHD. In addition, the scalar and vector self-energies obtained demonstrate a significant degree of cancellation, which is another essential ingredient of relativistic nuclear physics. The degree of cancellation is sensitive to the ratio of the nucleon σ term to the sum of the up and down current quark masses [59].

There are many refinements to our initial calculations that we have started to investigate. They include:

- The inclusion of higher-dimensional condensates in the OPE correlator.

- Further investigation of the in-medium dispersion relation used to relate the phenomenological spectrum to the phenomenological correlator.

- The inclusion of continuum contributions to the phenomenological correlator.

QCD sum-rule studies of the nucleon σ term

The nucleon σ term gives a measure of the change in the quark condensate relative to the vacuum value within a nucleon. It can be defined by

$$\sigma_N = \left(\frac{m_u + m_d}{2}\right) \int d^3x \, (\langle N|\bar{u}u + \bar{d}d|N\rangle - \langle \text{vac}|\bar{u}u + \bar{d}d|\text{vac}\rangle \ ,$$

where u and d are the up and down quark fields with current quark masses m_u and m_d. The σ term can be extracted from π-N scattering; its value is about 45 MeV with an uncertainty of 7–10 MeV [64]. The σ term is particularly relevant to our studies since it sets the scale for the change in the quark condensate in the nuclear medium. Our preliminary finite-density QCD sum-rule calculations [59] suggest that the degree of cancellation of the scalar and vector nucleon self-energies is set by the ratio of the σ term to the sum of the up and down current quark masses. Thus an investigation of the σ term in the context of QCD sum rules might possibly give a clearer understanding of the cancellation of the scalar and vector potentials in relativistic nuclear physics.

We have recently begun such an analysis of the σ term. This analysis is based on the Hellmann–Feynman theorem, which, in this case, is used to relate the σ term to the quark-mass derivative of the nucleon mass. From QCD sum rules and other phenomenological models, we believe that the scale of the nucleon mass is set by the quark condensate. Using QCD sum rules, one thus obtains an expression for the σ term that depends on the quark condensate and its derivative with respect to the current quark mass. The latter can be related to the chiral σ meson propagator through PCAC; however, the determination of the σ propagator is model dependent. We have recently begun an investigation that will consider a number of different models in order to determine the "strength" of this model dependence and to determine whether reliable results can be obtained.

Depending on the success of our determination of the σ term, we hope to extend these techniques to determine the quark-mass derivatives of other hadron masses. Such derivatives can then be used to improve our understanding of the in-medium quark condensate, as discussed above.

3.8 Non-relativistic Theory of Nucleon-Nucleus Reactions

The Nuclear Spin Response in Extended RPA Theories

[M.H. Macfarlane, W. Unkelbach, J. Wambach (Univ. Illinois), J. Speth (KFA Jülich, Germany)]

The study of the spin-isospin response of nuclei has been an area of intense interest, both, theoretically and experimentally. The major issues are:

1) the existence of spin resonances excited at forward scattering angles and small energy loss

2) the relative enhancement of the spin response in the nuclear continuum

3) the spin–longitudinal collectivity in the quasielastic region.

The latter is related to the enhancement of the virtual pion field in the nucleus. This can be of great importance in the interpretation of the EMC-effect and recent Drell-Yan measurements of the quark sea in the nuclear medium. Theoretically, the main uncertainty is the role of the short–range nucleon correlations in screening the pion field. In a somewhat simplified fashion, such screening effects are summarized by the Fermi liquid parameter g'.

Inelastic hadron–nucleus scattering is an appropriate tool for such studies. Energy and momentum loss can be transferred independently to the nucleus. The scattering process is sensitive to collective excitations. Spin–longitudinal as well as spin–transverse transitions are excited, whereas electron and pion scattering are sensitive only to spin–transverse excitations of the nucleus.

The isoscalar electric resonances have been studied intensively from the early 70's by inelastic α–scattering at incident energies between 100 MeV and 200 MeV. Spin–isospin excitations as the Gamov–Teller resonance have been measured in (p,n) and (n,p) reactions. Also in the (p,p') reaction, spin resonances are excited at higher momentum transfer q, which have not yet been thoroughly studied. The cross sections are dominated by ΔS=0 transitions because of the weak S=1–component of the projectile–target interaction.

The availability of polarized proton beams, coupled with scattered particle detection by magnetic spectrometers and polarization analysis with focal plane polarimeters has resulted in measurements of the spin–transfer coefficients $D_{ij'}$, giving detailed information on the momentum–spin correlations. Such experiments can be performed at IUCF. To single out ΔS=1 transitions, we concentrate on the spin–flip probability

$S_{nn'}$, determined by measuring the normal–component spin–transfer coefficient $D_{nn'}$ ($S_{nn'} = 1/2(1 - D_{nn'})$). The further determination of $D_{ll'}$ and $D_{ss'}$ (longitudinal and sideways spin–transfer coefficients) allow the investigation of the longitudinal and transverse spin–flip probabilities S_L and S_T, respectively. So spin–longitudinal and spin–transverse excitations, related to the π and ρ exchange, respectively, can be studied.

Measurements are now available over a large range of excitation energies and a variety of targets, stimulating considerable theoretical interest. We have calculated (p,p') cross sections and spin observables for several nuclei from ^{12}C to ^{208}Pb at incident proton energies between 200 MeV and 800 MeV and energy loss up to 50 MeV in the forward direction [65]. In this kinematical region, collective modes are predominantely excited, and one begins to see the onset of quasielastic scattering. We had a close collaboration with J. Lisantti and E. Stephenson at IUCF, who have performed $(\vec{p}, \vec{p}')$ measurements on ^{208}Pb using a 200 MeV polarized proton beam [66].

In our calculations the nuclear structure has been described in terms of the Random Phase Approximation RPA using a $\pi + \rho$ exchange force as residual interaction, taking into account the 2p2h–damping in an approximate way [67]. The reaction part is based on the DWIA, assuming a single scattering process.

The double differential cross sections $d^2\sigma/d\Omega dE'$ are dominated by the Isoscalar Giant Quadrupole Resonance. The spin–flip probablities $S_{nn'}$ are generally increasing with excitation energy ω. This is due to the exhaustion of ΔS=0 strength in the giant resonance region. At energies ω above these resonances, spin resonances lead to an enhancement of $S_{nn'}$. For ^{40}Ca a spin–dipole resonance has been identified experimentally by a multipole decomposition as a broad resonance structure around ω=25 MeV [68] and has been verified in our calculation [65]. The spin–dipole resonance consists of $1\hbar\omega$ transitions, pushed up in energy by the repulsive residual interaction in the vector–isovector channel. Spin resonances of higher multipolarity (spin–quadrupole etc.) can also be seen in our calculations. They are responsible for the enhancement of $S_{nn'}$ at higher excitation energies ω.

A more detailed analysis of the spin resonances for different nuclei, different momentum transfers q and with different probes (e.g. deuterons to get an isospin decomposition) is important to get a better understanding of the role of short range correlations and the modified $\pi + \rho$ exchange in the nuclear medium. To study these effects also a collaboration with E. Stephenson from IUCF has started, who has measured a complete set of D_{ij}'s as well as double differential cross sections for stretched 4^- states in ^{16}O with 200 MeV polarized protons.

A comparison with Plane Wave calculations shows that $S_{nn'}$ is sensitive on distortions. This came out as surprise as the main effect of distortions lies in absorption due to the imaginary part of the central optical potential, which should not affect spin observables. Further investigations have shown that spin–orbit distortions are mainly responsible for this effect. This becomes even more obvious by looking to S_L and S_T. The ratio S_L/S_T is increased by more than a factor of 2 after inclusion of distortions. This is theoretically not well understood yet. Calculations are in progress in concert with experimental studies by C. Glashausser (Rutgers). There are, so far, no indications for an enhanced pion field in the nucleus. Important information about this can also be obtained by a comparison with the $(\bar{p}, \bar{p}')$ reaction, which is much more sensitive to spin–longitudinal excitations due to the strong absorption and the longer range of the longitudinally coupled π–meson. Some work on this has started using different versions of the Bonn-Jülich $N\bar{N}$ potential [65].

At incident energies above 300 MeV, pion production plays an important role for the NN interaction. The Bonn–Jülich group is working on an extension of the Bonn potential for energies above the pion threshold. The influence of pion production on nuclear reactions should be studied.

For the proposed projects a close collaboration with experimentalists at IUCF and with the nuclear theory group at the Forschungszentrum Jülich is of great importance.

A review article [69] on the spin-flip and orbital components of the M1 giant resonance, as revealed by inelastic proton and electron scattering across the periodic table, has been accepted for publication.

Microscopic Theory of Nucleon-Nucleus Reactions

[M. H. Macfarlane, J. T. Londergan (IUNTC), R. Mehrem (IUNTC), G. E. Walker (IUNTC)]

Microscopic studies of $(N, N'\pi)$ reactions on light nuclei using DWIA (distorted-wave impulse approximation) lead to numerical integrals involving three or more oscillatory functions. Similar integrals enter the calculations of near-threshold pion production discovered in Section 3.3, above. Identities for such integrals, involving sums over angular-momentum coupling coefficients have been derived, and [70] shown to lead to fast and stable quadrature methods, always competitive with and sometimes superior to alternative methods.

4. References

1. B. D. Serot and J. D. Walecka, "The Relativistic Nuclear Many-Body Problem," Adv. Nucl. Phys. **16**, J. W. Negele and E. Vogt, eds. (Plenum, New York, 1986).
2. R. J. Furnstahl and C. J. Horowitz, Nucl. Phys. **A485** (1988) 632.
3. K. Lim and C. J. Horowitz, Nucl. Phys. **A501** (1989) 729.
4. K. Lim, Ph. D. thesis, Indiana University, 1990.
5. M. P. Allendes, IU/NTC preprint 91–09, submitted to Journal of Physics G.
6. J. Milana, Phys. Rev. **C 44** 527 (1991).
7. G. Baym and L. P. Kadanoff, Phys. Rev. **124** (1961) 287.
8. G. Baym, Phys. Rev. **127** (1962) 1391.
9. J. W. Durso, A. D. Jackson, and B. J. Verwest, Nucl. Phys. **A345** (1980) 471.
10. W. Lin and B. D. Serot, Nucl. Phys. **A512** (1990) 637.
11. W. Lin and B. D. Serot, Phys. Lett. **233B** (1989) 23.
12. B. D. Serot and J. D. Walecka, Proc. Seventh Int'l. Conf. on Recent Progress in Many-Body Theories, C. Campbell and E. Krotscheck, eds. (Plenum, New York, 1991), in press.
13. N. Weiss, Phys. Rev. **D27** (1983) 899.
14. T. Matsui and B. D. Serot, Ann. Phys. (N.Y.) **144** (1982) 107.
15. K. Wehrberger, R. Wittman, and B. D. Serot, Phys. Rev. **C42** (1990) 2680.
16. W. Lin and B. D. Serot, Nucl. Phys. **A524** (1991) 601.
17. R. J. Furnstahl and B. D. Serot, Phys. Rev. **C43** (1991) 105.
18. R. J. Furnstahl and B. D. Serot, Phys. Rev. **C44** (1991), in press.
19. R. J. Furnstahl and B. D. Serot, Phys. Rev. **C41** (1990) 262.
20. C. J. Horowitz and P. Blunden, Phys. Lett. **B240** (1990) 6.
21. C. J. Horowitz and J. Piekarewicz, Phys. Rev. Lett. **62** (1989) 391.
22. C. J. Horowitz and J. Piekarewicz, Nucl. Phys. **A511** (1990) 461.
23. C. J. Horowitz, Phys. Lett **B208** (1988) 8.
24. C. J. Horowitz, Proceedings of Dronten Summer School on "The Structure of Hadrons and Hadronic Matter", Dronten, Netherlands, to be published, 1991.

25. C. J. Horowitz and D. P. Murdock, Phys. Rev. **C37** (1988) 2032.

26. C. J. Horowitz and J. Piekarewicz, in preparation.

27. C. J. Horowitz and H. O. Meyer et al, submitted to Phys. Rev. C, 1991.

28. C. J. Horowitz and K. Wehrberger, Phys. Lett. **B266** (1991) 236.

29. C. J. Horowitz and K. Wehrberger, Phys. Rev. Lett. **66** (1991) 272.

30. C. J. Horowitz and K. Wehrberger, Nucl. Phys. A, in press 1991.

31. C. J. Horowitz and J. Piekarewicz, Phys. Rev. C, in press 1991.

32. C. J. Horowitz and J. Piekarewicz, Nucl. Phys. A, in press 1991.

33. A. K. Kerman, T. Matsui and B. Svetitsky, Phys. Rev. Lett. **20** (1986) 219; similar models have been discussed earlier by others, e.g. H. Etamo, J. Lindfors and L. McLerran, Z. Phys. **C18** (1983) 341; T. S. Biro, H. B. Nielsen and J. Knoll, Nucl. Phys. **B245** (1984) 449; A. Bialas and W. Czyz, Phys. Rev. **D31** (1985) 198.

34. F. Low, Phys. Rev. **D12** (1975) 1286; S. Nussinov, Phys. Rev. Lett. **34** (1975) 1286.

35. J. Schwinger, Phys. Rev. **82** (1951) 664; A. Casher, H. Neuberger and S. Nussinov, Phys. Rev. **D20** (1979) 179.

36. K. Kajantie and T. Matsui, Phys. Lett. **164B** (1985) 373.

37. G. Gatoff, A. Kerman and T. Matsui, Phys. Rev. **D36** (1987) 114.

38. M. Kataja and T. Matsui, Ann. Phys. **191** (1989) 383.

39. M. Asakawa and T. Matsui Phys. Rev. **D43** (1991) 2871.

40. G. Baym, G. Friedman and I. Sarcevic, Phys. Lett. **219B** (1989) 205.

41. C. Martin and D. Vautherin, Phys. Rev. **D38** (1988) 3593.

42. Y. Kluger, J. M. Eizenberg, B. Svetitsky, F. Cooper and E. Mottola, Phys. Rev. Lett. **67** (1991) 2427; I. Bialynicki-Birula, P. Górnicki and J. Rafelski, Phys. Rev. **D44** (1991) 1825.

43. T. Matsui and H. Satz, Phys. Lett. **178B** (1986) 416.

44. A. Bussier *et al.* (NA38 collaboration), Z. Phys. **C38** (1988) 129; L. Kluberg, Nucl. Phys. **A488** (1988) 613c; J. Grossiord, Nucl. Phys. **A498** (1989) 249c; C. Baglin et al., Phys. Lett. **B220** (1989) 471.

45. M.-C. Chu and T. Matsui, Phys. Rev. **D37** (1988) 1851.

46. F. Karsch and R. Petronzio, Phys. Lett. **193B** (1987) 105; J. P. Blaizot and J. Y. Ollitrault, Phys. Lett. **199B** (1987) 499.

47. M.-C. Chu and T. Matsui, Phys. Rev. **D39** (1989) 1892.

48. T. Matsui, Ann. Phys. **196** (1989) 182.

49. S. Gavin and M. Gyulassy, Phys. Lett. **B214** (1988) 241; J. Hüfner, Y. Kurihara and H. J. Pirner, Phys. Lett. **215B** (1988) 218; J.-P. Blaizot and J.-Y. Ollitrault, Phys. Rev. **D39** (1989) 232.

50. Y. Koike and T. Matsui, Indiana University preprint IU/NTC 91-17 (1991).

51. J. Rafelski and R. Hagedorn, in *Thermodynamics of Quarks and Gluons*, ed. H. Satz (North-Holland, Amsterdam, 1981)

52. T. Matsui, L. D. McLerran and B. Svetitsky, Phys. Rev. **D34** (1986) 783; 2047; J. Kapusta and A. Mekjian, Phys. Rev. **D33** (1986) 1304; P. Koch B. Müller and J. Rafelski, Phys. Rep. **C142** (1986) 167.

53. J. D. Bjorken,Phys. Rev. **D27** (1983) 419.

54. T. Matsui and T. Otofuji, in progress.

55. G. E. Brown, C. B. Dover, P. B. Siegel, and W. Weise, Phys. Rev. Lett. **60**, 2723 (1988).

56. G. E. Brown and M. Rho, Phys. Lett. B **222**, 324 (1989).

57. G. E. Brown and M. Rho, Phys. Lett. B **237**, 3 (1990).

58. L. J. Reinders, H. R. Rubinstein, and S. Yazaki, Phys. Rep. **127**, 1 (1985).

59. T. D. Cohen, R. J. Furnstahl, and D. K. Griegel, Phys. Rev. Lett. **67**, 961 (1991).

60. T. Hatsuda and S. H. Lee, University of Washington Report No. INT91-00-02 (1991).

61. E. G. Drukarev and E. M. Levin, Nucl. Phys. **A511** (1990) 679 [Erratum: **A516** (1990) 715];

62. T. Hatsuda, H. Høgaasen, and M. Prakash, Phys. Rev. Lett. **66** (1991) 2851; C. Adami and G. E. Brown, Z. Phys. A **340** (1991) 93.

63. T. D. Cohen, R. J. Furnstahl, and D. K. Griegel, University of Maryland Report No. DOE/ER/40322-118 (to be published).

64. J. Gasser, H. Leutwyler, and M. E. Sainio, Phys. Lett. B **253**, 252 (1991).

65. W. Unkelbach, Ph.D thesis, University of Bonn, Jül.–Bericht 2477, 1991.

66. J. Lisantti et al., Phys. Rev **C44** (1991) R1233.

67. R. D. Smith and J. Wambach, Phys. Rev. **C38** (1988) 100.

68. F. T. Baker et al., Phys. Rev. **C40** (1989) 1847.

69. M. H. Macfarlane and J. Speth, Comments on Nuclear and Particle Physics, to be published, 1991.

70. R. E. Mehrem, J. T. Londergan and M. H. Macfarlane, J. Phys. **A24** (1991) 1435.

5. 1992–93 Budget

April 1, 1992 - March 31, 1993

Summer Salaries		
Macfarlane	\$74,793 × 0.225 =	\$16,828
Serot	\$68,106 × 0.225 =	\$15,324
Horowitz	\$53,000 × 0.225 =	\$11,925
Matsui	\$51,000 × 0.225 =	\$11,475
Visitors' Salaries		0
Other Visitors' Expenses		0
Research Associates	(1.25 × \$30,000/yr.)	\$37,500
Graduate Students	(5 × \$14,400/yr.)	\$72,000
Travel		\$8,354
Publications		\$3,500
Supplies and Equipment		\$5,504
Fringe Benefits		
Summer Salaries	(\$55,552 × 0.1488)	\$8,266
Postdocs	(\$37,500 × 0.2613)	\$9,799
Student Health Insurance	(5 × \$346)	\$1,730
Subtotal		\$202,205
Overhead	(\$202,205 × 0.49)	\$99,080
Student Fee Remissions	(\$2,343 × 5)	\$11,715
Total		\$313,000

6. Contributions During 1991

Publications

1. THE RELATIVISTIC IMPULSE APPROXIMATION
   C. J. Horowitz, D. P. Murdock, and Brian D. Serot
   Computational Nuclear Physics, S. E. Koonin, K. Langanke, J. Maruhn, and M. Zirnbauer, eds. (Springer, New York, 1991), p. 129.

2. PION-NUCLEON SCATTERING IN THE P_{33} CHANNEL IN THE LINEAR SIGMA MODEL
   Wei Lin and Brian D. Serot
   Nuclear Physics **A524** (1991) 601.

3. COVARIANT FEYNMAN RULES AT FINITE TEMPERATURE: APPLICATION TO NUCLEAR MATTER
   R. J. Furnstahl and Brian D. Serot
   Physical Review **C43** (1991) 105.

4. COVARIANT FEYNMAN RULES AT FINITE TEMPERATURE: TIME-PATH FORMULATION
   R. J. Furnstahl and Brian D. Serot
   Physical Review **C44** (1991) 2141.

5. NEUTRINO NEUTRAL CURRENT INTERACTIONS IN HOT DENSE MATTER
   C. J. Horowitz and K. Wehrberger
   Phys. Lett. **B266** (1991) 236.

6. NEUTRINO NEUTRAL CURRENT INTERACTIONS IN NUCLEAR MATTER
   C. J. Horowitz and K. Wehrberger
   Nucl. Phys. **A531** (1991).

7. INTEGRALS OF PRODUCTS OF SPHERICAL BESSEL FUNCTIONS
   R. E. Mehrem, J. T. Londergan and M. H. Macfarlane
   J. Phys. **A24** (1991) 1435.

8. NEUTRINO INTERACTIONS IN A DENSE PLASMA
   C. J. Horowitz and K. Wehrberger
   Phys. Rev. Lett. **66** (1991) 272.

Submitted or Accepted

1. Relativistic Effects on Spin Observables
   C. J. Horowitz
   Proc. Int'l. Conf. on Spin and Isospin in Nuclear Reactions, Telluride, CO, 1991.

2. Quark Models of Nuclear Matter: I. Basic Models and Ground State Properties
   C. J. Horowitz and J. Piekarewicz
   To be published in Nuclear Physics A, 1991.

3. Spatially Periodic Nuclear Matter Systems
   M. Allendes
   Submitted to Nuclear Physics A, 1991.

4. The Nuclear to Quark-Matter Transition in the String-Flip Model
   C. J. Horowitz and J. Piekarewicz
   Phys. Rev. C (1991) in press.

5. Relativistic Nuclear Many-Body Theory
   Brian D. Serot and John Dirk Walecka
   Proc. Seventh Int'l. Conf. on Recent Progress in Many-Body Theories, Minneapolis, MN (August 26–31, 1991), C. Campbell and E. Krotscheck, eds. (Plenum, New York, 1991), in press.

6. Proceedings of Dronten Summer School on 'The Structure of Hadrons and Hadronic Matter" Dronten, Netherlands
   C. J. Horowitz
   To be published in 1991.

7. Total Cross Section For $p+p \rightarrow p+p+\pi^o$ Close to Threshold
   C. J. Horowitz and H. O. Meyer et al.
   Submitted to Phys. Rev. C, 1991.

8. No Evidence For A CUSP in $pp \rightarrow pp\pi^o$ At The Thresholds For $pp \rightarrow d\pi^+$ And $pp \rightarrow pn\pi^+$
   C. J. Horowitz and H. O. Meyer et al.
   Contributed paper: XIII Int'l. Conf. on Few-Body Problems in Physics, Adelaide, Australia, to be held Jan. 1992.

9. Passage of High-Energy Partons Through a Quark-Gluon Plasma
Y. Koike and T. Matsui
Submitted to Phys. Rev. D, 1991.

10. The Nuclear M1 Response
M. H. Macfarlane and J. Speth
Accepted for publication in Comments on Nuclear and Particle Physics

Invited Talks at Conferences and Workshops

1. Relativistic Nuclear Many-Body Theory
B. D. Serot
Seventh International Conference on Recent Progress in Many-Body Theories, University of Minnesota, August 27, 1991.

2. Diagnosing collective plasma behaviors in superdense hadronic matter
T. Matsui
APS – Division of Nuclear Physics meeting, Michigan State University, Michigan, October, 1991.

3. Relativistic Effects on Spin Observables
C. J. Horowitz
International Conference on Spin and Isospin in Nuclear Reactions, Telluride, CO, March, 1991.

4. Microscopic Theory of the Nucleon-Nucleus Optical Potential
M. H. Macfarlane
Workshop on Nucleon-Nucleus Interactions, LAMPF, June 1991.

5. Relativistic Mean Field Theory
C. J. Horowitz
Lectures at Summer Nuclear Physics Institute, TRIUMF, Vancouver, Canada, July, 1991.

6. Microscopic Theories of Nuclear Reactions
M. H. Macfarlane
Lectures at Summer Nuclear Physics Institute, TRIUMF, Vancouver, Canada, July 1991.

7. Electromagnetic Currents in Meson Nuclear Models
C. J. Horowitz
The Nuclear Hamiltonian and Current Operator for the 1990's, Argonne, IL, August, 1991.

END

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