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THEORETICAL STUDIES IN MEDIUM-ENERGY NUCLEAR AND HADRONIC PHYSICS

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A Research Proposal to the US Department of Energy

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1. Statement of the Proposal

We request $1,251,693 to support research in theoretical nuclear physics at the Indiana University Nuclear Theory Center from April 1, 1993 to March 31, 1996: $415,854 for the first year, $403,409 for the second year, and $432,430 for the third year. This contract will support four senior faculty members (Horowitz, Macfarlane, Matsui, and Serot), one and a half postdoctoral research associates, and five graduate students. It will be a continuation of DOE contract DE–FG02–87ER40365, which provided $1,281,000 over the period June 1, 1987 to March 31, 1993. The annual budget for the last year of this contract was $280,000.

Over the past three years, DOE research support has resulted in 50 publications and 70 invited talks, of which 21 were invited papers at national and international conferences (Appendixes I and II). Highlights of this research are briefly described in Section 2. This work has dealt primarily with medium-energy nuclear physics, relativistic theories of nuclei and the nuclear response, the nuclear equation of state under extreme conditions, the dynamics of the quark-gluon plasma in relativistic heavy-ion collisions, and theories of the nucleon–nucleon force. The thrust of the proposed research is along similar lines, with an emphasis on providing theoretical support for the new generation of high-energy and high-precision accelerators involving electrons, hadrons, and heavy ions.

Detailed descriptions of the proposed research in these areas are given in Section 3. Our research program addresses both phenomenological issues in medium-energy nuclear physics and fundamental issues in nuclear many-body theory. Staff to be supported by the proposed DOE contract is listed in Section 4.

The proposed research should also be considered within the larger context of the Indiana University Nuclear Theory Center (IUNTC) and the Indiana University Cyclotron Facility (IUCF). As of September 1992, the IUNTC has six permanent faculty members: C. J. Horowitz, M. H. Macfarlane, T. Matsui, and B. D. Serot, supported at $280,000 per annum by DOE; and J. T. Londergan and G. E. Walker, supported at roughly $165,000 per annum by NSF. The IUNTC also receives approximately $120,000 per annum from the state of Indiana and $40,000 from Indiana University.

The current IUNTC staff is listed in Appendix III. Some of the research supported by the NSF grant is described in Appendix IV. The IUNTC and IUCF, with which it shares office space, together form a major center of nuclear physics research with a broad and varied research program.

In summary, we request support for theoretical nuclear physics research at the Indiana University Nuclear Theory Center to cover four faculty members, one and a half postdoctoral research associates, and five graduate students for three years at an average rate of roughly $104,000 per principal investigator per year. This figure is comparable to the support provided (per investigator) on other DOE contracts for nuclear theory groups of a size similar to ours. This request will allow us to continue research at approximately the current level. We believe the request for five graduate students and one and a half postdoctoral research associates is reasonable on the basis of past experience. At Indiana University we have been able to attract some of the best students (away from the high-energy or condensed-matter groups) into nuclear theory. The size and composition of the IUNTC, we believe, provides a stimulating environment for postdoctoral associates. We also request an additional $40,000 in the first year of the contract to continue our upgrade of computer equipment. This request is motivated and discussed further in the section on the proposed budget.

2. Highlights of Recent Research

2.1 Electroweak Interactions In Dense Matter

[C.J. Horowitz]

A long-term program at Indiana University in relativistic nuclear reaction theory has recently focused on electroweak interactions in dense matter. Applications have been made to neutrino interactions in astrophysics and to laboratory neutrino and parity-violating electron scattering.

Neutrinos interacting with a plasma of ions and relativistic electrons provides a nontrivial example of a relativistic many-body system where the interactions are presumed known (given by the standard Weinberg–Salam model). Studying this system may provide important insight for a relativistic description of nuclear matter. Furthermore, there are important applications in astrophysics, including neutrino transport in a supernova. (This is crucial to understanding the explosion.)

We calculated cross sections for a variety of neutrino neutral-current reactions using a relativistic random-phase approximation (RPA). For a dense plasma, relativistic RPA is essentially exact and has no free parameters. We find important mixing between weak and electromagnetic modes of excitation. For example, Thomas–Fermi screening provided by the dense electron gas may significantly reduce neutrino-nucleus elastic scattering cross sections.[1] (These large cross sections are important for neutrino trapping.) A neutrino can either couple directly to a nucleus or first excite an electron particle-hole pair, which then couples electromagnetically to the highly charged nucleus. These (and related) screening effects should be included in supernova simulations.

We also studied neutrino interactions in neutron matter at higher densities using a real-time quantum field theory formalism to include the effects of finite temperature.[2,3] Finally, we examined medium effects on nuclear de-excitation via neutrino pair production.[4] Here a nucleus can decay electromagnetically, virtually exciting the electron gas, which then produces a neutrino pair. Collective effects involving plasma oscillations of the electrons can enhance nuclear decay rates by a factor of 10^5 or more. This enhancement may be important in supernovae and in neutron star cooling.

We also applied our relativistic RPA formalism to calculate laboratory neutrino and parity-violating electron scattering. In principle, parity-violating quasielastic electron scattering can provide important information on strange quark matrix elements in the nucleon. However, we found significant complications from relativistic and nuclear structure effects.[5] Instead, quasielastic neutrino scattering can provide valuable strange quark information and we are performing calculations to optimize proposed neutrino scattering experiments.[6]

2.2 Hadron Properties from QCD Sum Rules

[D. Griegel, R. Furnstahl (Ohio State), T. Cohen and X. Jin (Maryland)]

A preliminary investigation of nucleon properties in nuclear matter using QCD sum rules[7] suggested that large and cancelling scalar and vector self-energies arise naturally due to changes in the scalar and vector quark condensates, $\langle \overline{q}q \rangle$ and $\langle q^{\dagger}q \rangle$, at finite density. These self-energies are in qualitative agreement with the scalar and vector optical potentials of relativistic nuclear physics. However, there were several simplifications made in this initial work. On the operator product expansion (OPE) side of the sum rule, only the most singular terms were retained; on the phenomenological side, only a single quasinucleon pole was considered. In the past year, these shortcomings have been addressed and, to a large extent, resolved.

We have calculated higher-order contributions to the OPE side of the sum rule, including condensates up to mass dimension six (the "four-quark" condensates).[8] The main challenge in this calculation is estimating the in-medium condensates. For example, the quark condensate $\langle \overline{q}q \rangle$ depends on the nucleon σ term, and the gluon condensate $\langle (gG)^2 \rangle$ depends on the σ term and the strangeness content of the nucleon. Other quark and gluon condensates depend on parton (quark, antiquark, and gluon) distribution functions in the nucleon that are measured in deep-inelastic scattering experiments. One of the mixed quark-gluon condensates depends on the leading-power correction to the Gross–Llewellyn-Smith sum rule. One of the most interesting aspects of this work is the diverse array of physics involved.

We have also extended the phenomenological side of the sum rule[9] to include not only a quasinucleon pole, but also the estimated contributions from higher-energy (continuum) states. The approach is based on the standard Lehmann representation used in many-body physics. One crucial difference between vacuum and finite-density sum-rule calculations is the lack of charge-conjugation invariance in the ground state. Thus the positive- and negative-energy nucleon poles are characteristically different. We have devised a way to suppress the contributions to the sum rule from the negative-energy quasinucleon "pole" along with the contributions from higher-energy states. The phenomenological side of the sum rule is therefore dominated by the contribution from the positive-energy quasinucleon pole.

With these improvements to the sum rules, we find that the qualitative features of our initial investigation indeed survive.[7] We also find that the self-energies predicted by the sum rules agree remarkably well with those from a phenomenological mean-field model.[10] The main difficulty is the sensitivity to the density dependence of some of the four-quark condensates. In order to obtain results that agree with well-known phenomenology, we must assume that the density dependence of the four-quark condensates is much weaker that that predicted by a naive factorization approximation.

2.3 Relativistic Many-Body Theory of Nuclei and Nuclear Matter

[M. P. Allendes, B. D. Serot, H. B. Tang, R. Furnstahl (Ohio State)]

Relativistic meson–baryon field theories ("quantum hadrodynamics" or QHD) have proven to be useful models of the nuclear many-body problem.[11] 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.

In a relativisitic quantum field theory, the vacuum is a dynamical object that responds to the presence of nucleons at finite density. Because existing QHD field theories are not asymptotically free, the construction of reliable approximations that include vacuum dynamics is a difficult (and unsolved) problem. We have recently studied a relativistic generalization of the random-phase approxmiation (RRPA), which includes vacuum loops. The renormalization of the RRPA is very intricate, since divergences occur at all orders in loops. Recently, K. Lim devised a nonperturbative numerical renormalization scheme that produced finite RRPA results for a theory of baryons and scalars;[12] this has now been extended by H. Tang to the Walecka model containing baryons and neutral scalar and vector mesons. We are currently evaluating the resulting finite RRPA energy using vertex functions calculated within the QHD framework, as described below.

Loop corrections in QHD also generate vertex modifications, which include the part of the hadronic structure that comes from virtual hadron loops. Although QCD in principle gives a complete description of nucleon structure, some part of the internal properties of the nucleon, particularly at large distances, must be equivalent to that provided by these virtual hadron loops. In fact, as pointed out recently by Milana,[13] in a theory with baryons and vector mesons, the proper vertex functions are highly damped at large spacelike momentum transfers 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 meson mass) and so should be calculable within the QHD framework.

Allendes and Serot recently computed the effects of these vertex corrections on the vacuum polarization in the vector meson propagator,[14] which was computed earlier for point-like vertices by Furnstahl and Horowitz.[15] As a first approximation, the off-shell vertex was replaced by its on-shell form at zero density, which has a simpler Dirac-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 $|q| \approx 5M$. 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 with the approximation discussed above. 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.

We have also studied how chiral symmetry manifests itself in hadronic field theories. W. Lin and Serot recently used the σ-model Lagrangian to construct a dynamical model of the mid-range NN attraction through explicit $\pi\pi$ rescattering.[16] The integrated strength of the resulting scalar-isoscalar interaction is large enough to account for nuclear binding. Moreover, the mid-range attraction arises in this framework even when the σ mass in the Lagrangian is large. A large chiral σ mass reduces the strength of the nonlinear scalar interactions that lead to unwanted strong many-body forces when one studies nuclear matter.

This calculation is relevant in light of recent work carried out by Furnstahl and Serot.[17] It was shown that although some chiral models with a linear realization of the symmetry can reproduce the saturation point of nuclear matter in the Hartree approximation, they fail *generically* to reproduce observed properties of finite nuclei. In fact, the linear chiral models are overconstrained, and the strong many-nucleon forces preclude a satisfactory description of spin-orbit splittings, the nuclear shell structure, charge densities, and surface energetics. These deficiencies imply that this implementation of chiral symmetry is incorrect.

When taken together with the work of Lin and Serot, these results suggest a different realization of chiral symmetry in hadronic theories of nuclear systems. Here one takes the scalar mass to be *large* to eliminate the unwanted nonlinearities and generates the mid-range attraction between nucleons *dynamically* through correlated two-pion exchange. This picture can be implemented with a nonlinear realization of the chiral symmetry, and at the mean-field level, the strong scalar-isoscalar two-pion exchange can be simulated by adding a low-mass "effective" scalar field coupled directly to the nucleons. Since the pion mean field vanishes, the resulting chiral mean-field theory looks just like the mean-field Walecka model, with a strong NN attraction mediated by the low-mass scalar and small many-nucleon forces. This approach provides 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.

It is also important to include charged vector mesons (like the ρ) in chiral models, as these are necessary for an accurate description of the NN interaction and electromagnetic interactions with nuclei. In a recent paper, Serot and Walecka[18] constructed a chirally invariant Lagrangian that contains nucleons, pions, omegas, and rhos using a Yang–Mills theory based on the local gauge symmetry $SU(2)_R \times SU(2)_L$. Predictions can now be made for various hadronic observables; for example, the decay width of the a_1 meson can be calculated in terms of parameters determined from other processes (such as ρ meson decay), and the theory can be enlarged to include electromagnetic interactions. This will allow us to compute hadronic electromagnetic vertices and anomalous moments in a model with both vector mesons and chiral symmetry.

2.4 Passage of High-Energy Partons through a Quark-Gluon Plasma

[T. Matsui, Y. Koike (Michigan State)]

The energy loss of a fast charged particle passing through matter is a classic problem in electrodynamics and of special importance in plasma physics, where the stopping power of the plasma is related to the dielectric properties of the plasma medium. The QCD analog of this familiar problem has attracted much attention recently with the hope that the distortion of various hard collision process in ultrarelativistic nucleus–nucleus collisions may be used as probes of the quark-gluon plasma produced by the collision. We studied the energy loss mechanism in the quark-gluon plasma in terms of semiclassical kinetic theory.[19] This method describes the plasma response to an external test charge in terms of the change in the one-body distribution function of plasma constituents and provides a physically intuitive result for the energy loss mechanism. Our stopping power formula for a single test charge derived by this method coincides with that obtained by different methods. We also calculated the distribution of the energy deposited by the parton in the quark-gluon plasma and extended the method to calculate the plasma stopping power for a color dipole ("proto-charmonium") passing through the plasma medium. It was found that although the dipole stopping power is expected to be suppressed due to the additional screening, it in fact *increases* as the size of the dipole grows and becomes comparable to the single-charge stopping power when the internal size of the dipole ($q\bar{q}$ pair) is large compared with the inverse momentum of the pair. The implication of our results on charmonium production in ultrarelativistic nucleus–nucleus collision requires a more dynamical treatment that takes into account the plasma expansion and the time evolution of the charmonium wave function in the plasma.

A review article on the signatures of the quark-gluon plasma was written.[20] It summarizes two dynamical pictures of ultrarelativistic nucleus–nucleus collisions based on relativistic hydrodynamics and gives a critical review of four proposed signatures of the quark-gluon plasma: the correlation between average transverse momentum and multiplicity, strangeness production, dilepton production, and J/ψ suppression. An extended version is now being prepared for publication in *Advances in Nuclear Physics*.

2.5 The Nuclear Spin and Isospin Response to Intermediate-Energy Nucleons

[M. H. Macfarlane, W. Unkelbach]

Hadronic reactions on nuclei at intermediate energies (100 MeV $\lesssim T \lesssim$ 1 GeV) have been a subject of intense studies in recent years. The inelastic scattering process is sensitive to collective effects in nuclei. These lead to enhanced or diminished cross sections as compared with single-particle-like transitions in a shell model. Energy and momentum are transferred independently to the nucleus. Different transitions are excited by different components of the interaction between projectile and target. The nucleus can be treated as a filter to study different components of the interaction, so we get an appropriate tool to study several aspects of nuclear structure and the effective projectile-target interaction.

In the region of small momentum transfer ($q \leq 1\,\mathrm{fm}^{-1}$) and small energy transfer ($\omega \leq 50\,\mathrm{MeV}$), the spectra are dominated by giant resonances of low multipolarity like the giant quadrupole resonance or the Gamow–Teller resonance. These resonances can be interpreted microscopically as a coherent superposition of particle-hole (ph) transitions in a shell model. The inclusion of 2p2h configurations leads to a damping of these transitions.

In our model, nuclear structure is described in terms of the Random-Phase Approximation (RPA) using a $\pi + \rho$ exchange force as the residual interaction, and taking into account the 2p2h damping in an approximate way.[21] The reaction part is based on the Distorted Wave Impulse Approximation (DWIA), assuming a single scattering process. Double differential cross sections as well as spin observables can be determined.

In the charge-exchange reactions (n,p) and (p,n), vector-isovector transitions are predominantly excited, due to the dominant component of the isovector part of the T matrix. Both reactions are complementary for nuclei with $T_0 \neq 0$. In the (n,p) case, only states with $T_f = T_0 + 1$ can be excited due to isospin conservation, so no Fermi transitions are induced. In the (p,n) reaction, final states with $T_f = T_0 - 1$, T_0, and $T_0 + 1$ can be excited, with $T_f = T_0 - 1$ dominating. At forward scattering angles, the spectra are dominated by the Gamow–Teller (GT) resonance and the Giant Spin Dipole Resonance (GSDR). In the (p,n) case, the scalar Isobaric Analog State (IAS) and the the Giant Dipole Resonance (GDR) also have to be considered.

In collaboration with the Svedberg Laboratory in Uppsala, the $^{54,56}\mathrm{Fe}(n,p)^{54,56}\mathrm{Mn}$ reaction at $T = 97\,\mathrm{MeV}$ has been studied.[22] For this calculation, multiple scattering processes have also been taken into account. RPA correlations reduce the GT strength compared with a simple shell model. For $^{54}\mathrm{Fe}$ a smaller amount of GT strength is found experimentally, which cannot be reproduced theoretically. The distribution of GT strength can be used to estimate electron capture rates, which are important for understanding the dynamics of supernovae. The spectra show a broad dipole resonance at around 12 MeV excitation energy. Theoretically the resonance peaks at lower energy, but the location is very sensitive to details in the single-particle space.

A reanalysis of the $^{90}\mathrm{Zr}(n,p)^{90}\mathrm{Y}$ data at $T = 65\,\mathrm{MeV}$ has been done in collaboration with F. P. Brady and J. L. Romero (UC Davis).[23] Multistep contributions are very important for these low energies, especially for higher excitation energies ($\omega > 20$ MeV). Evidence of the Isovector Monopole Resonance (IVMR) has been found. The GT transition for this reaction is strongly suppressed by Pauli blocking.

In collaboration with J. Rapaport (Ohio U.) and B. K. Park (New Mexico State), the $^{32}\mathrm{S}(n,p)^{32}\mathrm{P}$ reaction has been analyzed using a white neutron source with incident neutron energies between 60 MeV and 260 MeV.[24] The energy dependence of the GT resonance and the dipole resonances (GDR, GSDR) could thus be studied. The

GDR depends sensitively on the energy because the scalar component of the projectile-target interaction drops drastically with energy until it reaches a minimum at around 200 MeV, while the vector part remains almost constant.

In (p, n) reactions on nuclei with neutron excess, the GT resonance and the IAS peak at about the same excitation energy. They can be disentangled by measuring the spin transfer coefficient $D_{nn'}$, which is a sensitive probe of whether J^{π} for a given transition is of natural or unnatural parity. This allows the dipole resonance to be decomposed into its natural parity 1^- and the unnatural 0^- and 2^- components. It can also help to identify GT strength in the continuum. Double differential cross sections and $D_{nn'}$ values have been analyzed for the $(\vec{p}, \vec{n})$ reaction on ^{48}Ca and ^{208}Pb at $T = 135\,\mathrm{MeV}$ in collaboration with J. W. Watson (Kent State) and Y. Wang (IUCF).

In (p, p') reactions, spin resonances can also be excited. To extract them from the dominant scalar-isoscalar transitons due to the strong component of the T matrix, the spin-flip probability $S_{nn'} = 1/2(1 - D_{nn'})$ and the spin-flip cross section $\sigma S_{nn'}$ is considered. For ^{40}Ca, the spin-dipole resonance has been identified as a broad resonance at roughly 25 MeV. Spin resonances of higher multipolarity can also be found in the calculation. $S_{nn'}$ depends sensitively on the distortions, especially on spin-orbit distortions. The additional determination of $D_{ss'}$ and $D_{\ell\ell'}$ allows a decomposition of $S_{nn'}$ into spin-longitudinal and spin-transverse components S_L and S_T, corresponding to the π and ρ exchange force, respectively. At $q = 0.5\,\mathrm{fm}^{-1}$, the ratio S_L/S_T is increased by more than a factor of two by distortions. The spin-longitudinal response σS_L depends sensitively on the spin-orbit distortion, while the transverse response σS_T stays almost unchanged due to the different ranges of the π and ρ exchange.[25] These investigations are done in collaboration with C. Glashausser (Rutgers), F. T. Baker and W. G. Love (Georgia) and A. Green (LAMPF).

A paper published two years ago[26] with J. Speth (KFA Jülich) and C. Zawischa (Hanover) predicted a large concentration of M1 spin-flip strength at excitation energy of 5 to 10 MeV in heavy deformed nuclei. At that time no experimental data was available to check these predictions. Recent inelastic electron-scattering experiments at the Darmstadt Linear Electron Accelerator, as yet unpublished,[27] appear to confirm our prediction both for the location and the total strength of the spin-flip M1 excitation. A paper has been prepared on the current experimental and theoretical situation and on implications for the microscopoic structure of heavy deformed nuclei.[28]

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3. Detailed Description of Proposed Research

In this section of the proposal, we discuss work in our main areas of active research and plans for the future growing out of this work. Our focus is on nuclear physics at intermediate and high energies. The topics touched upon cover a wide range: from the nonrelativistic nuclear physics of nucleons, pions and deltas, through relativistic nuclear many-body physics involving hadronic degrees of freedom (QHD), to studies of the quark–gluon plasma and the role of the color degrees of freedom and the quark and gluon condensates in nuclear systems. We do not try to identify in any consistent way the role of each principal investigator; however, the contributions of external collaborators, research associates, and graduate students are identified explicitly. In general, the editorial "we" refers to the principal investigators. Citations are to the list of references at the end of this section.

3.1 Relativistic Many-Body Theory of Nuclei and Nuclear Matter

[M. P. Allendes, C. J. Horowitz, B. D. Serot, H. B. Tang, R. J. Furnstahl (Ohio State)]

A central goal of nuclear theory is to describe atomic nuclei in terms of their fundamental constituents. This goal is especially relevant now, in view of the new accelerators that will probe nuclei with high energies and high precision using electrons, hadrons, and heavy ions. These accelerators are expected to reveal new physics involving the properties of mesons inside nuclei, the nuclear matter phase diagram, the role of relativity, and the dynamics of the quantum vacuum. Moreover, we hope to learn not only about hadron dynamics but also about the role of explicit quark and gluon degrees of freedom.

Although the Schrödinger equation has been basically successful in describing nuclei at low energies, this framework must be extended if we are to compare calculations with the data of the future. A more complete treatment of hadronic systems should include relativistic nucleon motion, dynamical mesons and baryon resonances, modifications of the hadron structure in the nucleus, and the dynamics of the quantum vacuum, while respecting the general principles of quantum mechanics, Lorentz covariance, gauge invariance and microscopic causality. These physical effects will be relevant regardless of the degrees of freedom used to describe the system, and they must be studied simultaneously and consistently to draw definite conclusions about nuclear dynamics at high temperatures, high densities, and short distances.

In principle, quantum chromodynamics (QCD) should provide such a description, since QCD is believed to be the fundamental theory of the strong interaction. Nevertheless, QCD predictions at nuclear length scales with the precision of existing (and anticipated) data are not now available, and this state of affairs will probably persist for some time. Even if it becomes possible to use QCD to describe nuclei directly, this description is likely to be awkward, since quarks cluster into hadrons at low energies, and hadrons (not quarks or gluons) are the degrees of freedom actually observed in experiments.

Given the present inadequacy of both the Schrödinger equation and QCD for formulating an improved description of nuclear dynamics, we must consider alternatives. Since hadrons are the relevant experimental degrees of freedom, it is important to see if practical, reliable, and accurate hadronic descriptions can be developed for the energy, density, and temperature regimes obtainable with the new experimental facilities. A consistent hadronic approach to nuclear dynamics would place important constraints on the low-energy, large-distance behavior of QCD. Moreover, to discover essential manifestations of the quark and gluon degrees of freedom in nuclei, we must push hadronic descriptions to their limits and find clear-cut failures.

Relativistic meson–baryon 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. There is evidence from QCD sum rules[2] (as discussed below), that these large effects are dynamical consequences of the underlying chromodynamics. The initial successes of QHD have stimulated several new areas of investigation.

Renormalizable QHD models are characterized by a finite number of coupling constants and masses, so that consistent calculations can be carried out without introducing additional parameters (such as vertex cutoffs) determined solely by short-distance input. At present, renormalizable models provide the only known framework for performing relativistic calculations that respect the important general principles mentioned above. Nevertheless, since the quark-gluon structure of hadrons is important at short distances, a description solely in terms of hadrons must ultimately break down. QHD will still be useful if nuclear observables of interest are insensitive to short-distance contributions. One of our continuing goals is to test this strategy and uncover its limitations by performing calculations in a consistent, self-contained relativistic framework.

Relativistic Nuclear Structure Theory

The Walecka model of baryons interacting with σ, ω, and ρ mesons has been solved in the mean-field approximation for closed-shell (spherical) nuclei from ^{16}O to ^{208}Pb and gives a realistic description of bulk nuclear properties and the spin-orbit force.[3] Furthermore, the calculations yield Dirac wave functions, proton and neutron densities, and meson fields that have been used by a large number of researchers. For example, these calculations provide the scalar and baryon densities for most relativistic proton–nucleus elastic scattering calculations.[4] Recently, these relativistic nuclear-structure calculations have been extended to include nonlinear forces.[5,6,7] The subsequent application to deformed nuclei[5,8] and odd-A nuclei one with one particle added or removed from a closed shell are successful at a level that is comparable with nonrelativistic calculations based on the Skyrme force.[9]

Although these mean-field calculations provide a successful phenomenology, primarily because of the presence of strong Lorentz scalar and vector fields at typical nuclear densities, this approximation should be improved to provide a more complete and consistent relativistic description of nuclear structure. This will allow for the calculation of realistic relativistic nuclear wave functions that can be used in studies of elastic and inelastic electron and hadron scattering from nuclei. For example, at the energy and momentum transfers of roughly 1 GeV that will become available at CEBAF, it is essential to have a relativistic description of the nuclear wave functions.

It is therefore imperative to improve on existing relativistic calculations of nuclear structure. Practical, reliable techniques for going beyond the mean-field approximation must be developed. This will require us to understand the quantum field-theoretic structure of QHD. Moreover, few calculations have included a relativistic description of the pion dynamics, which is known to be important in nonrelativistic approaches. These issues motivate several studies that we intend to undertake.

The Role of the Quantum Vacuum

In a relativistic quantum field theory, the vacuum is a dynamical object that responds to the presence of nucleons at finite density. 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. Present technology allows for an essentially exact computation of finite nuclear ground states and currents at the one-loop level (sometimes called the "Relativistic Hartree Approximation" or RHA).[10–15] These calculations, together with random-phase approximation (RPA) studies of excited nuclear states,[16] imply that vacuum dynamics cannot be neglected in relativistic meson–baryon field theories, both because of the size of these effects and their importance in maintaining various conservation laws. However, the vacuum terms increase in strength at small distances because existing QHD field theories are not asymptotically free.

One consequence of this behavior is that including the vacuum effects using a straightforward loop expansion is not sufficient. This was demonstrated by Furnstahl, Perry, and Serot,[17] who carried out the first two-loop calculation for nuclear matter, including all vacuum-polarization effects. On the other hand, summing these loop contributions to all orders, which defines a relativistic extension of the RPA (usually called the RRPA), reveals a second consequence of the asymptotic "slavery" of QHD: new, unphysical 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.

The appearance of these new "ghost" poles has a dramatic effect on the collective response of nuclear matter. These poles also imply that the uniform ground state is unstable against short-wavelength perturbations, as shown by Furnstahl and Horowitz[18] (among others), and thus the RRPA energy density contains a large imaginary part.[19] Thus one facet of the development of the RRPA is to to determine the normal modes, such as zero sound, that are ***not*** sensitive to the unphysical poles. These modes are an important part of the low-energy excitation spectrum of nuclear matter. We have studied these modes quantitatively as a function of both density and wavelength.[20] The spectrum of these modes is far richer than previously thought and involves a subtle interplay between meson and nucleon–antinucleon degrees of freedom. We plan to continue work in this area.

A second facet of the RRPA program is to compute the energy density of nuclear matter at this level in a way that incorporates the vacuum effects more realistically. There are two distinct technical problems here. The first is that renormalization in the RRPA is very intricate, since divergences occur at all orders in loops. It is necessary to devise numerical renormalization procedures that not only produce finite results, but that also guarantee that the finite values are ***consistent*** with the renormalization conditions imposed on divergent subdiagrams, such as the meson polarization and baryon self-energy. To our knowledge, this had never been done in a nonperturbative approximation like the RRPA. Recently, K. Lim achieved this goal for a theory of baryons and scalars,[19] and this has now been extended by H. Tang to the Walecka model containing baryons and neutral scalar and vector mesons. (This work will form part of Mr. Tang's Ph. D. thesis.)

The second problem is that although the resulting expressions for the RRPA energy are finite, they still contain imaginary parts due to the ghost poles. Two techniques have so far been proposed for removing these poles to obtain realistic values for the nuclear matter energy within the framework of QHD. The first is based on the work of Redmond,[21,22] who used dispersion techniques to "surgically" remove the unwanted poles and restore the analytic structure of the meson propagator to that guaranteed by the Lehmann representation. The second technique involves the inclusion of vertex corrections in the calculation of the energy. As discussed more fully below, one expects that these vertex functions will be highly damped at large spacelike momenta in the Walecka model.[23] These momenta are the ones that enter in the calculation of the RRPA energy and lead to the ghost poles when point-nucleon vertices are used; thus, the insertion of QHD-model vertex functions should improve this approximation. One could, of course, simply insert ***ad hoc*** vertex functions to achieve similar effects, but the point of our investigation is to determine how much vertex damping can be achieved within the framework of the model. Work is currently underway on both of these schemes and will be actively pursued over the course of this contract. Other questions involving the role of vacuum loops on the energy density are also relevant, such as the importance of short-range correlations and the modifications that occur when one interprets the Walecka-model scalar field not as "elementary" but as simulating the exchange of two correlated, s-wave pions; both of these topics are considered below, and we propose to study their impact on the nuclear vacuum energy.

Although computing the nuclear matter energy at the level of the RRPA (with the modifications mentioned above) is important, it should be viewed as just one step in the development of systematic approximation schemes that maintain various conservation laws. We are currently studying the work of Baym and Kadanoff[24] on "conserving approximations" in nonrelativistic systems (with instantaneous potentials) 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.

There are other techniques that may be useful for extending QHD calculations beyond the mean-field theory, and we plan to examine some of these. For example, the coupled-cluster expansion has been used to great advantage in nonrelativistic systems, but its extension to the relativistic many-body problem requires the development of new techniques to handle divergences nonperturbatively. The renormalization group has been used to study the behavior of QCD at high temperatures and densities, and this may also prove valuable for studying these limits in QHD; here the presence of the scalar field makes the extension nontrivial, since one must go beyond the leading terms to derive the necessary self-consistency conditions. We have also given some thought to the development of nonrenormalizable theories that would still be constrained to a finite number of parameters. One example is chiral perturbation theory, where an expansion around the soft-pion limit introduces a finite number of parameters at each successive order in the square of the pion momentum. While the problem of meaningful nonrenormalizable theories has been studied intensely by many smart people, and chiral perturbation theory is probably not useful for the problems discussed above, there may be some particular aspects of the nuclear many-body problem that will allow progress to be made on this idea.

Nucleon Structure from Meson Loops

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 modifications, and an improved approximation to the vacuum terms would include these corrections inside the vacuum loops. Although QCD in principle gives a complete description of nucleon structure, some part of the internal properties of the nucleon, particularly at large distances, must be equivalent to that provided by virtual hadron loops. In fact, as pointed out recently by Milana,[25] in a theory with baryons and vector mesons, the proper vertex functions are highly damped at large spacelike momentum transfers 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 meson 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. Although it may be impossible to achieve a truly quantitative description of the hadron structure within a QHD model, due to the complicated nature of the vertex functions, our goal is to at least understand the qualitative features of the vertex functions implied in a hadronic theory and how these features affect calculations with vacuum loops.

Allendes and Serot recently computed the effects of these vertex corrections on the vacuum polarization in the vector meson propagator,[23] which was computed earlier for point-like vertices by Furnstahl and Horowitz.[18] 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, the off-shell vertex was replaced by its on-shell form at zero density, which has a simpler Dirac-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 $|q| \approx 5M$. 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 with the approximation discussed above. 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.

We are currently extending this calculation by evaluating the fully off-shell vertex (including the complete Dirac-matrix structure) at spacelike momenta. We have developed a consistent renormalization scheme for including the vertex inside the vacuum-polarization loop so that the standard renormalization conditions are maintained. The asymptotic behavior of the off-shell vertex is again relevant and indicates significant damping at large spacelike momenta, but the behavior at small momenta is less well known. This is true because there have been very few model studies of off-shell hadronic vertices, and little is known empirically, because most calculations using *ad hoc* vertex factors simply *assume* that one can use an on-shell vertex in its place. Thus one of our goals in this calculation is to understand the qualitative dependence of the vertex on the off-shell (baryon) momenta as implied by QHD, and to study the applicability of the often-used approximation of assuming the vertex to have its on-shell form. Another important goal is to study the interplay of the infrared behavior coming from the vertex insertion and the self-energy insertions in the polarization loop, which is known to be important in QED. In the present case, we expect that the finite mass of the vector meson will lead to qualitatively different results.

These vertex functions will be used in the RRPA calculations of the nuclear matter energy discussed above; work is underway on including the on-shell vertex determined in Ref. 23 in these loops, and we will later include the off-shell vertex to test the accuracy of the on-shell results. Part of this study involves the extension of the vertex calculation from a theory containing only baryons and vector mesons to the full Walecka model. Further work involves the inclusion of the density-dependent parts of the vertex function (which have so far been neglected) as well as the contributions from virtual pion loops, which are expected to improve the longest-range part of the vertex function. (These pionic effects may be included by explicitly evaluating loop diagrams or perhaps through semiclassical approximations involving a pion cloud or "hedgehog".) Both of these issues are linked to the inclusion of pion dynamics in a chirally invariant fashion (as discussed below), and they are relevant to computations of nucleon electromagnetic vertices, which we consider next.

In addition to computing vertex corrections for inclusion in vacuum loops, we are performing similar calculations to study 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 structure. 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?

The study of hadronic vertex structure is also important for assessing 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 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

Quantum hadrodynamics is a field-theoretic model of the underlying dynamics of quarks and gluons. As such, it should be constrained by the symmetries of QCD. One of these symmetries is chiral symmetry, which is a property of the QCD Lagrangian with massless u and d quarks. Moreover, as has been discussed repeatedly in the literature (see, for example, Ref. 26), chiral symmetry is necessary for producing low-energy pion dynamics that is consistent with experiment.

The relevant question, however, is how the chiral symmetry is realized in a model constructed from hadronic degrees of freedom. If the symmetry is realized in a linear fashion (as in the well-known linear σ model), the strong nonlinear interactions of the σ mesons introduce severe problems in the description of nuclear matter and nuclei, as we describe further below. 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 (NN) interaction.

It was suggested some time ago[27] that this mid-range attraction is restored by the *correlated* exchange of two pions between the nucleons. Lin and Serot recently used the σ-model Lagrangian to construct a dynamical model of the mid-range attraction through explicit $\pi\pi$ rescattering.[28] 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 distributed mass. The integrated strength of the scalar-isoscalar interaction is large enough to account for nuclear binding. 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.

This calculation is relevant in light of recent work carried out by Furnstahl and Serot.[29] It was shown that although some chiral models with a linear realization of the symmetry can reproduce the saturation point of nuclear matter in the Hartree approximation, they fail *generically* to reproduce observed properties of finite nuclei. In fact, the linear chiral models are overconstrained, and the strong many-nucleon forces preclude a satisfactory description of spin-orbit splittings, the nuclear shell structure, charge densities, and surface energetics. These deficiencies imply that this implementation of chiral symmetry is incorrect.

When taken together with the work of Lin and Serot, these results suggest a different realization of chiral symmetry in hadronic theories of nuclear systems. Here one takes the scalar mass to be *large* to eliminate the unwanted nonlinearities and generates the mid-range attraction between nucleons *dynamically* through correlated two-pion exchange, as discussed previously. This picture can be implemented with a nonlinear realization of the chiral symmetry, with the heavy chiral scalar merely playing the role of a regulator to maintain the renormalizability of the linear σ model.[26] If one calculates beyond the mean-field theory, the mid-range NN attraction arises naturally through two-nucleon correlations that include correlated two-pion exchange; a light scalar meson is no longer needed or wanted. To work at the mean-field level, the strong scalar-isoscalar two-pion exchange can be simulated by adding a low-mass "effective" scalar field coupled directly to the nucleons.

Since the pion mean field vanishes, the resulting chiral mean-field theory looks just like the mean-field Walecka model, with a strong NN attraction mediated by the low-mass scalar and small many-nucleon forces. This approach provides 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.

We have also made progress recently in other aspects of chiral hadronic models. For example, Lin and Serot extended the preceding ideas[30] 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 dynamically 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. It is essential to have the Δ degree of freedom in the theory to realistically describe low-energy pion–nucleus physics.

It is also important to include charged vector mesons (like the ρ) in chiral models, as these are important for accurately describing the NN interaction and electromagnetic interactions with nuclei. In a recent paper, Serot and Walecka[31] constructed a chirally invariant Lagrangian that contains nucleons, pions, omegas, and rhos using a Yang–Mills theory based on the local gauge symmetry $SU(2)_R \times SU(2)_L$. The baryon mass is generated through spontaneous symmetry breaking, and the charged vector meson masses (for both the ρ and the a_1) are produced through the Higgs mechanism. The theory is parity conserving. Two baryon isodoublets with opposite hypercharge are required to eliminate chiral anomalies, and for definiteness, the second isodoublet was taken to be the cascade (Ξ), with hypercharge $y = -1$. Because of the chiral symmetry and parity conservation, this model requires only one additional parameter (M_Ξ) beyond that needed in a non-chiral model of N, π, ω, and ρ. The new model is specifically designed to describe the physics in the non-strange sector, where the Ξ enters only in internal loops. Predictions can now be made for various hadronic observables; for example, the decay width of the a_1 meson can be calculated in terms of parameters determined from other processes (such as ρ meson decay), and the theory can be enlarged to include electromagnetic interactions. This will allow us to compute hadronic electromagnetic vertices and anomalous moments in a model with both vector mesons and chiral symmetry. We intend to study the predictions of this new model (called QHD–III), as the inclusion of vector meson degrees of freedom in a hadronic model that respects the symmetries of QCD is an important topic.

The basic conclusion of the $\pi\pi$ rescattering work discussed above is that important (and usually 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 enhanced or 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, we plan to study the impact of approximating the correlated two-pion exchange as a well-defined scalar meson by performing calculations with a scalar with a distributed mass and a nonlocal coupling to the nucleon. The parameters for this mass and coupling can be determined (at least qualitatively) from the dispersion-theoretic calculation based on the underlying σ-model Lagrangian. We also plan to investigate how the properties of the light scalar are modified at finite density and temperature, and we will attempt self-consistent nuclear matter calculations in which the baryon propagators in the dispersion theory are modified by the scalar field. Similar studies can be carried out using the dispersion approach to the properties of the Δ resonance, for example, how the properties of this resonance change at finite density in a chiral model, and whether it is useful to introduce the interactions of this resonance in the medium through simple couplings to scalar and vector fields.

We also plan to use the chiral models to improve the description of pion dynamics in relativistic nuclear matter. Note that vacuum dynamics 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 have been no previous calculations that include 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,[32] 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,[26] and Wehrberger, Wittman, and Serot extended this approach to the next order, which amounts to the RRPA discussed earlier.[33] We verified that renormalizability and chiral symmetry are maintained in this approximation, and also showed that the tachyon poles present in the conventional loop expansion are avoided to a large extent. Unfortunately, there are still unphysical "ghost" poles from the short-distance behavior of the QHD vacuum discussed above. This leads to large imaginary contributions to the nuclear matter energy, just as in the Walecka model. We plan to include modifications to the meson propagators and meson–baryon vertices similar to those discussed above for the Walecka model to extract realistic predictions for the RRPA energy including pion loops. We will also study the impact of replacing the low-mass scalar meson with a more realistic description involving a distributed mass and a nonlocal coupling.

The Relationship Between the Relativistic Two-Body and Many-Body Problems

In nonrelativistic nuclear theory, the two-body problem can be solved exactly, and it can be used to specify the dynamics for the many-body problem. In a relativistic theory, however, the two-body problem cannot be solved exactly, and one must relate an approximate solution of this problem to an approximate solution of the many-body problem.

In recent years, the conventional Brueckner–Bethe–Goldstone theory of nuclear matter has been extended by using the Dirac equation to describe the nucleon motion, resulting in the so-called "Dirac–Brueckner" theory.[34] This formalism allows NN correlations to be included in a self-consistent, Lorentz-covariant fashion.[35] However, a consistent relativistic treatment of nuclear matter saturation involves other new features that go beyond the simple introduction of Dirac wave functions into the traditional formalism. Many of these additional features (for example, retardation in the nucleon–nucleon interaction, the role of negative-energy baryon states, a proper relativistic evaluation of the nucleon self-energy and nuclear matter energy density, and the role of off-shell effects and density-dependence in the nucleon–meson form factors) have no counterparts in the traditional non-relativistic approach, and their impact on the nuclear matter saturation problem have never been examined systematically. All of these factors may be important, because relativistic descriptions typically involve large potential energies (several hundred MeV) and achieve the small nuclear binding energy ($\simeq$ 16 MeV) through delicate cancellations. These new features must therefore be investigated in detail before a truly relativistic theory of nuclear saturation can be achieved.

For example, our preliminary calculations show that different definitions of the self-consistent baryon self-energy can produce large variations in the nuclear matter binding energy when pion exchange is included in the Dirac–Brueckner calculations.[36] Recent calculations by the group at the University of Kentucky[37] have verified these results, and these authors have proposed alternative self-consistent methods based on thermodynamic constraints. These new methods, however, do not provide unique answers and still do not address the basic problem of including the vacuum dynamics in the two-body problem *in the medium.*

Moreover, in light of the previous discussion of chiral models, it is important to develop consistent approximations for the relativistic two- and many-body problems that include chiral symmetry dynamically (rather than by *ad hoc* "pair suppression," for example). These formulations should contain a finite number of parameters and both "elementary" and "effective" degrees of freedom. The construction of such descriptions has not been widely studied in the past, in part because they produce energy-dependent and nonlocal nucleon–nucleon interactions, which have been difficult to apply in nuclear structure calculations. However, with the recent advances in available computing power, it should now be feasible to deal directly with interactions of such form, and the construction of a new "modern" boson-exchange description of the nucleon–nucleon interaction, containing the dynamically generated resonances, is a worthwhile endeavor. All of the preceding topics will be important areas of our future research.

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

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. Such conditions exist in astrophysical objects, such as neutron stars and supernovae, and may also be achieved in 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,[1,38,39] and even these have not fully exploited the covariant aspects of QHD.

Furnstahl and Serot have recently completed a major program involving covariant many-body theory at finite temperature and density.[40–43] We generated the Feynman rules for both real-time, finite-temperature (matrix) Green's functions and the more conventional imaginary-time functions. 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. In particular, one of our goals is to extend the discussion of conserving approximations in nonrelativistic systems to allow for a fully covariant specification of the relevant constraints.

The derivation of the covariant Feynman rules using a path-integral (time-path) formalism is discussed in Ref. 43. 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 to define the propagators. 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 performed a manifestly covariant calculation of nuclear matter properties in the Relativistic Hartree Approximation.[42] 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,[41] when we applied the model in a simple hydrodynamic picture to discuss the phenomenology of heavy-ion collisions and astrophysical systems.

We plan to develop this work in several directions to study the properties of hot, dense nuclear systems. First, we want to extend the calculations beyond the mean-field approximation to include the effects of correlations and vacuum loops, along the lines discussed earlier for zero-temperature nuclear matter. Second, we want to develop a covariant description of nonequilibrium systems and transport processes by building on the well-known Schwinger–Keldysh and Baym–Kadanoff formalisms. Finally, we want to connect the results of purely hadronic calculations to those obtained by working directly with a quark–gluon plasma, as discussed later in this proposal, to develop a framework that will be relevant for describing relativistic heavy-ion collisions at extremely high energies, such as those that will occur at RHIC.

3.2 Quasifree Electroweak Scattering and Strange Quarks in Nuclei

There is considerable interest in possible contributions of strange quarks to nucleon form factors. Information on these would provide insight into QCD and place constraints on phenomenological models of hadron structure. Strange-quark contributions can be investigated in parity-violating electron scattering and in neutral-current neutrino scattering. However, there are many different contributions and experimental complications. Therefore, one foresees an experimental program to combine information from several experiments rather then just one or two measurements.

Two obvious experiments are parity violation in elastic electron–proton scattering (which is sensitive primarily to strange quark contributions to the proton's magnetic from factor) and elastic neutrino–proton scattering (which is sensitive primarily to strange quark contributions to the axial current). There are, however, both theoretical and experimental complications to each of these experiments that can be avoided by also measuring quasifree electron and neutrino scattering from *nuclei*. Nuclei contain neutrons and hence provide a different combination of isospin responses than measurements on free protons. This allows one to separate some backgrounds from the desired strange-quark contributions. Furthermore, for large neutrino detectors, heavier nuclei are much more convenient targets than pure hydrogen.

Before quasifree scattering data can be combined with free proton experiments, however, two questions must be addressed. First, are the strange-quark matrix elements themselves different in a nucleus than in an isolated nucleon? Second, are there uncertainties from conventional nuclear structure effects which complicate the extraction of strange quark matrix elements from quasifree scattering data?

The first question is very interesting. What is the density dependence of the strange quark content? The old EMC effect showed that quark distribution functions are about 10% different in a nucleus than in an isolated nucleon. Furthermore, there are general arguments that suggest that the strange quark content should increase with density. Basically, the increasing quark Fermi energies and the interactions between hadrons should help to overcome the inhibitory effect of the strange quark mass. In the limit of very high density, a transition from nuclear to quark matter is expected. Furthermore, it is possible that the ground state of quark matter (in weak equilibrium) has a large strange quark content.

The same conclusion can be reached in hadronic models. Here strange quark contributions can be modeled as loops involving kaons (or other strange mesons) and hyperons. Calculations of neutron matter suggest that at high densities there will be significant contributions from real hyperons. Indeed, if a kaon condensate occurs at high densities, this could imply a very large strange quark content.

Unfortunately, not much is presently known about strange quark contributions to the nucleon, much less their density dependence. Nevertheless, we plan to investigate density dependence in a variety of relativistic hadronic field theory models and in our string-flip quark model. We will see if normal nuclear matter is dense enough to enhance strangeness significantly. Furthermore, as information on strange quark contributions in free nucleons becomes available, we will be able to refine these models of strange quarks in nuclear matter.

The second question mentioned above is more straightforward but still very important. Will complications from conventional nuclear structure effects impede the extraction of strange-quark matrix elements? Understanding nuclear structure effects is a clear prerequisite before a large experiment can be mounted at CEBAF or elsewhere. We are examining both electron and neutrino scattering proposals.

Parity Violating Quasifree Electron Scattering

[C.J. Horowitz and J. Piekarewicz (Florida State)]

Donnelly *et al.*[44] proposed measuring the parity-violating analyzing power A in quasielastic electron scattering from a nucleus such as ^{12}C. When combined with existing (and proposed) elastic electron–proton scattering data, this could significantly improve the determination of the strange anomalous moment of the nucleon. Furthermore, quasifree scattering is attractive experimentally because it has a large cross section and a relatively large analyzing power.

In these experiments, A is dominated by the transverse response and is sensitive to isoscalar contributions. In general, the transverse isoscalar response is expected to be small because of the small isoscalar anomalous moment of the nucleon. However, the small isoscalar transverse response is poorly known experimentally.

We are performing calculations in both nuclear matter and in a finite nucleus to study relativistic, long-range correlation (RPA), vacuum polarization, and other effects both on the isoscalar transverse response and on A. In a first paper, we found that relativistic effects from a small effective nucleon mass increase the isoscalar transverse response by a large amount.[45] This correction could be larger than the strange quark effects. Therefore, a quasifree experiment may be difficult to interpret (and hence not worth doing). A longer paper presenting more complete calculations (with the same conclusion) is in preparation.

Quasifree Neutrino Scattering

[C. J. Horowitz, H. C. Kim, and S. Pollock (Washington)]

Neutrino neutral-current scattering is sensitive to strange quark effects. [Charged currents, on the other hand, are insensitive to the (presumed) isoscalar strange quark currents.] Information can be extracted from elastic νp (or $\overline{\nu} p$) scattering. However, most neutrino detectors also involve heavier nuclei. One must therefore understand "backgrounds" from quasifree scattering including nuclear effects on these quasielastic reactions. Furthermore, nuclear targets allow one to observe knocked-out neutrons. The ratio of proton to neutron yields is very sensitive to strange quark effects and may be insensitive to a variety of systematic errors.

We are therefore considering a variety of possible neutrino quasifree scattering experiments in order to optimize the extraction of strange-quark parameters and minimize systematic errors. These errors are both theoretical (from nuclear structure and other effects) and experimental. Both low-energy experiments at Los Alamos (with neutrinos of roughly 150 MeV) and higher-energy experiments (near 1 GeV) at Brookhaven or elsewhere are being studied.

Quasifree (γ, K) Reactions

[C.J. Horowitz, C. Bennhold (American U.) and C. Hyde-Wright (Washington)]

These reactions study virtual strange quarks in nuclei. One can also study real strange quarks with the (γ, K) reaction. Here the photon produces an $s\overline{s}$ pair, with the $\overline{s}$ quark detected in a K meson. This leaves behind a hypernucleus. By studying these reactions, one can learn about various nucleon-hyperon-strange meson coupling constants and about the behavior of strange quarks in nuclei. Most of the work to date has been for bound hyperons. However, most of the production cross section (given the large excitation energies of the particles) is to quasifree states.

There is an approved experiment in Hall B at CEBAF to measure quasifree K^+ and K^0 yields from a nuclear target. We are modeling this reaction with a relativistic Fermi gas and a simple hadronic production model. Predictions are made for the six reaction channels starting with either neutrons or protons and producing either Λ, Σ^0, or $\Sigma^{\pm}$. Many of these production channels are poorly known even for scattering from free nucleons. These studies will allow one to greatly refine the various nucleon-hyperon-strange meson couplings. Furthermore, we may learn something about the Λ mean field (optical potential) for scattering states. At present, the energy dependence of the mean field acting on the Λ in nuclei is unknown. We may also be able to search for any collective effects in Λ–nucleon-hole modes of excitation in nuclei. Finally, the refinement in the production mechanism (from our study) should greatly aid future (bound) hypernuclear studies at CEBAF.

3.3 Dynamical Effects in $(e, e'p)$ Scattering at Large Momentum Transfer

[S. Gardner and J. Piekarewicz (Florida State)]

The nuclear and momentum-transfer (Q^2) dependence of quasielastic $(e, e'p)$ scattering at large Q^2 and at small missing energies (measured at SLAC) is currently being analyzed to see if "color transparency", an anomalous weakening of the final-state interactions, exists for momentum transfers less than 7 $(\mathrm{GeV/c})^2$. At high Q^2, a conventional picture of the $(e, e'p)$ reaction may be altered in two different ways.

First, the struck proton can be diffractively excited as it transits the nucleus. At large proton momenta p, transitions that would yield excited baryon states require momentum transfers of $t = ((M_{N^*}^2 - M_N^2)/2p)^2$. Consequently, at large Q^2, baryon resonances can be produced easily, so that the relative phases of the components of the outgoing particle's wavefunction become scrambled with each interaction with the nuclear medium. The possibility of diffractive excitation (known as Gribov corrections for inelastic shadowing) alters the attenuation of a proton through the medium from a simple Glauber estimate, because strength shifted to the resonances through diffractive excitation can be returned to the proton channel through further medium interactions. Consequently, final-state interactions at high Q^2 cannot be described by a simple black disk.

Second, the ejectile emitted as a result of the hard process may decrease in transverse size as Q^2 increases. This effect is predicted by perturbative QCD, though it is unclear at what momentum transfers such a prediction is reliable. In a hadronic basis, one can understand the decreasing size of the ejectile with increasing Q^2 as the creation of a superposition of baryon excited states whose transverse size is smaller than that of the proton. In QCD, the interaction of a hadronic object is proportional to its transverse size, so that one expects that a small object propagating through the nuclear medium should suffer smaller final-state interactions, hence the name "color transparency". The mechanism by which a small state composed of many baryonic states interacts weakly is through the Gribov corrections discussed above; these quantum-mechanical interference effects allow the strong interactions of the individual baryon states to cancel, at least in part. At accessible energies, the evolution of the ejectile through the nuclear medium is complicated, since the different phases of the components of the wave function cause it to expand dynamically with time. The problem is also technically demanding, as it involves the solution of a large set of coupled-channel equations.[46]

Current models of these effects treat the nucleus in a disturbingly simple way: as a continuous medium with some density profile $\rho(r)$. However, correlations in the nuclear ground state change the Q^2 where the effects discussed above are likely to be relevant.[47] Consequently, we would like to improve the situation by computing the $(e, e'p)$ cross section at small missing energies in a Fermi gas model of the nucleus, in which the two effects discussed above will be included as well. The coupling to the N^*s in the hard process and through diffractive excitation is model dependent. We would like to understand how such model dependence affects the final qualitative results.

Detailed theoretical studies at high Q^2 are lacking, yet they will be essential for understanding the SLAC results. These studies are also necessary to determine the role CEBAF may play in disentangling this puzzle.

3.4 Investigating the Nucleon's Parton Sea with Polarized Leptoproduction

[S. Gardner]

The dearth of data on the flavor and polarization of the nucleon's parton sea is a major gap in our understanding of the nucleon's structure. In addition to being important in its own right, it is highly relevant to understanding the so-called "proton spin crisis." To this end, polarized leptoproduction of hadrons from a polarized proton target is considered. One can argue that the flavors associated with the fast hadrons produced in the direction of the momentum transfer $\vec{q}$ is indicative of the flavor of the parton which initiated the jet.

To be definite, consider the polarized structure function $g_1^{p/h}(x,z)$ for the semi-inclusive production of a hadron h from a proton in leading twist:

$$2g_1^{p/h}(x,z) = \sum_i e_i^2[\Delta q_i(x) D_i^h(z) + \Delta \overline{q}_i(x) D_{\overline{i}}^h(z)]\,,$$

where the sum over i runs over all flavors. Here $q_i(x)$ is the parton distribution function of flavor i, and $D_i^h(z)$ is the fragmentation function for production of a hadron h given a struck quark of flavor i. (Note that $z \equiv p\cdot P/q\cdot P$, where P is the target four-momentum, p is the hadron four-momentum, and q is the four-momentum transfer.) The preceding equation is a straightforward generalization of the leading-twist expression for the unpolarized structure function, F_1.[48] Note that the ratio $g_1^{p/h}(x,z)/F_1^{p/h}(x,z)$ is the experimentally measured asymmetry in the scattering of longitudinally polarized muons from a longitudinally polarized target.

Accessing the flavor and polarization of the parton distributions in x relies on the empirical fact that certain fragmentation functions dominate in the $z \to 1$ limit. In general, the fragmentation function $D_i^{p/h}$ will be favored if the quark of flavor i is part of the valence quark content of the hadron h. For example, the favored fragmentation function D_u^{p/π^+} is phenomenologically related to the unfavored function D_u^{p/π^-} via $D_u^{p/\pi^+} = \eta(z) D_u^{p/\pi^-}$, where $\eta(z) = (1+z)/(1-z)$.

Exploiting these ideas, Close and Milner suggested that large z semi-inclusive K^- production would be sensitive to the polarization of the $\overline{u}$ and s quark content of the nucleon sea, as the $\overline{u}$ and s fragmentation functions are favored in K^- production.[49] What is most desirable, however, is an identification of *both* the flavor and polarization of the sea. Here the idea is to study the extent to which identification of the leading and sub-leading hadrons in the jet allows one to disentangle these two quantities. Naively, one imagines that an event with the structure $z_{K^-} > z_{K^+} \gg 0$ allows one to infer that the struck quark was a $\overline{u}$, whereas an event of structure $z_{K^-} > z_{ns} \gg 0$ (where ns

denotes "non-strange") would lead one to believe that the struck quark was a s. (Playing similar tricks with $\pi^{\pm}$ production should yield information about other distributions as a function of x.) However, given the vagaries of the hadronization process, these expectations are statistical in nature. One would like to develop some intuition for the probability that an event of a particular structure was the result of hitting a particular flavor of quark.

One can readily start with some existing string model code, such as JETSET, in order to get some initial impression. However, such studies are not sufficient. String models are expected to be deficient in the $z \rightarrow 1$ limit as gluon radiation (a major source of partonic energy loss) is ignored in such hadronization treatments. Moreover, intermediate resonance formation (here K^*), which is also ignored in string model treatments, could be important in modifying the probability that a given event is associated with striking a particular flavor of quark. The ultimate feasibility of these considerations could result in a major experimental program at the proposed European Electron Accelerator Facility. It should be noted, however, that even if the experiments were not feasible, studies of the limitations of string models in describing hadronization are sorely lacking and would be of great use.

3.5 Physics of Ultrarelativistic Nucleus–Nucleus Collisions

Overview: General Questions and Remarks

According to the modern theory of the strong interaction based on quantum chromodynamics (QCD), hadrons are expected to lose their identity at sufficiently high temperatures or baryon densities and dissolve into 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 most important outstanding problems of modern physics. It is widely believed that the transition from the quark-gluon plasma to a dilute hadron gas occurred at a stage of the evolution of the Universe as early as several microseconds after the Big Bang, when the temperature of the Universe reached the hadronic scale of roughly 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 spacetime region. This line of experimental research has already started at Brookhaven and CERN with light ions and is expected to reach its maturity with the relativistic heavy ion collider (RHIC) that is now being constructed at Brookhaven. The interpretation of these experiments and the identification of the signals of new physics pose a great challenge for contemporary nuclear theory.

Nuclear collisions at collider energies are very complex phenomena that may comprise a sequence of interesting events of distinct physical nature, characterized by different scales and different degrees of freedom. Inevitably, there are a diverse range of interesting questions. For instance, at earlier times on the order of 0.1 to 1.0 fm (in natural units), one is concerned with the mechanism of energy deposition that leads to a macroscopic excitation of the vacuum. This is the realm of quark-parton physics, since the relevant scale is much smaller than the size of hadrons. An important theoretical problem is to describe the initial excitation stage starting from a transient system of interpenetrating beams of primary partons to the formation of a dense compound system of excited partons or a quark-gluon plasma.

Many interesting questions are related to what happens next: does the newly created dense matter exhibit any interesting collective behavior? To be more specific, we may ask:

1. How does the many-body behavior of the collective plasma (such as dynamical screening and collective plasma oscillation) manifest itself in the evolution of matter in the deconfining phase?
2. How do these collective effects change the final stage of hard processes (charmonium formation and jets)?
3. How does the dense quark-gluon plasma hadronize as it is diluted by rapid expansion?
4. Are there interesting new phenomena associated with possible phase transition(s)?
5. How does the dynamical (chiral) symmetry break down as the system cools?

More mundane but equally important questions deal with what happens in the later phases of matter evolution on larger time scales:

1. Is hydrodynamic collective flow generated in such relatively small systems?
2. What is the most effective way to establish the flow effects and learn the equation of state of dense hadronic matter?
3. How do transport processes in the hadronic fluid affect observables like entropy production and baryon number diffusion?
4. Is there interesting collective behavior in dilute hadronic matter caused by the residual interactions between hadrons?
5. How do the hadrons cease to interact and reach an asymptotic state?

These questions are all related to the most pressing issues of the field: What information about the early conditions of the matter survives the complex evolution and will be reflected in the observables? How can one infer the evidence of new physical phenomena taking place in dense matter? The theoretical study of these problems requires an interdisciplinary approach that may involve sophisticated applications of modern concepts and methods from many branches of physics with bold new ideas. In the following, we discuss briefly some specific topics of current interest.

Flux-Tube Model for Ultrarelativistic Nucleus-Nucleus Collisions

[T. Matsui]

This model has been proposed[50] to describe the initial energy-deposition mechanism in high-energy nuclear collisions based on the Low–Nussinov picture of hadronic interactions.[51] In this reaction picture, it is assumed that high-energy nuclear collisions produce a strong color field due to random color exchange between the two colliding nuclei. The decay of such a strong color field due to the Schwinger mechanism (pair creation in an external background field[52]) and the subsequent formation and evolution of a quark-gluon plasma has been described in terms of generalized relativistic Boltzmann–Vlasov kinetic theory.[53,54] In this work, we focused on the baryon-free central rapidity region employing the symmetry of Lorentz-boost invariance along the collision axis, and we studied various problems in this model: the transverse expansion of the plasma,[54] the hadronization mechanism,[55] and the spontaneous excitation of collective plasma oscillation and dilepton production.[56]

There are still many important problems remaining to be examined in this direction, for example: the inclusion of the nuclear fragmentation regions, fluctuations in the color field, and quantum kinetic theory for spontaneous pair creation.

The first problem requires one to implement the correct boundary conditions at the longitudinal edges of the system, removing the simplifying assumption of Lorentz-boost symmetry, and to incorporate baryon number conservation. These are relatively straightforward extensions of the earlier work, although considerably more extensive numerical computation is required to study realistic three-dimensional geometries. Less well understood are the initial fluctuations in the color field due to random color exchange processes and their impact on the later evolution of the system. This problem is relevant for understanding the observed non-statistical large fluctuations in the transverse energy distribution in nuclear collisions.[57] 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 used a semiclassical kinetic equation with a particle source term that is constructed by transcribing Schwinger's result for a uniform constant electric field in the same spirit as in the Thomas–Fermi approximation. Our recent study of non-equilibrium dilepton production[56] showed that the 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 the particle production mechanism. New progress has been made by others in extending Schwinger's result to include finite size effects[58] and in formulating and solving the pair-creation problem as an initial-value problem in quantum field theory.[59] We will continue to work on this problem in light of these new insights.

Charmonium Suppression by the Quark-Gluon Plasma

[T. Matsui, Y. Koike (Michigan State)]

One of the proposed signals of quark-gluon plasma formation is a suppression of charmonium production due to the plasma screening of the $c\bar{c}$ binding force.[60] This predicted effect was subsequently observed by one of the first experiments at SPS (NA38 collaboration),[61] and their data was interpreted successfully by us[62] and by others[63] in terms of a simple semiclassical model of the charmonium formation that includes the finite spacetime extension of the plasma produced in the collisions. Encouraged by the qualitative success of this interpretation, further theoretical work has been directed toward refining the understanding of the plasma suppression mechanism. This includes the study of the dynamic screening of the $c\bar{c}$ pair traversing the plasma medium[64] and the fully quantum-mechanical formulation of the charmonium formation and suppression problem.[65] These more detailed studies revealed, however, a considerable weakening of some of the prominent features, such as the strong p_T dependence and threshold effect, which were once thought to be characteristics of the plasma suppression mechanism, in contrast to various other non-plasma suppression mechanisms proposed by others.[66] More realistic calculations will be performed to make more quantitative predictions for the J/ψ suppression by the plasma formation by incorporating various plasma effects, such as dynamic screening[64] and energy loss of $q\bar{q}$ pairs in the plasma.[67]

Freeze-out Kinetics of Chemical Composition

[T. Matsui, T. Otofuji (Akita U., Japan)]

The relative particle abundances are potentially important probes 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,[68] later more dynamical studies[69] 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 simple descriptions of the matter expansion based on Bjorken's one-dimensional scaling solution;[70] this is adequate, at best, only for the very early stages of the expansion. Indeed, it can be shown that the system always reaches chemical equilibrium in the one-dimensional (scaling) adiabatic expansion, and therefore the kaon/pion relative abundance approaches zero. This indicates that the freeze-out process of this ratio is very sensitive to the expansion dynamics. We will refine previous calculations by including a more realistic treatment of the expansion dynamics and the chemical kinetics at the freeze-out stage based on a vector-meson-dominance model for hadronic rate equations, together with a numerical simulation of the multidimensional hydrodynamic expansion of the hadron gas.

Shadowing in Pion Interferometry

[M. Chu (Caltech), S. Gardner, T. Matsui]

Intensity interferometry in optics, known as the Hanbury-Brown–Twiss effect, has been successfully applied to heavy-ion physics, where one may use the momentum correlation of two identical particles produced by the collision (for example, pions) to extract information on the size and shape of the particle emitter.[71] It is well known that the relative phase shift caused by final-state interactions between the two detected particles leads to a distortion in the correlation function.[72] Less well understood is the effect of the final-state interaction between the observed particles and the rest of the system, which leads to the distortion of the single-particle wave functions. This problem is particularly interesting when the pion emitter has a nontrivial substructure, which is expected in the droplet model of the first-order phase transition[73] associated with the hadronization of the quark-gluon plasma. In this case, each plasma droplet plays the role of both an emitter and absorber of pions, and the latter effect may lead to modifications of the correlation pattern due to the shadowing of the pion single-particle wave function. We will study this problem to examine whether one can extract further information on the condition of the environment where the pions are emitted.

Dynamics of the Chiral Phase Transition

[T. Matsui, H.-S. Roh]

One well-known symmetry of the QCD lagrangian is the approximate chiral symmetry, which is exact in the limit of vanishing quark masses. This symmetry is broken spontaneously in the QCD vacuum and realized by the existence of (nearly) massless Goldstone modes (pions). It is predicted by both effective mean-field theory[74] and numerical Monte Carlo simulation of lattice QCD[75] that at sufficiently high temperatures, chiral symmetry is restored and the Goldstone modes acquire a finite mass. We expect that during the time evolution of the superdense hadronic matter created by the nuclear collision, the system undergoes a drastic change in its bulk properties due to the dynamical breakdown of chiral symmetry. One interesting question is whether the system can maintain an equilibrum configuration of the condensate (order parameter) during fast cooling by rapid expansion. We speculate that the cooling takes place so fast that the system may first experience a brief period of a domain structure of the chiral condensate by spinodal decomposition, and the equilibrium configuration of the condensate will then be reached gradually by some kind of dissipative mechanism in which the fluctuation of the order parameter (coherent field) plays the central role. Some of the important symmetries of the strong interaction (such as isospin symmetry) may be broken in some of the domains where a pion condensate develops and may result in some interesting observable consequences in the particle composition and spectrum. We will study these non-equilibrium problems associated with the chiral phase transition and their possible observable consequences by using effective theories such as (linear or nonlinear) sigma models.

3.6 QCD Sum Rules and Hadronic Properties

[D. Griegel, S. Schramm, and M. H. Macfarlane]

QCD sum rules provide a promising means, perhaps the only one currently available, of connecting nuclear phenomena and the scales governing them to the underlying structure of QCD. Our work will center both on theoretical aspects of this new field and on its implications for the new generation of nuclear experiments.

One of the crucial problems with QCD sum-rule estimates of hadronic spectral properties in nuclear matter is the strong sensitivity to the density dependence of the four-quark condensates. In all finite-density QCD sum-rule calculations to date, the four-quark condensates have been estimated by the factorization approximation, in which a complete set of intermediate states in inserted in the middle of a four-quark matrix element, but only the ground-state contribution is retained. Thus the four-quark condensates are estimated in terms of $\langle\overline{q}q\rangle^2$, $\langle\overline{q}q\rangle\langle q^\dagger q\rangle$, and $\langle q^\dagger q\rangle^2$. This approximation is believed to be reasonable in the vacuum, where there is a large separation in energy between the vacuum and the next excited state. However, at finite density, there are a number of states that are close to the ground state, so the factorization approximation may not be reliable.

We propose to study alternative methods of estimating in-medium four-quark condensates. One possibility is the instanton liquid model of the QCD vacuum. This model has already been used to estimate four-quark condensates in the vacuum[76] ; we propose to generalize these estimates to finite density systems.

The Nucleon σ Term

[D. Griegel and R. Furnstahl (Ohio State)]

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

$$\sigma_N = \left(\frac{m_u + m_d}{2}\right) \langle N|\overline{u}u + \overline{d}d|N\rangle \ ,$$

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 πN scattering; its value is about 45 MeV with an uncertainty of 7–10 MeV.[77] The σ term is particularly relevant to our studies, since it sets the scale for the change in the quark condensate $\langle\overline{q}q\rangle$ in the nuclear medium, which in turn gives the leading behavior of the scalar self-energy. Leading-order QCD sum-rule calculations[7] 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 give a clearer understanding of the cancellation of the scalar and vector potentials in relativistic nuclear physics.

In studying the σ term, it is important to be consistent with known results from chiral perturbation theory. In previous sum-rule calculations of the σ term, this requirement has been overlooked. It is believed that consistency with chiral perturbation theory can be achieved if well-known pion physics is included on the phenomenological side of the sum rule; however, this program has not yet been carried out.

Experimental Implications of the QCD Sum-Rule Approach to Medium Effects

[D. Griegel and M. H. Macfarlane]

In QCD sum rules—as in all sum rules—the connection between experiment and the underlying microscopic theory resides in ground-state expectation values of various operators. The greatest uncertainty in QCD sum-rule studies of the behavior of hadrons in nuclei is in the values of these ground-state expectation values or condensates. We know relatively little about the density dependence of these condensates that have free-particle analogs nor about the sizeable number of condensates that have no free-particle analogs. If indeed QCD sum rules are to be a viable way of forging a quantitative link between nuclear phenomena and QCD, experiments must be identified which can provide factual constraints on the theoretical assumptions made about condensates and their density dependence. In general, this quest is sure to place new stress on experimental studies of the propagation of hadrons (nucleons, deltas, hyperons, pions, etas, kaons) in nuclei. Work is in progress on sharpening this general statement and on writing a report on the general subject of medium effects from the viewpoint of QCD sum rules.

3.7 Non-Relativistic Models of Nuclear Reactions

Coupled-Channels Calculations for Direct Nuclear Reactions

[M. H. Macfarlane and M. Rhoades-Brown (Brookhaven)]

Around 1980, a coupled-channels program was created to carry out heavy-ion inelastic-scattering calculations. It was subsequently used extensively at various experimental laboratories and in connection with studies of sub-barrier heavy-ion fusion. It is still in widespread use and its creators (who moved on to other things between 1980 and 1985) still receive requests for instructions in its use and suggestions for its extension. The program is based on iterative solution of the coupled scattering equations (the Born–Neumann series), with Padé acceleration to counter the problem that the Born–Neumann series diverges in almost all practical situations. Developments since 1980 in computer design and in the black art of convergence acceleration have conspired to strengthen our belief that accelerated Born–Neumann iteration is the most efficient way to carry out nuclear direct-reaction calculations. This is true not only of coupled-channel calculations but also of the distorted-wave Born Approximation, which appears as the first iteration of our procedure. We plan to resume work on our coupled-channels system, making

i) minor alterations to permit efficient inelastic proton-scattering calculations

ii) a major extension to include transfer channels

iii) a renovation of our convergence-acceleration package to include a variety of procedures we have learned about in the past years, such as Levin transforms, the Germaine–Bonne transform, and Dingle's Borel-based theory of terminants.

This extension of an existing system of programs should be of value in connection with collective effects in intermediate-energy proton scattering and in the new heavy-ion spectroscopy permitted by radioactive beam experiments.

Studies of Convergence Acceleration in Nuclear Physics

[M. H. Macfarlahe]

Methods for the acceleration of convergence of divergent or slowly-convergent series of complex numbers are of value in a variety of problems in nuclear physics, including for example, QCD sum rules (see §§2.2, 3.6, above) and nuclear-reaction calculations (see §3.7.i, above). Methods that are well known in applied numerical analysis, such as that of the Levin transform or Dingle's Borel-based 'theory' of terminants, are almost unknown in nuclear physics. An article on the subject is being written for the DOE's Computational Science Education Project, directed by C. Piottetov and M. Strayer of Oak Ridge National Laboratory.

Near-Threshold Pion Production in Nucleon–Nucleon Collisions

[M. H. Macfarlane and R. Roncaglia]

Recent experimental studies at the IUCF and theoretical studies supported by this contract revealed a striking conflict between theory and experiment. The cooler environment at IUCF permitted studies of the reaction $p+p \rightarrow p+p+\pi^0$ very close to threshold and of unprecedented accuracy. This process, within a few MeV of threshold, should be dominated by s-wave pions. These are two contributory processes: direct pion *bremsstrahlung* and *bremsstrahlung* with scattering. Calculations from the 1960's predicted

i) that the rescattering term, using an on-shell rescattered pion, give a negligible contribution

ii) an absolute cross-section from the *bremsstrahlung* term in fair agreement with the results of the IUCF experiment.

Horowitz concluded, however, that the original *bremsstrahlung* calculation was in error and that in part the *bremsstrahlung* cross section is about a factor of five too small. One possible origin for the discrepancy is the use of an on-shell pion-nucleon amplitude to estimate the rescattering term, where the intermediate pion is far off-shell. We propose to study available phenomenological evidence on the behavior of the pion-nucleon T matrix in the vicinity of on-shell and soft-pion points. Perhaps a better treatment of the pertinent off-shell pion-nucleon T matrix will yield a large enough rescattering contribution to bring the calculated $pp\pi^0$ cross-section into qualitative agreement with experiment.

3.8 Spin and Color Correlations in a Quark-Exchange Model of Nuclear Matter

[S. Gardner, W. Melendez, and C. J. Horowitz]

The quark-exchange model is a simple realization of an adiabatic approximation to the strong-coupling limit of QCD: the quarks always coalesce into the lowest energy set of flux tubes. Nuclear matter is thus modeled in terms of its quarks. We wish to study the correlations imposed by the antisymmetry of the wavefunction when spin and color degrees of freedom are included. To begin with, we have considered one-dimensional matter with a $SU(2)$ color internal degree of freedom only. We proceed by constructing a totally antisymmetric, color-singlet *Ansatz* characterized by a variational parameter λ (which describes the length scale over which two quarks in the system are clustered into hadrons) and by performing a variational Monte Carlo calculation to optimize λ for a fixed density. We plan to calculate both the energy and quark-quark correlation function as a function of density. The latter yields information about both the ground state's spatial composition and the excitation spectrum. As the system has a rich internal structure, a study of its excitations may reveal departures from conventional hadronic models of nuclear matter.

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

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74. T. D. Lee and G. C. Wick, Phys. Rev. **D9** (1974) 2291; G. Baym and G. Grinstein, Phys. Rev. **D15** (1977) 2897; B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. **16** (1986) 1; J. Gasser and H. Leutwyler, Phys. Lett. **188B** (1987) 477.

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

4. Scientific Personnel to be Supported by Proposed Contract

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. V. Gardner, Research Associate [from August 1, 1992]†

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

M. P. Allendes, Graduate Student

H. C. Kim, Graduate Student

W. Melendez, Graduate Student

H. S. Roh, Graduate Student

H. B. Tang, Graduate Student

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† Ms. Gardner is supported by CEBAF for academic year 1992–93.

budget removed.
dz

6. Vitae

CHARLES J. HOROWITZ

Department of Physics
Indiana University, Bloomington

CURRICULUM VITAE

[redacted] [redacted]

Education:

Degree	*Institution*	*Date*
B.S.	Harvey Mudd College	1978
Ph.D.	Stanford University Thesis: *Structure of Nuclei in a Relativistic Meson-Baryon Quantum Field Theory* J. D. Walecka, Advisor	1981

Fellowships:

National Science Foundation Predoctoral Fellowship	Stanford University	1978–81
Chester Davis Fellowship	Indiana University	1987

Academic Positions:

Postdoctoral Fellow	Niels Bohr Institute, Copenhagen, Denmark and Massachusetts Institute of Technology	1982–83
Assistant Professor	Massachusetts Institute of Technology	1984–86
Associate Professor	Indiana University (Tenure granted 1989)	1987–1991
Full Professor	Indiana University	1991-

Administrative Positions

Director	Indiana University Nuclear Theory Center	1990-
Chairman	International Conference on Spin Observables of Nuclear Probes, Telluride, CO	1988
	Midwest Nuclear Theory Get-Together	1991

	Indiana University Nuclear Theory Center	
Member	Long-Range Planning Committee, Indiana University Cyclotron Facility	1989-
	Program Advisory Committee, Indiana University Cyclotron Facility	1990-

Personal:

Chess Federation expert rating

PUBLICATIONS (Since 1988)

Journal Articles and Conference Proceedings

1. VACUUM FLUCTUATION EFFECTS ON MESON PROPAGATORS
   C. J. Horowitz and R. J. Furnstahl
   Nuclear Phys. **A485** (1988) 632.

2. QUASIELASTIC PROTON–NUCLEUS SCATTERING IN A RELATIVISTIC PLANE WAVE IMPULSE APPROXIMATION
   C. J. Horowitz and D. P. Murdock
   Phys. Rev. **C37** (1988) 2032.

3. COMMENT ON RELATIVISTIC HARTREE CALCULATIONS FOR AXIALLY DEFORMED NUCLEI
   R. J. Furnstahl, C. J. Horowitz, C. E. Price, B. D. Serot, and G. E. Walker
   Phys. Rev. Lett. **60** (1988) 162.

4. VACUUM POLARIZATION AND COULOMB SUM RULE
   C. J. Horowitz
   Phys. Lett. **208B** (1988) 8.

5. RELATIVISTIC DYNAMICS FOR HEAVY ION COLLISIONS
   C. J. Horowitz
   Invited Talk at the International Workshop XIV on Gross Properties of Nuclei, Hirschegg, Austria (1988).

6. RELATIVISTIC EFFECTS ON QUASIELASTIC SPIN OBSERVABLES
   C. J. Horowitz
   Invited talk at the 3rd Conference on the Intersections Between Particle and Nuclear Physics, Rockport, Maine, May, 1988 (to be published by AIP.)

7. THE RELATIVISTIC NUCLEAR RESPONSE
   C. J. Horowitz
   Invited Talk at the International Conference on Spin Observables of Nuclear Probes, Telluride, CO, March, 1988 (Plenum, NY 1989).

8. COLLECTIVE MODES IN A RELATIVISTIC ELECTRON GAS: A SOURCE FOR ≈ 300 KEV ELECTRON LINES?
C. J. Horowitz
Phys. Lett. **B219** (1989) 210.

9. ELASTIC MAGNETIC ELECTRON SCATTERING AND VACUUM POLARIZATION
P. Blunden and C. J. Horowitz
Phys. Lett. **B240** (1990) 6.

10. QUASIELASTIC ELECTRON SCATTERING AND VACUUM POLARIZATION
C. J. Horowitz and J. Piekarewicz
Phys. Rev. Lett. **62** (1989) 391.

11. COLLECTIVE MODES IN A RELATIVISTIC MESON-NUCLEON SYSTEM
K. Lim and C. J. Horowitz
Nucl. Phys. **A501** (1989) 729.

12. COLD NUCLEAR FUSION IN METALLIC HYDROGEN AND NORMAL METALS
C. J. Horowitz
Phys. Rev. **C40** (1989) R1555.

13. NUCLEAR RESPONSE FUNCTIONS IN QUASIELASTIC ELECTRON SCATTERING
C. J. Horowitz and J. Piekarewicz
Nucl. Phys. **A511** (1990) 461.

14. COLD NUCLEAR FUSION IN DENSE METALLIC HYDROGEN
C. J. Horowitz
Astrophysical J. **367** (1991) 288.

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

16. NEUTRINO NEUTRAL CURRENT INTERACTIONS IN NUCLEAR MATTER
C. J. Horowitz and K. Wehrberger
Nucl. Phys. **A531** (1991) 665.

17. ELECTROMAGNETIC CURRENTS IN RELATIVISTIC MODELS
C. J. Horowitz
Dronten Summer School Lectures in "The Structure of Hadrons and Hadronic Matter", Aug. 1990.

18. RELATIVISITIC EFFECTS ON SPIN OBSERVABLES
C. J. Horowitz
Proc. Int'l. Conference on Spin and Isospin in Nuclear Reactions, ed. S. Wissink et al. (Plenum, NY 1991).

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

20. THE NUCLEAR TO QUARK-MATTER TRANSITION IN THE STRING-FLIP MODEL
    C. J. Horowitz and J. Piekarewicz
        Phys. Rev. **C44** (1991) 2753.

21. QUARK MODELS OF NUCLEAR MATTER: I. BASIC MODELS AND GROUND STATE PROPERTIES
    C. J. Horowitz and J. Piekarewicz
        Nucl. Phys. A (1992), in press.

22. TOTAL CROSS SECTION FOR $pp \rightarrow p + p + \pi^0$ CLOSE TO THRESHOLD
    C. J. Horowitz and H. O. Meyer et al.
        Nucl. Phys. **A539** (1992) 633.

23. NO EVIDENCE FOR A CUSP IN $pp \rightarrow pp\pi^0$ AT THE THRESHOLDS FOR $pp \rightarrow d\pi^+$ AND $pp \rightarrow pn\pi^+$,
    C. J. Horowitz and H. O. Meyer et al.
        Proc. XIII Int'l. Conf. on Few-Body Problems in Physics, Adelaide, Australia, Jan. 1992.

24. QUARK MODELS OF NUCLEAR MATTER
    C. J. Horowitz
        Proc. XV Nuclear Physics Symposium, Oaxtapec, Mexico, Jan. 1992.

25. DENSITY DEPENDENCE OF NUCLEAR NEUTRINO PAIR PRODUCTION
    C. J. Horowitz
        Phys. Rev. Lett. **69** (1992) 2627.

26. PARITY-VIOLATING QUASIELASTIC ELECTRON SCATTERING
    C. J. Horowitz
        Phys. Rev. C. (1992), in press.

27. THE ELECTROWEAK RESPONSE IN RELATIVISTIC RPA
    C. J. Horowitz
        Proc. Dirk Walecka 60^{th} Birthday Symposium, CEBAF, April 1992.

28. QUASIFREE CHARGE-EXCHANGE AT INTERMEDIATE ENERGIES
    K. H. Hicks, P. Alford, A. Celler, R. S. Henderson, K. P. Jackson, C. A. Miller, M. C. Vetterli, S. Yen, F. Brieva, C. J. Horowitz, J. Piekarewicz
        Submitted to Phys. Rev. C.

29. SPIN-LONGITUDINAL TO SPIN-TRANSVERSE RATIO IN QUASIELASTIC $(\vec{p}, \vec{n})$ SCATTERING
    C. J. Horowitz and J. Piekarewicz
        Submitted to Phys. Lett. B.

Book Edited

1. Spin Observables of Nuclear Probes
   Editors C. J. Horowitz, C. Goodman and G. E. Walker
   (Plenum Press, New York, 1989).

Book Chapter

1. The Relativistic Impulse Approximation
   C. J. Horowitz, D. P. Murdock and Brian D. Serot
   in Computational Nuclear Physics, S. E. Koonin, K. Langanke, J. Maruhn, M. Zirnbauer, eds. (Springer, New York) 1991.

INVITED TALKS (Since 1988)

1. Density Momentum and Frame Dependence of the Optical Potential: Implications of Relativity
   C. J. Horowitz
   Gross Properties of Nuclei and Nuclear Excitations International Workshop XVI, Hirschegg, Kleinwalsertal, Austria, January, 1988.

2. The Relativistic Nuclear Response
   C. J. Horowitz
   International Conference on Spin Observables of Nuclear Probes, Telluride, Colorado, March, 1988.

3. Relativistic RPA Response of Nuclear Matter
   C. J. Horowitz
   Workshop on Relativistic Nuclear Many–Body Physics, Columbus, Ohio, June, 1988.

4. Relativistic Effects on Quasielastic Spin Observables
   C. J. Horowitz
   3rd Conference on the Intersections Between Particle and Nuclear Physics, Rockport, Maine, May, 1988.

5. Relativistic Nuclear Structure
   C. J. Horowitz
   International Conference on Contemporary Topics in Nuclear Structure, Cocoyoc, Mexico, June, 1988.

6. Quantum Hadrodynamics and the Dynamical Quantum Vacuum
   C. J. Horowitz
   Conference on Nuclear and Particle Physics on the Light Cone, Los Alamos, NM, July, 1988.

7. HOT AND COLD NUCLEAR FUSION
   C. J. Horowitz
   Nuclear Physics Gordon Conference, Tilton, New Hampshire, July, 1989.

8. ELECTROMAGNETIC CURRENTS IN THE 1990'S
   C. J. Horowitz
   APS/DNP Town Meeting on Nuclear Theory, East Lansing, MI, April, 1989.

9. TOWARDS A RELATIVISTIC NUCLEAR REACTION THEORY
   C. J. Horowitz
   Dubna USSR, February, 1990.

10. TOWARDS A RELATIVISITIC NUCLEAR REACTION THEORY
    C. J. Horowitz
    Novosibirsk USSR, March, 1990.

11. TOWARDS A RELATIVISTIC NUCLEAR REACTION THEORY
    C. J. Horowitz
    University of Iowa, Ames, Iowa, April, 1990.

12. ELECTROMAGNETIC CURRENTS IN RELATIVISTIC MODELS
    C. J. Horowitz
    Gordon Conference on Photonuclear Reactions, Tilton, New Hampshire, August, 1990.

13. RELATIVISTIC MESON-NUCLEON MODELS
    C. J. Horowitz
    Lecture Series at Dronten Summer School, Dronten, Holland, August, 1990.

14. QUARK MODELS OF NUCLEAR MATTER
    C. J. Horowitz
    Supercomputer Computations Research Institute, Florida State, January, 1991.

15. RELATIVISTIC EFFECTS ON SPIN OBSERVABLES
    C. J. Horowitz
    Int'l. Conference on Spin and Isospin in Nuclear Reactions, Telluride, CO, March, 1991.

16. RELATIVISTIC EFFECTS ON SPIN OBSERVABLES
    C. J. Horowitz
    Lampf, Los Alamos, May, 1991.

17. QUARK MODELS OF NUCLEAR MATTER
    C. J. Horowitz
    TRIUMF, July, 1991.

18. RELATIVISTIC MEAN FIELD THEORY
C. J. Horowitz
Series of Lectures at Summer Nuclear Institute, TRIUMF, July, 1991.

19. ELECTROMAGNETIC CURRENTS IN RELATIVISTIC MESON-NUCLEON MODELS
C. J. Horowitz
Workshop on The Nuclear Hamiltonian and Electromagnetic Current for the 1990s, Argonne, IL, August, 1991.

20. QUARK MODELS OF DENSE MATTER
C. J. Horowitz
Carleton, Ottawa, November, 1991.

21. QUARK MODELS OF DENSE MATTER
C. J. Horowitz
Boulder, CO, November, 1991.

22. QUARK MODEL CALCULATIONS
C. J. Horowitz
Washington University, St. Louis, MO, November, 1991.

23. RELATIVISTIC RPA FOR QUASIELASTIC E, P, AND ν SCATTERING
C. J. Horowitz
INT, Seattle, WA, December, 1991.

24. QUARK MODELS OF NUCLEAR MATTER
C. J. Horowitz
XV Nuclear Physics Symposium, Oaxtapec, Mexico, January, 1992.

25. THE ELECTROWEAK RESPONSE IN RELATIVISTIC RPA
C. J. Horowitz
Dirk Walecka 60^{th} Birthday Symposium, CEBAF, Newport News, VA, April, 1992.

26. RELATIVISTIC DESCRIPTIONS OF QUASIFREE SCATTERING
C. J. Horowitz
TRIUMF, Vancouver, Canada, May, 1992.

27. RELATIVISTIC NUCLEAR STRUCTURE
C. J. Horowitz
Institute for Nuclear Theory, Seattle, WA, October, 1992.

28. ELECTROWEAK CURRENTS IN RELATIVISTIC MODELS
C. J. Horowitz
University of Washington, Seattle, WA, November, 1992.

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CURRICULUM VITAE

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Education:

Degree	*Institution*	*Date*
M.A.	Edinburgh University	1955
Ph.D.	University of Rochester Thesis: *Single-Nucleon Transfer Reactions* J. B. French, Advisor	1959

Scholarships:

John Welsh Bursary Mathematics Scholarship	Edinburgh University	1951
Vans Dunlop Scholarship	Edinburgh University	1955

Fellowships:

John Simon Guggenheim Fellowship	Oxford University	1966
Alexander von Humboldt Fellowship	University of Bonn	1985

Academic Positions:

Research Associate	Argonne National Laboratory	1959–60
Assistant Professor	University of Rochester	1960–61
Associate Physicist	Argonne National Laboratory	1961–66
Visiting Fellow	Oxford University	1966–67
Senior Physicist	Argonne National Laboratory	1967–80
Professor	University of Chicago	1969–80
Visiting Professor	Indiana University	1976–77
Professor	Indiana University	1980–

Administrative Positions:

Associate Editor	Physical Review Letters	1973–78
Director	Nuclear Theory Center	1981–85
Chairman	Graduate Advising Committee	1983–84
Member	Nuclear Science Advisory Committee	1983–

Member	Science Policy Advisory Committee	1983–
Member	Program Advisory Committee IUCF	1983–85
Member	Physics Advisory Committee ORNL	1985–
Member	Program Advisory Committee MIT-Bates Linear Electron Accelerator	1987–88
Chairman	Program Advisory Committee MIT-Bates Linear Electron Accelerator	1988–90
Member	Physics Division Review Committee Argonne National Laboratory	1990–

Professional and Academic Societies:

American Physical Society

Executive Committee of the American Physical Society

PUBLICATIONS (Since 1988)

Journal Articles and Chapters

1. PHYSICAL CONTENT OF PSEUDOPOTENTIAL INTERACTIONS
   M. H. Macfarlane and E. F. Redish
   Phys. Rev. **C37** (1988) 2245.

2. MAGNETIC DIPOLE STRENGTH FUNCTIONS IN HEAVY DEFORMED NUCLEI
   D. Zawischa, M. H. Macfarlane and J. Speth
   Phys. Rev. **C42** (1990) 1461.

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

4. THE ISOVECTOR M1 RESPONSE OF DEFORMED NUCLEI
   D. Zawischa, M. H. Macfarlane, and J. Speth
   Accepted for publication in *Comments on Nuclear and Particle Physics*

Invited Papers at International Conferences, National–Society Meetings and Summer Schools

1. THE NUCLEAR MAGNETIC DIPOLE RESPONSE
   M. H. Macfarlane
   Symposium on Nuclear Reaction Mechanisms, Calcutta, India (1989).

2. CONCLUDING REMARKS
   M.H. Macfarlane
   Symposium on Nuclear Reaction Mechanisms, Calcutta, India (1989).

3. The Nucleon-Nucleon Interaction On and Off the Energy Shell
M. H. Macfarlane
Conference on Nuclear Direct Reactions, Bangalore, India (1989).

4. Conference Summary
M. H. Macfarlane
Conference on Nuclear Direct Reactions, Bangalore, India (1989).

5. Survey of Nucleon-Nucleon Interaction Potentials
M. H. Macfarlane
Australian Universities Summer School on Physics (1989).

6. Conference Summary
M. H. Macfarlane
Symposium on Nucleon–Nucleon Bremsstrahlung, Los Alamos, NM (1990).

7. Conference Summary
M. H. Macfarlane
Symposium on the Theory of the Nucleon–Nucleus Optical Potential, Los Alamos, NM, (1991).

8. Theory of Nuclear Reactions
M. H. Macfarlane
6 Lectures at TRIUMF Summer Nuclear Institute, (1992).

COLLOQUIA AND SEMINARS (1991-92)

1. The Nucleon–Nucleon Interaction—Status after Half-a-Century's Labor
M. H. Macfarlane
Colloquium, Washington University, St. Louis, MO, February, 1991.

2. Near-threshold Pion Production in NN Collisions
M. H. Macfarlane
Seminar, University of Bochum, Germany, June, 1991.

3. Near-threshold Pion Production in NN Collisions
M. H. Macfarlane
Seminar, University of Nijmegan, Holland, June, 1991.

4. Theory of Nuclear Reactions
M. H. Macfarlane
Lecture Series, KFA Jülich, Germany, June, 1991.

5. The Nuclear M1 Response; a Status Report
M. H. Macfarlane
Seminar, Indiana University Nuclear Theory Center, Bloomington, Indiana, October, 1991.

6. Convergence–Acceleration; Applications in Nuclear and Particle Physics

M. H. Macfarlane

Seminar, Indiana University Nuclear Theory Center, Bloomington, Indiana, March, 1992.

7. QCD Sum Rules for Nuclear Physicists

M. H. Macfarlane

Series of 3 Lectures, KFA Jülich, Germany, July-August, 1992.

8. Lectures on QCD Sum Rules

M. H. Macfarlane

Series of Lectures, Indiana University Nuclear Theory Center, Bloomington, Indiana May-September, 1992.

9. QCD Sum Rules

M. H. Macfarlane

Colloquium, Indiana University Physics Department, Bloomington, Indiana, December, 1992.

BRIAN DAVID SEROT
Department of Physics
Indiana University, Bloomington

CURRICULUM VITAE

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Education:

Degree	*Institution*	*Date*
B. S.	Yale University Graduated *summa cum laude* Distinction in Physics	1975
M. S.	Stanford University	1977
Ph. D.	Stanford University Thesis: *Unified Gauge Theories in Nuclear Physics* J. D. Walecka, Advisor	1979

Fellowships:

Dr. Chaim Weizmann Postdoctoral Fellowship	M. I. T.	1979–80
Alfred P. Sloan Foundation Fellowship	Stanford University	1982–83
	and	
	Indiana University	1984–86

Academic Positions:

Postdoctoral Fellow	M. I. T.	1979–80
Assistant Professor	Stanford University	1980–83
Associate Professor	Indiana University (Granted tenure 1986)	1984–87
Professor	Indiana University	1987–
Director	Indiana University Nuclear Theory Center	1987–90

Professional Committees:

IUCF Program Advisory Committee, 1987–1990

Department of Energy (DOE) review panel for Nuclear Theory Institute proposals, 1989

Nuclear Science Advisory Committee (NSAC) Long-Range Plan Working Group, 1989

Nuclear Physics Division (American Physical Society) Ph. D. Dissertation Award Committee, 1989

Nuclear Physics Division (American Physical Society) Program Committee, 1990–92

Co-organizer, Program on Mesons and Fields in Nuclei, Institute for Nuclear Theory, University of Washington, 1991–2

Nuclear Physics Division (American Physical Society) Physics News Committee, 1992

LAMPF Progr~m Advisory Committee, 1992–

Professional and Academic Societies:

Phi Beta Kappa

American Physical Society

Sigma Xi

Award:

Outstanding Instructor of Graduate Students
Physics Department, Indiana University, 1985–86

PUBLICATIONS (Since 1988)

Book Chapters

A RELATIVISTIC THEORY OF NUCLEAR MATTER
Brian D. Serot
in *Nuclear Matter and Heavy Ion Collisions*, M. Soyeur, H. Flocard, B. Tamain, and M. Porneuf, eds. (Plenum, New York, 1989), p. 37.

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

Book Edited

DIRKFEST '92: A SYMPOSIUM IN HONOR OF J. DIRK WALECKA'S SIXTIETH BIRTHDAY
W. W. Buck, K. Maung Maung, and Brian D. Serot
World Scientific, Singapore, 1992.

Research Journal Articles

1. COMMENT ON "RELATIVISTIC HARTREE CALCULATIONS FOR AXIALLY DEFORMED NUCLEI"
R. J. Furnstahl, C. J. Horowitz, C. E. Price, B. D. Serot, and G. E. Walker
Physical Review Letters **60** (1988) 162.

2. DIRAC OPTICAL POTENTIALS CONSTRAINED BY A DIRAC–HARTREE APPROACH TO NUCLEAR STRUCTURE
S. Hama, B. C. Clark, R. E. Kozack, S. Shim, E. D. Cooper, R. L. Mercer, and B. D. Serot
Physical Review **C37** (1988) 1111.

3. LATTICE REGULARIZATION OF QUANTUM PARTITION FUNCTIONS
R. J. Furnstahl and B. D. Serot
Annals of Physics (N.Y.) **185** (1988) 138.

4. TWO-LOOP CORRECTIONS FOR NUCLEAR MATTER IN THE WALECKA MODEL
R. J. Furnstahl, R. J. Perry, and Brian D. Serot
Physical Review **C40** (1989) 321; **C41** (1990) 404 (E).

5. COMPATIBILITY OF CHIRAL AND NON-CHIRAL MODELS IN QUANTUM HADRODYNAMICS
Wei Lin and Brian D. Serot
Physics Letters **233B** (1989) 23.

6. COVARIANT MEAN-FIELD CALCULATIONS OF FINITE TEMPERATURE NUCLEAR MATTER
R. J. Furntstahl and Brian D. Serot
Physical Review **C41** (1990) 262.

7. MID-RANGE NUCLEON-NUCLEON INTERACTION IN THE LINEAR SIGMA MODEL
Wei Lin and Brian D. Serot
Nuclear Physics **A512** (1990) 637.

8. MODIFIED LOOP EXPANSION FOR NUCLEAR MATTER IN A CHIRAL MODEL
K. Wehrberger, R. Wittman, and Brian D. Serot
Physical Review **C42** (1990) 2680.

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

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

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

12. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories
M. P. Allendes and Brian D. Serot
Physical Review **C45** (1992) 2975.

13. Chiral QHD with Vector Mesons
Brian D. Serot and John Dirk Walecka
Acta Physica Polonica **B23** (1992) 655.

14. Quantum Hadrodynamics
Brian D. Serot
Reports on Progress in Physics **55** (1992) 1855.

15. Finite Nuclei in Relativistic Models with a Light Chiral Scalar Meson
R. J. Furnstahl and Brian D. Serot
Submitted to Physical Review C.

Invited Papers Published in Conference Proceedings

1. Covariant Calculations of Finite Temperature Nuclear Matter
Brian D. Serot
Relativistic Nuclear Many-Body Physics, B. C. Clark, R. J. Perry, and J. P. Vary, eds., (World Scientific, Singapore, 1989), p. 234.

2. Relativistic Correlations in Nuclear Matter
Brian D. Serot
Proc. CEBAF/SURA 1988 Summer Workshop (June 20–24, 1988, Newport News, VA), F. Gross and J. Lightbody, eds. (1989), p. 186.

3. Two-Loop Calculations in the Walecka Model
Brian D. Serot
Proc. Workshop on Gross Properties of Nuclei and Nuclear Excitations XVII, Hirschegg, Kleinwalsertal, Austria (January 16–21, 1989), H. Feldmeier, ed. (1989), p. 1.

4. Hot Relativistic Nuclear Matter
Brian D. Serot
Proc. Summer School on Computational Atomic and Nuclear Physics, C. Bottcher, M. R. Strayer, and J. B. McGrory, eds. (World Scientific, Singapore, 1990), p. 162.

5. Relativistic Many-Body Problems
Brian D. Serot
Proc. Workshop "From Fundamental Fields to Nuclear Physics," Boulder, CO (September 20–22, 1990), J. A. McNeil and C. E. Price, eds. (World Scientific, Singapore, 1991), p. 144.

6. RELATIVISTIC NUCLEAR MANY-BODY THEORY
   Brian D. Serot and John Dirk Walecka
   Recent Progress in Many-Body Theories, vol. 3, T. L. Ainsworth, C. E. Campbell, B. E. Clements, and E. Krotscheck, eds. (Plenum, New York, 1992), p. 49.

7. NUCLEAR STRUCTURE IN A RELATIVISTIC QUANTUM FIELD THEORY
   Brian D. Serot
   Dirkfest '92: A Symposium in Honor of J. Dirk Walecka's Sixtieth Birthday, Newport News, VA (April 24–25, 1992), W. W. Buck, K. Maung Maung, and Brian D. Serot, eds. (World Scientific, Singapore, 1992), in press.

Abstracts

1. FERMI-LIQUID PROPERTIES OF NUCLEAR MATTER IN A RELATIVISTIC HARTREE–FOCK APPROXIMATION
   H. Uechi and Brian D. Serot
   Spring Meeting of the American Physical Society, Baltimore, MD, April 18–21, 1988, Bulletin American Physical Society **33** (1988) 990.

2. MID-RANGE NUCLEON-NUCLEON INTERACTION IN THE LINEAR σ MODEL
   Wei Lin and Brian D. Serot
   Spring Meeting of the American Physical Society, Baltimore, MD, May 1–4, 1989, Bulletin American Physical Society **34** (1989) 1246.

3. ROLE OF THE SIGMA MESON IN THE P_{33} CHANNEL OF PION-NUCLEON SCATTERING
   Wei Lin and Brian D. Serot
   Spring Meeting of the American Physical Society, Baltimore, MD, April 16–19, 1990, Bulletin American Physical Society **35** (1990) 1019.

4. RELATIVISTIC RPA ENERGY IN A MESON-NUCLEON SYSTEM
   Kyungmi Lim and Brian D. Serot
   Spring Meeting of the American Physical Society, Baltimore, MD, April 16–19, 1990, Bulletin American Physical Society **35** (1990) 1040.

5. MODIFIED LOOP EXPANSION FOR NUCLEAR MATTER IN A CHIRAL MODEL
   K. Wehrberger, R. Wittman, and Brian D. Serot
   Twelfth International Conference on Particles and Nuclei (PANIC XII), Massachusetts Institute of Technology, June 25–29, 1990, contributed papers, p. II–74.

6. VERTEX CORRECTIONS TO VACUUM POLARIZATION IN HADRONIC FIELD THEORIES

   M. P. Allendes and Brian D. Serot

   Spring Meeting of the American Physical Society, Washington, DC, April 20–24, 1992, Bulletin American Physical Society **37** (1992) 1040.

7. FINITE NUCLEI IN RELATIVISTIC MODELS WITH A LIGHT CHIRAL SCALAR MESON

   Brian D. Serot and R. J. Furnstahl

   Nuclear Physics Division Meeting of the American Physical Society, Santa Fe, NM, October 14–17, 1992, Bulletin American Physical Society **37** (1992) 1287.

SEMINARS, COLLOQUIA, INVITED TALKS (Since 1990)

1. Covariant Calculations of Finite Temperature Nuclear Matter. Nuclear Theory Seminar, The Ohio State University, March 16, 1990.
2. Relativistic Nuclear Structure Physics. Physics Colloquium, Purdue University, March 22, 1990.
3. Relativistic Many-Body Problems. Invited talk given at the Workshop "From Fundamental Fields to Nuclear Phenomena," Boulder, CO, September 21, 1990.
4. Chiral Symmetry and Nuclear Structure. Physics Colloquium, Indiana University, October 17, 1990.
5. Relativistic Many-Body Problems. Nuclear Theory Seminar, Argonne National Laboratory, March 7, 1991.
6. Relativistic Many-Body Problems. Nuclear Theory Seminar, University of Illinois, Urbana-Champaign, April 3, 1991.
7. Relativistic Many-Body Problems. Nuclear Theory Seminar, CEBAF, May 15, 1991.
8. Relativistic Nuclear Many-Body Theory. Invited talk given at the Seventh International Conference on Recent Progress in Many-Body Theories, University of Minnesota, August 27, 1991.
9. Chiral Symmetry and Nuclear Structure. Theoretical Physics Seminar, University of Arizona, September 24, 1991.
10. Relativistic Nuclear Many-Body Theory. Physics Colloquium, University of Arizona, September 25, 1991.
11. The Meson–Baryon Vertex in Hadronic Field Theories. Contributed talk at the Annual Midwest Nuclear Theory Get-Together, Indiana University, September 28, 1991.
12. Covariant Feynman Rules at Finite Temperature. Nuclear Theory Seminar, Institute for Nuclear Theory, University of Washington, December 13, 1991.
13. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, Institute for Nuclear Theory, University of Washington, January 17, 1992.

14. Relativistic Nuclear Many-Body Theory. Physics Division Colloquium, Los Alamos National Laboratory, March 12, 1992.
15. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, CEBAF, April 3, 1992.
16. Relativistic Nuclear Many-Body Theory. Physics Colloquium, University of Wisconsin, Madison, April 10, 1992.
17. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, State University of New York at Stony Brook, April 16, 1992.
18. Nuclear Structure in a Relativistic Quantum Field Theory. Invited talk given at Dirkfest '92: A Symposium in Honor of J. Dirk Walecka's Sixtieth Birthday, CEBAF, April 25, 1992.
19. Relativistic Nuclear Many-Body Theory. Physics Department Colloquium, University of New Hampshire, Durham, May 11, 1992.
20. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, University of Maryland, May 18, 1992.
21. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, Ohio State University, June 16, 1992.
22. Relativistic Nuclear Many-Body Theory. Lectures given at the Fifth Annual Summer School in Nuclear Physics Research, Oregon State University, Corvallis, OR, July 5–11, 1992.

CURRICULUM VITAE

Tetsuo Matsui

Nationality:	Japanese Citizen / U.S. Permanent Resident
[redacted]:	[redacted]
[redacted]:	
Marital Status:	Married / two children
Home Address:	2114 S. Locust Court, Bloomington, IN 47401
Home Phone:	(812)336-6528
Present Position:	Associate Professor of Physics
Affiliation:	Nuclear Theory Center and Department of Physics Indiana University
Work Address:	Swain West 225, Physics Department Indiana University, Bloominton, IN 47405
Work Phone:	(812)855-2609

Education and Past Academic Positions:

1975	A.B., Physics, Kyoto University
1977	M.A., Physics, Nagoya University
1980	Ph.D., Physics, Nagoya University
1980	JSPS Fellow, Department of Physics, Nagoya University
1980-82	Research Associate, Department of Physics, Stanford University
1982-84	Research Associate, Nuclear Science Division, Lawrence Berkeley Laboratory, University of California
1984-86	Research Scientist, Laboratory for Nuclear Science, Massachusetts Institute of Technology
1986-1991	Principal Research Scientist, Laboratory for Nuclear Science, Massachusetts Institute of Technology
1991-present	Associate Professor, Department of Physics Indiana University

Fellowship and Short-Term Visiting Positions:

1980	Fellow of Japan Society for Promotion of Science
1985	Visiting Fellow, Research Institute for Theoretical Physics, University of Helsinki
1988	Visiting Associate Professor, Institute de Physique Nucleaire, Universités Paris XI, Orsay

PUBLICATIONS (Since 1988)

1. J/ψ SUPPRESSION BY PLASMA FORMATION
   T. Matsui
   Z. Physik **C38** (1988) 245.

2. PATTERN OF J/ψ SUPPRESSION IN ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS
   T. Matsui and M.-C. Chu
   Phys. Rev. **D37** (1988) 1851.

3. DYNAMICS OF ULTRARELATIVISTIC COLLISIONS AND SINGNALS OF DECONFINEMENT
   T. Matsui
   Nucl. Phys. **A488** (1988) 535c (Invited talk at the Third International Conference of Nucleus-Nucleus Collisions, Saint-Malo, France, June 6-11, 1988).

4. DYNAMIC DEBYE SCREENING FOR A HEAVY QUARK-ANTIQUARK PAIR TRAVERSING A QUARK-GLUON PLASMA
   T. Matsui and M.-C. Chu
   Phys. Rev. **D39** (1989) 1892.

5. HADRONIZATION OF THE FLUX TUBES IN ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS
   T. Matsui and M. Kataja
   Ann. Phys. **191** (1989) 383.

6. DISTORTION OF CHARMONIUM FORMATION AMPLITUDE BY DECONFINED ENVIRONMENT
   T. Matsui
   Ann. Phys. **196** (1989) 182.

7. ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS AND THE QUARK-GLUON PLASMA IN *Intermediate Energy Nuclear Physics*,
   T. Matsui, ed. D.-P. Min
   Proceedings of the Second Symposium on Nuclear Physics, Kyungju, 1989, (Han Lim Won, 1990), p. 150 – 220.

8. DILEPTON PRODUCTION FROM A NONEQUILIBRIUM QUARK-GLUON PLASMA IN ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS
   T. Matsui and M. Asakawa
   Phys. Rev. **D43** (1991) 2871.

9. PASSAGE OF HIGH ENERGY PARTONS THROUGH A QUARK-GLUON PLASMA
   T. Matsui and Y. Koike
   Phys. Rev. **D45** (1992) 3237.

10. SIGNATURES OF THE QUARK-GLUON PLASMA IN ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

T. Matsui

Indiana University preprint NTC 92-17, to appear in the Proceedings of the Riken symposium on the Physics of Ultrarelativistic Nucleus-Nucleus Collisions, Riken, Wako, Japan, January 24 – 25, 1992.

INVITED TALKS (1991-92)

1. DIAGNOSING COLLECTIVE PLASMA BEHAVIORS IN SUPERDENSE HADRONIC MATTER

   T. Matsui

   Invited talk at Americal Physical Society – Division of Nuclear Physics – 1991 Fall Meeting, Michigan State University, East Lansing, MI, October 1991.

2. SIGNATURES OF THE QUARK-GLUON PLASMA

   T. Matsui

   Invited talk at Riken Symposiun on Physics of High Energy Heavy Ion Collisions, Institute of Physical and Chemical Research (Riken), Wako, Saitama, Japan, January 23-24, 1992.

CURRICULUM VITAE

DAVID K. GRIEGEL

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Indiana University
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[redacted]

Education:

University of Maryland, College Park, Maryland

Attended:	September 1985–August 1991
Degrees:	M.S. in Physics (May 1989)
	Ph.D. in Physics (December 1991)
Specialization:	Theoretical Nuclear Physics
Thesis:	Nucleon Propagation in Nuclear Matter: A QCD Sum Rule Approach
Advisor:	Thomas D. Cohen

Pennsylvania State University, University Park, Pennsylvania

Attended:	September 1982–May 1985
Degree:	B.S. in Physics (May 1985) with High Distinction and with Honors in Physics
Thesis:	Least Squares Momentum Reconstruction for the PS183 Spectrometer
Advisors:	Raymond A. Lewis and Stephen M. Playfer

Honors and Awards:

SURA/CEBAF Fellowship (1990–1991)
Teas Scholarship for Physics (1984–1985)

PUBLICATIONS:

1. Finite-Density Effective Sigma Meson Mass in Chiral Models, D. K. Griegel and T. D. Cohen, Phys. Rev. C **39**, 1032 (1989).
2. Vacuum Effects of Non-Nucleonic Baryons in Nuclear Matter, D. K. Griegel and T. D. Cohen, Nucl. Phys. **A510**, 671 (1990).
3. Effective Potential of the Δ Isobar in a Background Scalar Field, D. K. Griegel, Phys. Rev. C **43**, 904 (1991).

4. Exotic High-Isospin Baryons in the Skyrme Model: Experimental Observable or Large-N Artifact?, T. D. Cohen and D. K. Griegel, Phys. Rev. D **43**, 3089 (1991).
5. From QCD Sum Rules to Relativistic Nuclear Physics, T. D. Cohen, R. J. Furnstahl, and D. K. Griegel, Phys. Rev. Lett. **67**, 961 (1991).
6. Quark and Gluon Condensates in Nuclear Matter, T. D. Cohen, R. J. Furnstahl, and D. K. Griegel, Phys. Rev. C **45**, 1881 (1992).
7. QCD Sum Rules for Nucleons in Nuclear Matter, R. J. Furnstahl, D. K. Griegel, and T. D. Cohen, Phys. Rev. C **46**, 1507 (1992).
8. QCD Sum Rules for Nucleons in Nuclear Matter II, X. Jin, T. D. Cohen, R. J. Furnstahl, and D. K. Griegel, IUNTC Report No. 92–24.

SEMINARS:

1. FROM QCD SUM RULES TO RELATIVISTIC NUCLEAR PHYSICS:
   Los Alamos National Laboratory, January 1991
   Indiana University, February 1991
   University of Pennsylvania, February 1991
   Brookhaven National Laboratory, February 1991
2. QUARK AND GLUON CONDENSATES IN NUCLEAR MATTER:
   Indiana University, September 1991
3. INTRODUCTION TO QCD SUM RULES (LECTURE SERIES):
   Indiana University, February–March 1992
4. QCD SUM RULES AND THE NUCLEON SIGMA TERM:
   Ohio State University, February 1992
   Indiana University, February 1992

CONFERENCE TALKS:

1. THE FINITE-DENSITY EFFECTIVE SIGMA MESON MASS IN CHIRAL MODELS,
   American Physical Society Meeting, Baltimore, May 1989.
2. VACUUM EFFECTS OF NON-NUCLEONIC BARYONS IN NUCLEAR MATTER,
   American Physical Society Meeting, Washington, April 1990.
3. FINITE-DENSITY QUARK AND GLUON CONDENSATES FROM THE SIGMA COMMUTATOR,
   American Physical Society Meeting, Washington, April 1991.
4. QUARK CONDENSATES AND NUCLEON SELF-ENERGIES IN NUCLEAR MATTER,
   Midwest Nuclear Theory Get-Together, Indiana University, September 1991.
5. QCD SUM RULES AND THE NUCLEON SIGMA TERM, MESONS AND FIELDS IN NUCLEI WORKSHOP,
   University of Washington, January 1992;
   American Physical Society Meeting, Washington, April 1992.

Academic Positions:

Nuclear Theory Center, Indiana University
Research Associate
September 1991–present

Nuclear Theory Group, University of Maryland
Graduate Research Assistant
June 1988–August 1989
January 1990–August 1991

Goddard Space Flight Center, National Aeronautics and Space Administration
Graduate Research Assistant
June 1986–August 1986

Department of Physics and Astronomy, University of Maryland
Graduate Teaching Assistant
September 1985–May 1986
September 1986–May 1988
September 1989–December 1989

Laboratory for Elementary Particle Science, Pennsylvania State University
Undergraduate Research Assistant
September 1984–August 1985

Susan V. Gardner

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Tel: (812) 323-0361

Personal

[redacted] Citizenship: United States

Present Position

Postdoctoral Fellow, Nuclear Theory Center, Indiana University.

Education

MASSACHUSETTS INSTITUTE OF TECHNOLOGY — Cambridge, MA
Ph.D. degree in Theoretical Nuclear Physics, May, 1988.
Thesis "Effective Hadron Theories from a Quark Model" under the supervision of Prof. E. J. Moniz.

COLUMBIA UNIVERSITY — New York, NY
M.A. degree in Chemical Physics, October, 1983.

CALIFORNIA INSTITUTE OF TECHNOLOGY — Pasadena, CA
B.S. degree with honors in Physics and Chemistry, June, 1982.
Thesis "A Semi-classical Optical Model Potential for Quadrupole Coulomb Excitation of Heavy Ions" under the supervision of Prof. S. E. Koonin.

Experience

1. Postdoctoral fellow at the Nuclear Theory Center of Indiana University, 8/92–present.
2. Postdoctoral fellow in the Theory Group at CEBAF, 9/90–7/92.
3. Wissenschaftliche Mitarbeiterin am Institut für Theoretische Physik der Universität Heidelberg. Taught tutorials in topics in theoretical physics (Glauber theory, nuclear optical models, superconductivity, etc.) and TA'd (Spr. '89) Computational Physics - a course based on Koonin's textbook, 9/88–8/90.
4. Research assistant in the Center for Theoretical Physics, M.I.T. Organized a study group in nuclear astrophysics (Fall '87), 9/83–8/88.

5. Teaching fellow in the Chemistry Dept., Columbia University. Taught freshman chemistry laboratory, 9/82–6/83.
6. Summer research assistant in chemistry in Prof. B. V. McKoy's group, Caltech. Extended Fano theory of an autoionized state in a continuum to the calculation of the photoionization cross-section of acetylene, 6/82–9/82.
7. Summer research assistant in chemistry in Prof. W. A. Goddard's group, Caltech. Worked on gradient programs to optimize molecular geometries for any kind of molecular wavefunction efficiently, 6/81–9/81.
8. Summer research fellow in chemistry in Prof. W. A. Goddard's group, Caltech. Calculated *ab initio* bond energies and distances for the bound states of PdO using various types of wavefunctions, which differed in their treatment of the correlated many-electron problem, 6/80–9/80.
9. Technician in geophysics, Caltech. Wrote software and built hardware for Prof. G. Wasserburg's fully programmable mass spectrometer, 7/79–9/79.

Awards

Summer Undergraduate Research Fellowship, Caltech, 1980.
Phi Lambda Upsilon (chemistry honor society), 1982.
American Association of University Women Educational Foundation "Sarah Berliner" Fellowship in Physical Science, 1990-1991.

Conferences

1. *Gordon Conference on Nuclear Structure Physics*, Tilton, NH, July, 1984.
2. *ITP Workshop on Nuclear Chromodynamics*, Santa Barbara, CA, August, 1985.
3. *Gordon Conference on Photonuclear Reactions*, Plymouth, NH, August, 1986. (presented a poster.)
4. *"Ettore Majorana" International School of Nuclear Physics: "Quarks in Hadrons and Nuclei"*, Erice, Sicily, July, 1987. (presented a short talk.)
5. *Gordon Conference on Nuclear Structure Physics*, Tilton, NH, August, 1987. (presented a short talk.)
6. *Ohio State Workshop on Relativistic Nuclear Many-Body Physics*, Columbus, OH, June, 1988. (presented an invited talk.)
7. *Gordon Conference on Nuclear Physics*, Tilton, NH, July, 1988.
8. *NATO Advanced Study Institute: "Hadrons and Hadronic Matter"*, Cargèse, Corsica, July, 1989.
9. *PANIC XII International Conference on Particles and Nuclei*, M.I.T., Cambridge, MA, June, 1990.
10. 4^{th} *Conference on the Intersections between Particle and Nuclear Physics*, Tucson, AZ, May 24-29, 1991. (presented a contributed paper.)
11. *INT Program on N*'s and Nucleon Structure*, Seattle, WA, June - Sept., 1991. (presented a talk.)
12. *Baryons '92*, New Haven, CT, June 1-4, 1992.

13. *Working Session for the European Electron Accelerator*, Clermont-Ferrand, France, May 25-July 4, 1992. (presented a talk.)
14. *Workshop on the European Electron Facility*, Mainz, Germany, Oct. 7-9, 1992. (presented a talk.)

PUBLICATIONS (Since 1987)

1. S. Gardner and E. J. Moniz, "Effective Hadron Theories from a Quark Model," *Phys. Rev.* **C36** (1987) 2504.
2. S. Gardner, "From a Quark Model to Effective Hadron Theories," in "Quarks in Hadrons and Nuclei," *Proceedings of the "Ettore Majorana" International School of Nuclear Physics, Erice, 1987*, published in *Progress in Part. and Nuc. Physics*, Vol. 20, A. Faessler, ed. (Pergamon, New York, 1988), p. 47.
3. S. Gardner, "Effective Hadron Theories from a Quark Model," in "Relativistic Nuclear Many-Body Physics," *Proceedings of the Workshop held at The Ohio State University, June 6-9, 1988*, B. C. Clark, R. J. Perry, and J. P. Vary, ed. (World Scientific, Singapore, 1989), p. 77.
4. J. Hüfner, B. Povh, and S. Gardner, "Nuclear Absorption of a J/ψ Meson During Its Formation, *Phys. Lett.* **B238** (1990) 103.
5. S. Gardner, "Effective Hadron Theories from a Quark Model in $U(1)$ and $SU(N)$ Color," *Phys. Rev.* **C42** (1990) 2193.
6. S. Gardner, "Color Transparency and the Energy Evolution of Final-State Interactions in Charmonium Photoproduction," in *Proceedings of the* 4^{th} *Conference on the Intersections between Particle and Nuclear Physics, Tucson, AZ, May 24-29, 1991*, published in *AIP Conference Proceedings 243*, W. T. H. Van Oers, ed. (AIP, New York, 1992), p. 771.
7. S. Gardner, "Color Transparency and Final-State Interactions in Photonuclear Charmonium Production," CEBAF-PR-92-002 preprint, submitted to *Phys. Rev.* **C**, March, 1992.
8. S. Gardner, "High Energy Multiple Scattering Theory," lectures at the HUGS (Hampton University Graduate Studies) summer school at CEBAF, May, 1992, to be published in the proceedings.
9. S. Gardner, "Color Transparency in $(e, e'p)$ and the Electroproduction of N^* Resonances," IU/NTC 92–27 preprint, submitted to *Phys. Rev. Lett.*, August, 1992.
10. S. Gardner and C. J. Horowitz, "Dynamical $SU(2)$ Color Correlations in a Quark Exchange Model of Nuclear Matter," in preparation.

INVITED TALKS (1992)

1. THE ORIGINS OF COLOR TRANSPARENCY
   S. Gardner
   Saclay, France, October 2, 1992.

2. Color Transparency and the Electroproduction of N^* Resonances
S. Gardner
Workshop on the European Electron Facility, Mainz, Germany, Oct. 7-9, 1992.

3. The Origins of Color Transparency
S. Gardner
Ohio State University, Columbus, Ohio, October 26, 1992.

7. Appendixes

Appendix I. Publications under the Present Grant (1990–92).

Appendixes I and II contain two lists. The first (Appendix I) is of papers published in refereed journals and book chapters in the years 1990–92 covered by the existing grant; it contains 50 publications, of which 42 have either appeared in print or been accepted for publication. The second list (Appendix II) is of invited talks given by the four principal investigators during these three years and 2 postdoctoral fellows since their arrival at Indiana University; 70 invited talks were given, 21 of them at national or international conferences (including summer schools).

Journal Articles and Book Chapters Supported by Existing Grant.

1. Elastic Magnetic Electron Scattering and Vacuum Polarization, P. Blunden and C. J. Horowitz, Phys. Lett. **240B** (1990) 6.
2. Covariant Mean-Field Calculations of Finite Temperature Nuclear Matter, R. Furnstahl and B. Serot, Phys. Rev. **C41** (1990) 262.
3. Nuclear Response Functions in Quasielastic Electron Scattering, C. J. Horowitz and J. Piekarewicz, Nuclear Phys. **A511** (1990) 461.
4. Mid-Range Nucleon-Nucleon Interaction in the Linear Sigma Model, W. Lin and B. D. Serot, Nucl. Phys. **A512** (1990) 637.
5. Magnetic Dipole Strength Functions in Heavy Deformed Nuclei, D. Zawischa, M. H. Macfarlane and J. Speth, Phys. Rev. **C42** (1990) 1461.
6. Cold Nuclear Fusion in Dense Metallic Hydrogen, C. J. Horowitz, Astrophysical J **367** (1991) 288.
7. Hot Relativistic Nuclear Matter, B. D. Serot, Proc. Summer School on Computational Atomic and Nuclear Physics, C. Bottcher, M. R. Strayer, and J. B. McGrory, eds. (World Scientific, Singapore, 1990), p. 162.
8. Correlation Observables in $(p, p'\gamma)$ Reactions, J. Piekarewicz, E. Rost and J. R. Shepard, Phys. Rev. **C41** (1990) 2277.
9. Pauli Blocking for Effective Deltas in Nuclear Matter, K. Wehrberger and R. Wittman, Nucl. Phys. **A513** (1990) 603.
10. Vacuum Polarization Effects on the Electromagnetic Response of Low–Lying Isoscalar Excitations, J. Piekarewicz, Nucl. Phys. **A511** (1990) 487.
11. Nuclear Magnetic Dipole Excitations, M. Macfarlane, Symposium on Nuclear Reaction Mechanisms, Facsimile Press (Calcutta), 1990, p. 51.
12. The Relativistic Impulse Approximation, C. J. Horowitz, D. Murdock and B. D. Serot, in *Computational Nuclear Physics* vol. I, K. Langanke, J. Maruhn, and S. E. Koonin, eds. (Springer, New York, 1991), p. 129.
13. Imaginary Part of the Nucleon Self-Energy in a Relativistic Field Theory, A. E. L. Dieperink, J. Piekarewicz and K. Wehrberger, Phys. Rev. **C41** (1990) R2479.

14. Analytic Expressions for Integrals of Products of Spherical Bessel Functions, R. Mehrem, J. T. Londergan and M. H. Macfarlane, Jour. of Physics **A24** (1991) 1435.
15. Pion-Nucleon Scattering in the P_{33} Channel in the Linear Sigma Model, Wei Lin and B. D. Serot, Nucl. Phys. **A524** (1991) 601.
16. Modified Loop Expansion for Nuclear Matter in a Chiral Model, K. Wehrberger, R. Wittman and Brian D. Serot, Phys. Rev. **C42** (1990) 2680.
17. Covariant Feynman Rules at Finite Temperature: Application to Nuclear Matter, R. J. Furnstahl and B. D. Serot, Phys. Rev. **C43** (1991) 105.
18. Neutrino Interactions in a Dense Plasma, C. J. Horowitz and K. Wehrberger, Phys. Rev. Lett. **21** (1991) 272.
19. Electromagnetic Currents in Relativistic Models, C. J. Horowitz, Dronten Summer School Lectures, on "The structure of hadrons and hadronic matter," August 1990.
20. Relativistic Many-Body Problems, Brian D. Serot, Proc. Workshop "From Fundamental Fields to Nuclear Physics," Boulder, CO (September 20–22, 1990), J. A. McNeil and C. E. Price, eds. (World Scientific, 1991), p. 144.
21. Neutrino Neutral Current Interactions in Nuclear Matter, C. J. Horowitz and K. Wehrberger, Nucl. Phys. **A531** (1991) 665.
22. Relativistic Effects on Spin Observables, C. J. Horowitz, Proc. Int'l. Conference on Spin and Isospin in Nuclear Reactions, Telluride, CO, March 1991.
23. Quark Models of Nuclear Matter: I. Basic Models and Ground State Properties, C. J. Horowitz, Nucl. Phys. **A536** (1992) 669.
24. Neutrino Neutral Current Interactions in Hot Dense Matter, C. J. Horowitz and K. Wehrberger, Phys. Lett. **B266** (1991) 236.
25. Covariant Feynman Rules at Finite Temperature: A Time-Path Formulation, B. D. Serot and R. J. Furnstahl, Phys. Rev. **C44** (1991) 2141.
26. Total Cross Section for $p + p \rightarrow p + p + \pi^0$ Close to Threshold, H. O. Meyer, C. J. Horowitz, H. Nann, P. V. Pancella, S. F. Pate, R. E. Pollock, B. v. Przewoski, T. Rinckel, M. A. Ross, and F. Sperisen, Nucl. Phys. **A539** (1992) 633.
27. The Nuclear to Quark-Matter Transition in the String-Flip Model, C. J. Horowitz and J. Piekarewicz, Phys. Rev. **C44** (1991) 2753.
28. Relativistic Nuclear Many-Body Theory, B. D. Serot, J. D. Walecka, *Recent Progress in Many-Body Theories*, Vol. 3 (1992) p. 49.
29. No Evidence for a Cusp in $pp \rightarrow pp\pi^0$ at the Thresholds for $pp \rightarrow d\pi^+$ and $pp \rightarrow pn\pi^+$, C. J. Horowitz and H. O. Meyer et al., Proc. XIII Int'l. Conf. on Few-Body Problems in Physics, Adelaide, Australia, Jan., 1992.
30. Passage of High-Energy Partons through a Quark-Gluon Plasma, T. Matsui and Y. Koike, Phys. Rev. **D45** (1992) 3237.
31. Theory of Nuclear Reactions, M.H. Macfarlane, TRIUMF Summer School Lectures, 1991.
32. Quark Models of Nuclear Matter, C.J. Horowitz, Proc. XV Nuclear Physics Symposium, Oaxtapec, Mexico, Jan. 1992.

33. Vertex Corrections to Vacuum Polorization in Hadronic Field Theories, M.P. Allendes and B.D. Serot, Phys. Rev. **C45** (1992) 2975.
34. Quantum Hadrodynamics, B.D. Serot, Reports on Progress in Physics, **55** (1992) 1855.
35. Giant Dipole Resonance in ^{208}Pb Within the Approach Including $1p1h \otimes$ Phonon Configurations and Continuum, W.A. Unkelbach, S. Kamerdzhiev, and G. Tertychny, to be published in Phys. Lett. **B**.
36. Vacuum Pion Fluctuations Around the Bare Skrymion, H.B. Tang, to be published in Nucl. Phys. **A**.
37. Density Dependence of Nuclear Neutrino Pair Production, C.J. Horowitz, Phys. Rev. Lett. **69** (1992) 2627.
38. QCD Sum Rules for Nucleons in Nuclear Matter, R.J. Furnstahl, D.K. Griegel, and T.D. Cohen, Phys. Rev. **C46** (1992) 1507.
39. Signatures of the Quark Gluon Plasma in Ultra Relativistic Nucleus-Nucleus Collisions, T. Matsui, Proc. Physics of Ultrarelativisitic Nucleus-Nucleus Collisions at Riken, Wako, Saitama, Japan, Jan. 1992.
40. Chiral QHD With Vector Mesons, B.D. Serot and J.D. Walecka, Acta Physica Polonica **B23** (1992) 655.
41. Nuclear Structure in a Relativistic Quantum Field Theory, B.D. Serot, Proc. of Dirk Walecka 60th Birthday, CEBAF, Newport News, VA, April, 1992.
42. Parity-Violating Quasielastic Electron Scattering, C.J. Horowitz, Phys. Rev. **C**, in press.
43. QCD Sum Rules for Nucleons in Nuclear Matter II, X. Jin, T.D. Cohen, R.J. Furnstahl, D.K. Griegel, submitted to Phys. Rev. C.
44. The Electroweak Response in Relativistic RPA, C.J. Horowitz, Proc. Dirk Walecka 60th Birthday, CEBAF, Newport News, VA, April, 1992.
45. Quasifree Charge-Exchange at Intermediate Energies, C.J. Horowitz, Hicks et al, submitted to Phys. Rev. C.
46. Color Transparency in $(e, e'p)$ and the Electroproduction of N^* Resonances, S. Gardner, submitted to Phys. Rev. C.
47. Spin-longitudinal and Spin-transverse Ratio in Quasielastic $(\vec{p}\vec{n})$ Scattering, C.J. Horowitz and J. Piekarewicz, submitted to Phys. Lett. B.
48. Finite Nuclei in Relativistic Models with a Light Chiral Scalar Model, B.D Serot and R. Furnstahl, submitted to Phys. Rev. C.
49. QCD Sum Rules: objectives and origins, M.H. Macfarlane, lectures at Inst. Kernphysik, Jülich, Germany, Aug. 1992.
50. The Isovector M1 Response of Deformed Nuclei, D. Zawischa, M. H. Macfarlane, and J. Speth, to be published in *Comments on Nuclear and Particle Physics.*

Appendix II. Invited Talks under the Present Grant (1990-92)

C. J. HOROWITZ

1. Towards a Relativistic Nuclear Reaction Theory, Dubna USSR, February, 1990.
2. Towards a Relativistic Nuclear Reaction Theory, Novosibirsk USSR, March, 1990.
3. Towards a Relativistic Nuclear Reaction Theory, University of Iowa, Ames, Iowa, April, 1990.
4. Electromagnetic Currents in Relativistic Models, Gordon Conference on Photonuclear Reactions, Tilton, New Hampshire, August, 1990.
5. Relativistic Meson-Nucleon Models, Lecture Series at Dronten Summer School, Dronten, Holland, August, 1990.
6. Quark Models of Nuclear Matter, Supercomputer Computations Research Institute, Florida State, January, 1991.
7. Relativistic Effects on Spin Observables, Int'l. Conference on Spin and Isospin in Nuclear Reactions, Telluride, CO, March, 1991.
8. Relativisitic Effects on Spin Observables, LAMPF, Los Alamos, May, 1991.
9. Quark Models of Nuclear Matter, TRIUMF, July, 1991.
10. Relativistic Mean Field Theory, Series of Lectures at Summer Nuclear Institute, TRIUMF, July, 1991.
11. Electromagnetic Currents in Relativistic Meson-Nucleon Models, Workshop on The Nuclear Hamiltonian and Electromagnetic Current for the 1990s, Argonne, IL, August, 1991.
12. Quark Models of Dense Matter, Carleton, Ottawa, November, 1991.
13. Quark Models of Dense Matter, Boulder, CO, November, 1991.
14. Quark Model Calculations, Washington University, St. Louis, MO, November, 1991.
15. Relativistic RPA for Quasielastic e, p, and ν Scattering, Institute for Nuclear Theory, Seattle, WA, December, 1991.
16. Quark Models of Nuclear Matter, XV Nuclear Physics Symposium, Oaxtapec, Mexico, January, 1992.
17. The Electroweak Response in Relativistic RPA, Dirk Walecka 60^{th} Birthday Symposium, CEBAF, Newport News, VA, April, 1992.
18. Relativistic Descriptions of Quasifree Scattering, TRIUMF, Vancouver, Canada, May, 1992.
19. Relativistic Nuclear Structure, Institute for Nuclear Theory, Seattle, WA, October, 1992.
20. Electroweak Currents in Relativistic Models, University of Washington, Seattle, WA, November, 1992.

B. D. SEROT

1. Covariant Calculations of Finite Temperature Nuclear Matter. Nuclear Theory Seminar, The Ohio State University, March 16, 1990.

2. Relativistic Nuclear Structure Physics. Physics Colloquium, Purdue University, March 22, 1990.
3. Relativistic Many-Body Problems. Invited talk given at the Workshop "From Fundamental Fields to Nuclear Phenomena," Boulder, CO, September 21, 1990.
4. Chiral Symmetry and Nuclear Structure. Physics Colloquium, Indiana University, October 17, 1990.
5. Relativistic Many-Body Problems. Nuclear Theory Seminar, Argonne National Laboratory, March 7, 1991.
6. Relativistic Many-Body Problems. Nuclear Theory Seminar, University of Illinois, Urbana-Champaign, April 3, 1991.
7. Relativistic Many-Body Problems. Nuclear Theory Seminar, CEBAF, May 15, 1991.
8. Relativistic Nuclear Many-Body Theory. Invited talk given at the Seventh International Conference on Recent Progress in Many-Body Theories, University of Minnesota, August 27, 1991.
9. Chiral Symmetry and Nuclear Structure. Theoretical Physics Seminar, University of Arizona, September 24, 1991.
10. Relativistic Nuclear Many-Body Theory. Physics Colloquium, University of Arizona, September 25, 1991.
11. The Meson–Baryon Vertex in Hadronic Field Theories. Contributed talk at the Annual Midwest Nuclear Theory Get-Together, Indiana University, September 28, 1991.
12. Covariant Feynman Rules at Finite Temperature. Nuclear Theory Seminar, Institute for Nuclear Theory, University of Washington, December 13, 1991.
13. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, Institute for Nuclear Theory, University of Washington, January 17, 1992.
14. Relativistic Nuclear Many-Body Theory. Physics Division Colloquium, Los Alamos National Laboratory, March 12, 1992.
15. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, CEBAF, April 3, 1992.
16. Relativistic Nuclear Many-Body Theory. Physics Colloquium, University of Wisconsin, Madison, April 10, 1992.
17. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, State University of New York at Stony Brook, April 16, 1992.
18. Nuclear Structure in a Relativistic Quantum Field Theory. Invited talk given at Dirkfest '92: A Symposium in Honor of J. Dirk Walecka's Sixtieth Birthday, CEBAF, April 25, 1992.
19. Relativistic Nuclear Many-Body Theory. Physics Department Colloquium, University of New Hampshire, Durham, May 11, 1992.
20. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, University of Maryland, May 18, 1992.

21. Vertex Corrections to Vacuum Polarization in Hadronic Field Theories. Nuclear Theory Seminar, Ohio State University, June 16, 1992.
22. Relativistic Nuclear Many-Body Theory. Lectures given at the Fifth Annual Summer School in Nuclear Physics Research, Oregon State University, Corvallis, OR, July 5–11, 1992.

M. H. MACFARLANE

1. Conference Summary, Symposium on Nucleon–Nucleon Bremsstrahlung, Los Alamos, NM (1990).
2. Conference Summary, Symposium on the Theory of the Nucleon–Nucleus Optical Potential, Los Alamos, NM, (1991).
3. Theory of Nuclear Reactions, 6 Lectures at TRIUMF Summer Nuclear Institute, (1992).
4. The Nucleon–Nucleon Interaction—Status after Half-a-Century's Labor, Colloquium, Washington University, St. Louis, MO, February, 1991.
5. Near-Threshold Pion Production in NN Collisions, Seminar, University of Bochum, Germany, June, 1991.
6. Near-threshold Pion Production in NN Collisions, Seminar, University of Nijmegen, Holland, June, 1991.
7. Theory of Nuclear Reactions, Lecture Series, KFA Jülich, Germany, June, 1991.
8. The Nuclear M1 Response: a Status Report, Seminar, Indiana University Nuclear Theory Center, Bloomington, Indiana, October, 1991.
9. Convergence Acceleration: Applications in Nuclear and Particle Physics, Seminar, Indiana University Nuclear Theory Center, Bloomington, Indiana, March, 1992.
10. QCD Sum Rules for Nuclear Physicists, Series of 3 Lectures, KFA Jülich, Germany, July-August, 1992.
11. Lectures on QCD Sum Rules, Series of Lectures, Indiana University Nuclear Theory Center, Bloomington, Indiana May-September, 1992.
12. QCD Sum Rules, Colloquium, Indiana University Physics Department, Bloomington, Indiana, December, 1992.

T. MATSUI

1. Diagnosing Collective Plasma Behaviors in Superdense Hadronic matter, Invited talk at Americal Physical Society - Division of Nuclear Physics - 1991 Fall Meeting, Michigan State University, East Lansing, MI, October 1991.
2. Signatures of the Quark-Gluon Plasma, Invited talk at Riken Symposiun on Physics of High Energy Heavy Ion Collisions, Institute of Physical and Chemical Research (Riken), Wako, Saitama, Japan, January 23-24, 1992.

D. K. GRIEGEL

1. From QCD Sum Rules to Relativistic Nuclear Physics, Los Alamos National Laboratory, January 1991
2. From QCD Sum Rules to Relativistic Nuclear Physics, Indiana University, February 1991
3. From QCD Sum Rules to Relativistic Nuclear Physics, University of Pennsylvania, February 1991
4. From QCD Sum Rules to Relativistic Nuclear Physics, Brookhaven National Laboratory, February 1991
5. Quark and Gluon Condensates in Nuclear Matter, Indiana University, September 1991
6. Introduction to QCD Sum Rules (Lecture Series), Indiana University, February–March 1992
7. QCD Sum Rules and the Nucleon Sigma Term, Ohio State University, February 1992
8. QCD Sum Rules and Nucleon Sigma Term, Indiana University, February 1992
9. Quark Condensates and Nucleon Self-Energies in Nuclear Matter, Midwest Nuclear Theory Get-Together, Indiana University, September 1991.
10. QCD Sum Rules and the Nucleon Sigma Term, Mesons and Fields in Nuclei Workshop, University of Washington, January 1992;
11. QCD Sum Rules and the Nucleon Sigma Term, American Physical Society Meeting, Washington, April 1992.

S. GARDNER

1. The Origins of Color Transparency, Saclay, France, October 2, 1992.
2. Color Transparency and the Electroproduction of N^* Resonances, Workshop on the European Electron Facility, Mainz, Germany, Oct. 7-9, 1992.
3. The Origins of Color Transparency, Ohio State University, Columbus, Ohio, October 26, 1992.

Appendix III.

Current Staff of the Indiana University Nuclear Theory Center.

C. J. Horowitz, Professor of Physics

J. T. Londergan, Professor of Physics†

M. H. Macfarlane, Professor of Physics

T. Matsui, Associate Professor of Physics

B. D. Serot, Professor of Physics

G. E. Walker, Professor of Physics†

V. Dmitriev, Visiting Research Scientist

D. K. Griegel, Research Associate

S. Schramm, Research Associate†

W. A. Unkelbach, Visiting Research Associate*

S. Gardner, Visiting Research Associate‡

M. P. Allendes, Graduate Student

H. C. Kim, Graduate Student

H. B. Tang, Graduate Student

W. Melendez, Graduate Student**

H. S. Roh, Graduate Student

R. Roncaglia, Graduate Student†

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† Supported by NSF grant.

* Supported at 30% of salary for 1991–92; 50% for 1992–93.

‡ Supported by CEBAF for academic year 1992–93.

** Supported by Fellowship until August 1992.

Appendix IV. Research Topics of NSF-Supported Part of IUNTC

Examples of Research Topics for the NSF supported part of the Indiana University Nuclear Theory Center:

1. Pion and Eta Production from Intermediate Energy Protons.[1]
2. Flavor-Breaking Effects and the Gottfried Sum Rule.[2]
3. New EMC Effects.[3]
4. Bound States and Resonances in Quantum Wires and Waveguides.[4]
5. The Role of Retardation in Nuclear Structure and Response.[5]
6. Exchange-Current Effects in Medium-Energy Hadron–Nucleus Interactions.

[1]Distorted-Wave Calculation of $(p, p'\pi^+)$ Reaction, R. Mehrem, J. T. Londergan, and G. E. Walker, to be submitted to Phys. Rev. C.
[2]Origin of SU(2)-Flavor-Symmetry Breaking in Antiquark Distributions, S. Kumano and J. T. Londergan, Phys. Rev. **D44** (1991) 717.
[3]Improved Parton Distributions from the Quark Model, S. D. Bass, A. W. Schreiber, A. W. Thomas, and J. T. Londergan, Australian Jour. of Phys. **44** (1991) 363.
[4]Bound States and Resonances in Waveguides and Quantum Wires, J. P. Carini, J. T. Londergan, K. Mullen, and D. P. Murdock, submitted to Phys. Rev. Lett.
[5]Finite Velocity Meson Exchange in Nuclei, M. A. Crecca and G. E. Walker, Phys. Rev. **C43** (1991) 1709.

Appendix V. Visitors to NTC

Visitors to NTC Since January 1991

(* indicates more than 1 visit to NTC; † indicates extended visit)

Jouni Niskanen	University of Helsinki, Finland †
Stephan Mintz	Florida International University
Derek Leinweber	University of Maryland
Ming Chu	Caltech
Richard Furnstahl	Ohio State University
Anthony Thomas	University of Adelaide
Runan deKock	NAC, South Africa †
Greg Hillhouse	NAC, South Africa †
David Griegel	University of Maryland *
David Murdock	Tennessee Tech University *†
Brajesh K. Jain	Bhabha Atomic Institute, India †
Edward Redish	University of Maryland
Josef Speth	Institut fur Kernphysik, Germany
Stefan Schramm	Caltech
Susan Gardner	CEBAF *†
Oren Maxwell	Ohio State University *†
Siegfried Krewald	Institut fur Kernphysik, Germany
Edward Cooper	Ohio State University *†
Lon Chang Liu	Los Alamos National Lab
Boris Krippa	Russian Academy of Science, USSR †
Mahir Hussein	University of Sao Paulo, Brazil
Jorge Piekarewicz	Florida State University
Vladimir Dmitriev	Budker Inst. Nucl. Phys. Novosibirsk, Russia *†
Robert Jaffe	MIT
John Dawson	University of New Hampshire *
Gordon Baym	University of Illinois
Frank Close	Rutherford Lab, England
Tetsuo Matsui	MIT *
Klaus Wehrberger	Institut fur Kernphysik, Germany †
Wei Lin	University of Washington
Joseph Kapusta	University of Minnesota
Bernhard Blattel	University of Illinois
Robert McKeown	Caltech
Werner Koepf	Tech. Univ., Germany
Quentin Ingram	PSI, Switzerland

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