DOE/ER/40427-70

## Introduction

This is a closing summary of the Grant "Theoretical Nuclear Physics" (DOE-FG06-88ER40427), which continued our long-standing and vigorous program in Nuclear Theory.

As the three-year period FY93-FY96 ended, there were six senior investigators on the grant full-time: Bulgac, Henley, Miller, Savage, van Kolck and Wilets. This represents an increase of two members from the previous three-year period, achieved with only a two percent increase over the budget for FY90-FY93. In addition, the permanent staff of the Institute for Nuclear Theory (George Bertsch, Wick Haxton, and David Kaplan) continued to be intimately associated with our physics research efforts. Aurel Bulgac joined the Group in September, 1993 as an assistant professor, with promotion requested by the Department and College of Arts and Sciences by September, 1997. Martin Savage, who was at Carnegie-Mellon University, joined the Physics Department in September, 1996. U. van Kolck continued as research assistant professor, and we were supporting one postdoctoral research associate, Vesteinn Thorssen, who joined us in September, 1995. Seven graduate students were being supported by the Grant (Chuan-Tsung Chan, Michael Fosmire, William Hazelton, Jon Karakowski, Jeffrey Thompson, James Walden and Mitchell Watrous).

Recent years have seen a renewed surge of interest in the field of theoretical nuclear physics, in which studies of nuclei under a very broad array of conditions are pursued. Furthermore, the notion of using nuclei as a tool for fundamental studies in other fields such as astrophysics and particle physics has become very popular. In addition, the structure of the nucleon and other baryons, the relationship of quarks-gluons to nucleons-mesons, and the role of QCD in nuclear physics have emerged as topics of high interest to nuclear physicists. Our group, which has traditionally taken a very broad view of Nuclear Physics, has thrived in this atmosphere. Each group member has a vigorous and distinctive program of research. The publication records are strong, and we are repeatedly requested to present papers at major international and topical meetings and to serve on various national committees and review boards. Many of our students have gone on to successful careers in nuclear physics. In addition, Group members are actively involved in suggesting, proposing and collaborating on numerous kinds of experiments.

Since the research activities of our Group are broad and diverse, we have decided that the best way to present our work is to have each investigator present his or her activities and plans separately and in his or her own words. Before turning to the research topics, it is worthwhile to mention personnel categories in our Group. These are: (A) Senior Investigators, (B) Research Assistant Professor, (C) Postdoctoral positions, (D) Students, (E) Visitor Program, (F) Association with the Institute for Nuclear Theory, (G) Bridge Agreement with the College of Arts and Sciences and Association with the Continuous Beam Electron Accelerator Facility (CEBAF), and (H) Institutional Intellectual Support.

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A. Senior Investigators

Because a faculty position opened when Wick Haxton became Director of the INT in 1991, the Department carried out a search for a replacement at the assistant professor level. After an extensive search, an offer was made to and accepted by Tetsuo Hatsuda, who left in August, 1993 to accept a tenured position at Tsukuba University in Japan. The Department then hired Prof. Aurel Bulgac from Michigan State University. More recently, Prof. Henley and Wilets have decided to continue their work as Professors Emeriti. This development enabled the Department to negotiate a bridge agreement with the College of Arts and Sciences which allowed us to hire a new theorist. The agreement requires that the state fund the position after a specified number of retirements have occurred (approximately five years). Until then, the support will come from non-college sources. One advantage of this arrangement is that the new faculty member is required to teach only 50% of the full academic load. As discussed below in item G., Southeastern Universities Research Association, which is the Managing and Operating contractor for the Continuous Beam Accelerator facility (SURA/CEBAF) will provide a significant part of the funding for the position. We completed an extensive search, considering about 80 applicants and interviewing five excellent candidates. The unanimous choice of the Group, Search Committee, and indeed the entire Department was Martin Savage.

The other senior investigators in the Group are Profs. Bulgac, Henley, Miller, van Kolck and Wilets.

B. Research Assistant Professor

The Group's first Research Assistant Professor appointment was made in the Autumn of 1973. These positions are viewed as longer-term appointments (of course, subject to the availability of funds) to be filled by individuals who have the same qualifications as regular assistant professors.

The Research Assistant Professor position carries another important advantage. It has enabled research groups to channel suitably qualified persons into positions on the regular faculty. Several members of the current professorial staff started their University of Washington careers in temporary, research-funded positions. In Nuclear Theory, one example is Dr. Miller, who was promoted to the position of associate professor by University action in 1981. His position was converted in 1982 to one with full University support. He was promoted to full professor in 1985.

Budget constraints forced us to leave this position unfilled following 1986, when George Fuller left the University of Washington for a staff position in the IGPP group at Livermore. (He presently is a tenured associate professor at the University of California, San Diego.) In 1991, the DOE provided funds that allowed us to hire S. Huang, an outstanding young researcher from MIT and Boston University. He has left to work again at MIT. The opening was filled by Dr. U. van Kolck, an excellent researcher who did his Ph.D. thesis under the supervision of Steven Weinberg. van Kolck is a leading expert in the application of chiral perturbation theory to topics in nuclear physics.

C. Postdoctoral Positions

Our postdoctoral research associates make substantial contributions to the vitality of our program through their individual research efforts, their collaborations with the senior investigators, their interactions with the graduate students, and their organization of, and participation in, seminars and discussions. We have found that this infusion of new ideas and viewpoints is an invaluable stimulus to the entire research program. The only "job requirement" we have made historically is a willingness to work hard: the research associates are free to work on their own projects, with other young researchers, or with the senior staff, rather than being assigned to a pre-existing program.

Our previous research associates have had excellent success in obtaining academic positions. Caio Lewenkopf (November, 1995) took a permanent position at the State University of Rio de Janeiro, Brazil. Calvin Johnson (September, 1995) is now a faculty member at Louisiana State University. Yang Pang (September, 1990) is now on the staff at Brookhaven. Tony Williams (September, 1989) took a faculty position at Florida State University, and now is an assistant professor at Adelaide University, Australia. Previously, Dr. Robert Perry (September, 1987) took a faculty position at Ohio State University (where he has become a PYI), and Dr. Michael Birse (September, 1985) returned to England to assume a "new blood" faculty position at the University of Manchester. Similarly Dr. R.P. Bickerstaff is a faculty member of the University of Idaho, while Werner Koepf is at Ohio State Univ. We anticipate that there will continue to be frequent interactions between our Group and the visitors and young people associated with the INT.

D. Students

The training of graduate students is an important mission of our University role. The students also represent an important asset in our research activities and productivity. We maintain an average level of six students supported by the Grant. In addition, there are several students working with senior investigators who are not (yet) supported by the Grant.

E. Visitor Program

The activities of our Group and those of the Nuclear Physics Laboratory, and the closeness of the INT, have made it possible to attract leading researchers to the University of Washington for both short and long-term visits. In the past years we have had to turn down requests from a number of leading theorists due to a lack of funds, despite our desire to make the most of sabbatical leave and outside fellowship opportunities. The advantages of our visitor program have been discussed in the last several progress reports. The program, which combines DOE, University, and other support, continues as one of our most effective means of stimulating new activities and enhancing our research effort. We have requests from many more visitors than we can accommodate, many of whom are attracted to the UW by both our Group and the INT. Note that that the INT has only a limited sabbatical program for visitors not connected with some INT program.

During the FY93-FY96 period of the grant, we had the following long-term visitors:

Ian Aitchison, Oxford University

Peter Blunden, Manitoba

Isabela Porto Cavalcante, São Paulo

Bunny Clark, Ohio State

Thomas Cohen, U. Maryland

Giu Do Dang, U. Paris-Sud

Hong Jung, Seoul Women's U.

Stephane Pepin, Liege

Manoel Robilotta, São Paulo

Carlos da Rocha, São Paulo

Mitja Rosina, Ljubljani, Slovenia

Chang Liang Song, INT, Seattle

Maria Adamuţi–Trache, Bucharest

Rajagopal Venugopalan, INT, Seattle

There are two local persons with long-term connections to our group. Dr. Mary Alberg remains as an Affiliate Professor at the University of Washington, is an active collaborator in our Group, and frequently receives some summer salary support from this grant. She was a participant in the Spring, 1996 INT program on the Quark and Gluon Structure of Nuclear Matter. Prof. Robert Puff is a former member of the Group's senior faculty who continues to collaborate on problems involving nuclear physics and relativistic field theory.

We had the following short-term visitors during FY93-FY96:

R. Stephen Berry, U. Chicago
Louis Bloomfield, U. Virginia
Vladimir Braun, Hamburg
Sidney Coon, TRIUMF/U. Arizona
Zbigniew Dziembowski, Temple U.
Paul Ellis, U. Minnesota
Pierre l'Eplattenier, Toulouse
Rajiv Gavai, U. Minnesota
Chengquian Gong, Duke
Xiao-Gang He, U. Oregon
Eberhard Hilf, Oldenburg
W-Y.P. Hwang, Taiwan
Christopher Jarzynski, U.C. Berkeley
Byron Jennings, TRIUMF
Dmitri Kharzeev, CERN
Victor Khodel, Washington U.
Leonard Kisslinger, Carnegie Mellon
Yuval Kluger, Los Alamos
Gastao Krein, São Paulo

Peter Dale Kunz, Boulder, Colorado
Tsung-Shung Lee, Argonne
Derek Leinweber, Ohio State and TRIUMF
Zhenping Li, Carnegie Mellon
Harry Lipkin, Weizmann Institute
Hong Jung Lu, U. Maryland
Ma Luo, Iowa State
Joachim Maruhn, Frankfurt
Wally Melnitchouk, Regensburg
Joseph Milana, U. Maryland
Xing-Wang Pan, Drexel
Shashi Phatak, Oregon State
Daniel Phillips, U. Maryland
Gunther Piller, Adelaide
Thomas Schaefer, Stony Brook
Andreas Schreiber, Paul Scherrer Institute
Floarea Stancu, Liege
Eric Suraud, Toulouse

F. Institute for Nuclear Theory

In December, 1989, the DOE announced its decision to locate the national Institute for Nuclear Theory at the University of Washington. The principal investigators were deeply involved in preparing the INT proposal, and remain strongly involved in INT activities. Wick Haxton is the director, and George Bertsch and David Kaplan are Senior Fellows. All three are faculty members of the Department of Physics. The Group, the Department and the INT's National Advisory Committee have participated in the searches that led to these new hires. Ernest Henley also continues to help with the INT's administration, serving as Associate Director. Group members continue to take a role in organizing INT programs, with G.A. Miller serving as local organizer for the FY96 program on Quark and Gluon Structure of Nucleons and Nuclei.

G. Bridge Agreement With the College of Arts and Sciences and Joint Agreement With SURA/CEBAF

As mentioned above, the state funding for the new assistant professor is guaranteed after a suitable number of retirements. The need to generate outside funding caused us to begin negotiations to obtain partial funding from SURA/CEBAF. This was a natural choice, given that many of the long standing interests of the group have been consistent with the intellectual aims of that laboratory. SURA/CEBAF has agreed to support the position, and have signed the necessary Memorandum of Understanding (MOU) with the administration of the U.W.

The purpose of the MOU is to broaden and strengthen the cooperation between the two institutions by facilitating a new tenure track appointment at the U.W. in strong and electroweak theoretical nuclear physics research.

This faculty position requires teaching only 50% of the normal academic load.

H. Institutional Intellectual Support

With both our Nuclear Theory Group and the INT on campus, the University of Washington is perceived as an international center for nuclear physics. The connection with SURA/CEBAF is expected to further improve this perception. Furthermore other successes of the Department (Hans Dehmelt shared the 1989 Nobel Prize, David Thouless shared the Wolf Prize in 1990, Christopher Stubbs won an NAS junior investigator award in 1996, and Marjorie Olmstead has been awarded the Marie-Goepert Mayer prize in 1996) have increased the prominence of our physics program. The net result is unusually strong interest by young people (entering graduate students, postdocs) and visitors in coming to the University. In particular, many visitors who don't fit naturally into the organized INT programs request to visit campus under the auspices of the Nuclear Theory Group's visitor program. We have had, at most, funds to support one 9-month sabbatical visitor and a modest number of short-term visitors, and we are forced to turn down an unusually high percentage of such requests.

## Personnel

A. Regular Faculty Supported by the Grant

Aurel Bulgac, Ph.D., Assistant Professor of Physics
Ernest M. Henley, Ph.D., Professor Emeritus of Physics
Gerald A. Miller, Ph.D., Professor of Physics
Martin Savage, Ph. D. Assistant Professor of Physics
Lawrence Wilets, Ph.D., Professor Emeritus of Physics

The professional histories of these investigators are displayed in the section on biographical sketches. It is estimated that State-funded faculty typically devote approximately 40% of their time to contract activities during the academic year and full time during the summer. All faculty are supported during the academic year from university sources.

B. Research Assistant Professor

U. van Kolck continues with the Group, as discussed previously.

C. Research Associates

The FY96 research associates are listed below.

Dr. Derek Leinweber joined our group in August, 1995. He received his Ph.D. in 1990 under R.k. Bhadhuri, Mc Master University. His primary research interests are in non-perturbative aspects of QCD. His appointment was for one year only, due to funding limitations.

Dr. Vesteinn Thorsson joined our group in September, 1995. He received his Ph.D. from Stony Brook in 1992 under Ismail Zahed. He then joined Nordita in Copenhagen for a first postdoctoral position, until accepting the position at the University of Washington. His research interests include kaon energies in dense matter and in medium effective chiral Lagrangians.

D. Graduate Students

Below is a summary of the graduate students with successfully completed studies produced by our group during FY93-FY96.

William R. Greenberg, Ph.D. 1993 (Miller) "Vector Color Transparency." Bill took a postdoctoral position at the University of Pennsylvania, and is now working in the financial arena in New York.

David Makovoz, Ph.D. 1995 (Miller), "Lattice QCD Calculations For Color Transparency." David is now a postdoc at Ohio State University.

Students working with members of the nuclear physics group are:

William Beck (Wilets), part-time student working in industry, Semi-classical many body collisions for nuclei and atoms; capture of antiproton in liquid helium. Ph.D. achieved in FY97.

Chuan-Tsung Chan (Henley), QCD sum rules and application to mesons and nucleons. Ph.D. achieved in FY97.

Michael Fosmire (Bulgac), Scattering properties of sodium clusters.

William Hazelton (Wilets), Calculation of strangeness in the proton. Ph.D. expected in FY97.

Jon Karakowski (Miller), Compton scattering on the deuteron.

Jeffrey Thompson (Bulgac), Electronic structure of small clusters.

James Walden (Savage), Inclusive decays of B mesons. Ph.D. expected in FY97.

Mitchell Watrous (Wilets), Electronic screening of nuclear pairs in a finite temperature plasma under conditions relevant to fusion in laboratory and stellar plasmas. Ph.D. expected in FY97.

## L. Wilets

## PROGRESS 1993-96

**1. Strangeness content of the nucleon** (with W. Hazelton).

The admixture of states containing $s$-$\bar{s}$ quark pairs in the nucleon has been calculated in the context of the MIT model. Matrix diagonalization, rather than perturbation theory, is employed in order to allow for clustering of quark-antiquark pairs into meson-like structures — if such occur. The results for observables are compared with experiment and with meson-based models. Previous perturbation calculations by two other groups were found to contain errors.

**2. Many-nucleon/many-bag system in a periodic approximation**
(with W. Hazelton).

Using a variation of the Chromo-dielectric Soliton Model (CDM), infinite nuclear matter is being studied. The scalar and dielectric fields have fcc symmetry, and the quark structure is periodic in the basic tetrahedron of 12 quarks. The model ground state has 3 quarks per site in $(n,p)$, $(\uparrow,\downarrow)$ in the tetrahedron. Configuration mixing (which leads to color, flavor, spin, and quark percolation) obtains through quark hopping among sites; we allow for two hops. We work in the $m$-representation for color, isospin and spin. Although it appears at first to be a gigantic problem, it has been reduced to a tractable size. Work on the problem has been temporarily sidetracked by attention to item (1).

**3. The chirally invariant chromo-dielectric soliton model**
(with S. Pepin, Fl. Stancu and W. Koepf).

Solutions to the static 6-quark ($N$-$N$) problem and applications to the EMC effect have been published. We have addressed the dynamics problem both for head-on and general 3-D collisions. The main objective of the work is to combine the results with existing few and many nucleon calculations to calculate the quark substructure of nuclei. One application is the EMC effect: we found that as nucleons collide the confinement volume for quarks increases, as expected, but the quark momentum distribution does not decrease as some had predicted. This is due to configuration mixing. Thus the expanding nucleon in matter does not explain the EMC effect.

**4. The "non-hole" in He**
(with M. Alberg, J. Carlson, S. Pepin, Fl. Stancu and W. Koepf).

The measurement and analysis of electron scattering from $^3$He and $^4$He by Sick and collaborators reported 20 years ago remains a matter of current interest. They claimed a depression in the central point nucleon density, which is not found in few-body calculations based on realistic potentials. We find that using wave functions from such calculations we can obtain good fits to the He charge distributions under the assumption that the proton charge size expands toward the center of the nucleus. The relationship to 6-quark CDM calculations, item 3) above, is discussed. The expansion required is larger than than the predictions of mean field bag calculations by others or our CDM calculations in the independent pair approximation. The interest here is the search for a "smoking gun" signal of quark substructure.

**5. Classical equations of motion incorporating the Pauli and Heisenberg principles** (with W. Beck).

These equations, first proposed here, are being applied to many-electron systems. The work has been applied to the capture and trapping of antiprotons by He, now published. The model has been fine-tuned to obtain excellent fits to stopping powers of protons on various atoms (H, He, O, Ne). Numerous other applications, such as capture and pickup in atomic collisions and capture of exotics on molecules are being calculated.

**6. Shielding of nuclei in a finite temperature plasma** (with M. Watrous).

Screening of two nuclei in an electron gas is being studied; application is to the fusion process in stellar and laboratory plasmas. Finite density electron Green's functions are employed plus contour integration over the complex Matsubara poles. The one-center problem is nearly completed, illustrating the tractability of the method. The two-center problem using prolate spheroidal coordinates is next.

**7. Dynamics of the evolution of a flux tube to a plasma tube to mesons** (with R.D. Puff).

The study is addressed to structures formed in relativistic heavy ion collisions, including jets. A flux tube generates $q\overline{q}$ pairs and begins to collapse and oscillate. Electric pressure is augmented or replaced by plasma pressure. Oscillations are damped by quark collisions, calculated by the Boltzmann equation. The characteristic time for the process depends strongly on the assumed initial tube radius. Mean energy per meson is also obtained.

**8. $\overline{p}$-$p$ to $\overline{\Lambda}$-$\Lambda$ and $\overline{\Lambda}$-$\Sigma$ collisions** (with M. Alberg, E.M. Henley and D.A. Kunz).

Analysis of experimental data in terms of a quark model using both vector and scalar interactions has yielded the best fits for $\overline{\Lambda}$-$\Lambda$ to date. Two essential features of the calculation are the use of *both* vector and scalar interactions, and adjustment of the final state interaction which cannot be well deduced from the N-N interaction on the basis of current techniques using SU(3) symmetry. Several papers and conference proceedings have resulted. The work is continuing, with the prediction of a complete set of spin observables and extension to other rare processes.

**9. Relativistic meson-nucleon field theory**
(with G. Krein, M. Nielsen, R.D. Puff, M.E. Bracco, A. Eiras, G. Krein and C. da Rocha).

There has been renewed interest in meson-nucleon RFT. More than 20 years ago my students, collaborators and I studied various processes. The nucleon propagator dressed by planar meson diagrams was solved without cut-off. In addition to the continuum spectral function, a pair of complex conjugate poles appeared. These are physically unacceptable, but consistency demanded their inclusion in calculating physical processes and were found to play a crucial role in pi-nucleon and N-N scattering, nucleon magnetic moments, etc. Nutt, for example, obtained (1974) a better chi-squared for N-N scattering (with fewer parameters) than the Paris Potential, and the poles were found to be responsible for the satisfaction of the Adler low energy pi-nucleon scattering theorem. With the collaborators listed above, we have returned to the question of the origin of ghost poles, on the premise that they should disappear or recede with improved approximations – or to find if they are inherent to local relativistic field theories. They do appear also in QED. Dressing of the pion propagator hardly effects the poles. Introduction of vertex form factors can eliminate the poles, although when vector mesons are included a small region of negative spectral function appears (like in QED). With da Rocha and Krein we have also studied pi-nucleon scattering incorporating chiral symmetry through the linear sigma model.

## A. Bulgac

### PROGRESS 1993–96

My interests concern various aspects of many–body properties. For the sake of uniformity with the contributions presented by my colleagues here I shall present a short overview of the results obtained by my collaborators and me for this period, even though I joined the Nuclear Theory Group in Seattle during this funding period.

### Coherent Effects, Parton Distributions and Baryon Rich Matter in Central High Energy Heavy Ion Collisions

L. Frankfurt and I [1] presented arguments that the parton distributions measured in heavy ion collisions depend on the trigger for the centrality of the collisions as a result of coherent effects specific for the collisions of energetic composite particles. Percolation phase transitions in central heavy ion collisions are predicted and methods to form and to investigate such baryon rich matter are suggested.

### A Systematic Surface Contribution to the Ground State Binding Energies

V. Shaginyan and I [2, 3] have shown that if between the particles of a many body system there is a weak (perturbative) interaction, its contribution to the ground state binding energies is significantly enhanced by the presence of the surface. The naive first order perturbation estimate of the contribution of such an interaction severely underestimates the actual magnitude of the binding energy corrections, arising from an enhanced surface polarizability. We exemplify this mechanism by computing the contribution to the nuclear ground state energy coming from the Coulomb interaction between nucleons.

### Coupling Between Slow and Fast Degrees of Freedom in Systems with Complex Spectra

G. Do Dang, D. Kusnezov and I [4, 5, 6, 7, 8, 9, 10] considered the question of the microscopic origin of dissipation in collective motion of a quantum many body system in the framework of a parametric random matrix approach to the intrinsic dynamics. There are noticeable violations of the fluctuation–dissipation theorem and the energy diffusion has a markedly non–Gaussian character. Such features do not support a Langevin or Fokker–Planck approach to dissipation in large amplitude motion of many Fermion systems.

### Dynamics Beyond the Adiabatic Approximation

D. Kusnezov and I [11] explored the dynamics of mixed classical–quantum Hamiltonians, a class of systems that frequently appears in the study of physical systems characterized by both slow and fast modes, a typical example being nuclei. Traditionally such systems are studied within the adiabatic approximation and as a rule they display level crossings. We show that level crossings can have peculiar effects on the dynamics and, in the regime between the adiabatic and diabatic limits in both classical and quantum approaches, the full dynamics has a series of non–intuitive features, such as qualitative modification of the Landau–Zener mechanism, onset of chaotic behaviour and anomalous diffusion.

### The Shape of the Fermi Surface

J. Thompson and I [12] have shown that in the surface region, where the matter density falls off, the local momentum distribution of a many Fermion system is markedly anisotropic. The local Fermi surface has a predominantly prolate shape, with its long axis normal to the surface. We study this behaviour in the case of spherical and semi–infinite many Fermion systems.

### Excitation of Collective Plasmon States in Fullerenes

N. Ju, J.W. Keller and I [13, 14] considered the excitation of collective plasmon states in isolated fullerenes (gas targets). The large number of active electrons in a carbon cluster and the strong Coulomb interaction among them leads to a rich spectrum of collective states. States with total angular momentum up to $L = 8\hbar$ have a strong collective character. The equivalent of both $\pi$ and $\sigma$ plasmons in graphite are predicted for a whole range of carbon clusters $C_{20,\,60,\,70,\,100}$. In the low–energy region a strong dynamical screening is obtained, in good agreement with measured absorption spectra. The theoretical results compare very well with experimental photoexcitation results in $C_{60,\,70}$ and electron energy loss spectroscopy data on gas targets $C_{60,\,70}$.

### Stable Deformations in Large Metallic Clusters

C. Lewenkopf and I [15] have shown that only a relatively small number of metallic clusters exhibit a stable spherical shape. The majority of such clusters tend to acquire a deformed shape, in order to minimize the fluctuating part of the total energy, due to the bunching of the single particle electronic levels in a confined geometry. There is a large number of low lying shape isomers. Often the deformation energy surface develops rather wide shallow pockets and such clusters are particularly easy to deform. As a function of the electron number the cluster ground state deformations and isomer energies show some remarkable regularities.

### A Generalized Local Approximation Treatment of the Exchange Corrections

C. Lewenkopf, V. Mickrjukov and I [16] developed a new method to obtain a local parameterization for the exchange term in the many–body electronic problem. The approach amounts to the introduction of a coordinate dependent electron effective mass. Numerical results for metallic clusters in the jellium model are compared with other standard methods.

### Finite Temperature Properties of Sodium Clusters

N. Ju and I [17] performed an analysis of the geometric and energetic properties of sodium clusters with 8, 14, 20, 30, and 40 atoms using an effective many-body interaction among sodium atoms in the framework of an improved isothermal molecular-dynamics approach. These clusters undergo two phase transitions and the two transition temperatures increase with the cluster size. These phase transitions are the equivalents of bulk melting and of boiling in a finite system. However, finite particle effects are particularly strong. These clusters show a more pronounced thermal expansion than the bulk, with significant nonlinear effects. Both the shape and size change rather dramatically with the temperature. The ionic degrees of freedom give a dominating contribution to the entropy, thus effectively controlling the thermal behavior of these clusters.

### Temperature Dependence of the Optical Response of Small Sodium Clusters

C. Lewenkopf and I [18] studied the temperature dependence of the optical response of small sodium clusters in a temperature range bracketing the melting phase transition. When the temperature increases, the mean excitation energy undergoes a red shift and the plasmon is significantly broadened, in agreement with recent experimental data. Due to large thermal size and shape fluctuations, the single–particle levels acquire a prominent width.

### Neutron and X–Ray Scattering off Atomic Clusters

M. Fosmire and I [19] performed isothermal molecular dynamics simulations for sodium clusters of size $N=$ 8, 20, 100. Generalized pair correlation functions and static and dynamic structure factors are calculated for temperatures in the range of 100 – 400 K. $Na_{20}$ and $Na_{100}$ appear to undergo a melting transition, which is observable in both static and dynamic structure factors. Because of its small size, $Na_8$ shows no dramatic change in its properties with temperature. We conclude that X–ray and thermal neutron scattering in particular can be used as valuable sources of information on the ionic dynamics and structure of sodium clusters.

### Molecular Dynamics of Rigid Molecules

M. Adamuţi–Trache and I [20] developed a Hamiltonian formalism for an ensemble of rigid molecules in the quaternionic representation. In the quaternionic language, different symmetries of the rigid top dynamics acquire a simple and natural expression. Subsequently we describe the coupling of the ensemble of rigid molecules to a thermostat. The isothermal molecular dynamics is defined by introducing additional pseudofriction coefficients, according to a generalized Nosé–Hoover prescription.

### Parallel Processing for Scientific Computing

Together with my collaborators at MSU [21, 22] I studied various implementations and techniques for molecular dynamics of very large systems on massively parallel computers.


1. A. Bulgac and L. Frankfurt, Phys. Rev. **D 48**, 1894–1898 (1993).

2. A. Bulgac and V.R. Shaginyan, JETP Lett **62**, 843–848 (1995).

3. A. Bulgac and V.R. Shaginyan, Nucl.Phys. **A**, in press (1996).

4. A. Bulgac, D. Kusnezov and G. Do Dang, Ann. Phys. **242**, 1–51 (1995).

5. A. Bulgac, G. Do Dang and D. Kusnezov, Phys. Rep. **264**, 67–80 (1996).

6. A. Bulgac, G. Do Dang and D. Kusnezov, in *Collective Nuclear Dynamics*, ed. F.A. Ivanyuk, Nat. Acad. of Scien. of Ukraine, Kiev (1994), pp. 183–190.

7. A. Bulgac, G. Do Dang and D. Kusnezov, in *Recent Progress in Many Body Theories*, eds. E. Schachinger, H. Mitter and H. Sormann, vol. 4, p. 293–299 (1995), Plenum, New York.

8. A. Bulgac, G. Do Dang, A. Klein, D. Kusnezov and N.R. Walet, in *Int. Conf. on Nucl. Phys. and Related Topics*, eds. N. Ding Dang, D.H. Feng and N. Van Giai, World Scientific, pp. 156–164 (1995).

9. A. Bulgac, G. Do Dang and D. Kusnezov, "Quantum dissipation", preprint nucl–th/9507034.

10. A. Bulgac, G. Do Dang and D. Kusnezov, "A random matrix approach to quantum dissipation", to be submitted shortly.

11. A. Bulgac and D. Kusnezov, Chaos, Solitons and Fractals, **5**, 1051–1067 (1995)

12. A. Bulgac and J. Thompson, submitted March, 1996, "The shape of the Fermi surface."

13. N. Ju, A. Bulgac and J.W. Keller, Phys. Rev. **B 48**, 9071–9079 (1993).

14. N. Ju, A. Bulgac and J.W. Keller, Comp. Mater. Sci., **2**, 615–627 (1994).

15. A. Bulgac and C. Lewenkopf, Phys. Rev. Lett. **71**, 4130–4133 (1993).

16. A. Bulgac, C. Lewenkopf and V. Mickrjukov, Phys. Rev. **B 52**, 16476–16485 (1995).

17. N. Ju and A. Bulgac, Phys. Rev. **B 48**, 2721–2732 (1993).

18. A. Bulgac and C. Lewenkopf, Europhys. Lett. **31** 519–524 (1995).

19. M. Fosmire and A. Bulgac, Phys. Rev. **B 52**, 17509–17517 (1995).

20. A. Bulgac and M. Adamuţi–Trache, J. Chem. Phys. in press, July 15, (1996).

21. P. Nesbeitt, R. J. Enbody, A. Bulgac, D. Tománek, G. Overney, C. Severance, *Sixth SIAM Conference on Parallel Processing for Scientific Computing*, March, 1993, pp. 170–173.

22. C. Severance, R. J. Enbody, A. Bulgac, D. Tománek, *Sixth SIAM Conference on Parallel Processing for Scientific Computing*, March, 1993, pp. 979–982.

23. D.L. Hill and J.A. Wheeler, Phys. Rev. **89**, 1102 (1953); Representative works in the nuclear context include: V.M. Strutinsky, Z. Phys. **A280**, 99 (1977); V.M. Strutinsky, V.I. Abrosimov, and F.A. Ivanyuk, Z. Phys. **A306**, 273 (1982); V.M. Strutinsky, F.A. Ivanyuk and S.M. Vydrug-Vlasenko, Z. Phys. **A341**, 267 (1992); L. Wilets, *Theories of Nuclear Fission*, Clarendon, (1964); G. Schütte and L. Wilets, Z.Phys. **A286**, 313 (1978); R.W. Hasse, Rep. Prog. Phys. **41**, 1027 (1978); S.E. Koonin and J.R. Nix, Phys. Rev. **C13**, 209 (1976); T. Ledergerber, Z. Paltiel, Z.

Fraenkel and H.C. Pauli, Nucl. Phys. **A275**, 280 (1977); M.C. Nemes and H.A. Weidenmüller, Phys. Rev. **C24**, 944 (1981); M. Wilkinson, J. Phys. **A21**, 4021 (1988).

24. A. Lukasiak, W. Cassing and W. Nörenberg, Nucl. Phys. **A426**, 181 (1984); P.J. Siemens, A.S. Jensen and H. Hofmann, Nucl. Phys. **A441**, 410 (1985); B.W. Bush and G.F. Bertsch, Phys. Rev. **C45**, 1709 (1992); J. Blocki, Y. Boneh, J.R. Nix, J. Randrup, M. Robel, A. J. Sierk and W.J. Swiatecki, Ann.Phys. **113**, 330 (1978); J. Randrup and W.J. Swiatecki, Ann.Phys. **125**, 193 (1980); J. Blocki, C. Jarzynski and W.J. Swiatecki, Nucl. Phys. **A**, in press (1996); D.M. Brink, J. Neto and H.A. Weidenmüller, Phys. Lett. **80B**, 170 (1979); H.A. Weidenmüller, in *Progress in Particle and Nuclear Physics*, Vol. **3**, p. 49 Pergamon, Oxford (1980).

25. H. Hofmann, F.A. Ivanyuk and S. Yamaji, nucl-th/9510055, 28 Oct. 1995 ;*ibid*, nucl-th/9604024, 18 Apr. 1996.

26. L.P. Kadanoff and G. Baym, *Quantum statistical mechanics*, Benjamin, New York, 1962; J. Schwinger, J. Math. Phys. **2**, 407 (1961); L.V. Keldysh, JETP, **20**, 1018 (1965).

27. R.P. Feynman and F.L. Vernon, Ann. Phys. **24**, 118 (1963); P. Pechukas, Phys. Rev. **181**, 174 (1969); R.P. Feynman, *Statistical Mechanics*, Benjamin, Reading, 1972.

28. A.O. Caldeira and A.J. Leggett, Ann. Phys. **149**, 374 (1983); *ibid* **153**,445(E) (1984); A.J.Leggett, S. Chakravarty, A.T. Dorsey, M.P.A. Fisher, A. Garg and W. Zwerger, Rev. Mod. Phys. **59**, 1 (1987); A.Widom and T.D.Clark, Phys. Rev. Lett. **48**, 63 (1981); M.Büttiker and R.Landauer, Phys. Rev. Lett. **49**,1739 (1982); R.Bruinsma and P.Bak, Phys. Rev. Lett. **56**,420 (1986) and refences therein.

29. G. Leander, Phys. Rev. **C 25**, 2780 (1982).

30. B.L. Altshuler, B.D. Simons and A. Szafer, JETP Letters, **57**, 276 (1993); B.D. Simons, P.A. Lee and B.L. Altshuler, Phys. Rev. Lett. **70**, 4122 (1993); B.D. Simons and B.L. Altshuler, Phys. Rev. Lett. **70**, 4063 (1993).

31. B. Lauritzen, T. Døssing and R.A. Broglia, Nucl. Phys. **A457**, 61 (1986); M. Matsuo, T, Døssing, E. Vigezzi and R.A. Broglia, Phys. Rev. Lett. **70**, 2694, (1993); A. Braco, F. Alasia, S. Leoni, E. Vigezzi and R.A. Broglia, preprint "Nuclear rotations", preprint Milano NTGMI, December, 1995; R.A. Broglia, T. Dóssing, m. Matsuo, E. Vigezzi, P. Bosetti, A. Braco, S. Frattini, B. Herskind, S. Leoni and P. Rassmunssen, preprint Milano NTGMI, January, 1996.

32. S. Åberg, Prog. Part. Nucl. Phys. **28**, 11 (1992); S. Åberg and P. Pearsson, Phys. Rev. **E 52**, 148 (1995); S. Åberg, Phys. Rev. Lett. **64**, 3119 (1990); S. Åberg, preprint 1994.

33. M. Matsuo, T. Døssing, B. Herskind and S. Fraundorf, Nucl. Phys. **A564**, 345 (1993); K. Yoshida and M. Matsuo, nucl-th/9604015, 12, Apr. 1996.

34. V.G. Zelevinsky, M. Horoi and B.A Brown, Phys. Lett. **B 350**, 141 (1995); Phys. Rev. Lett. **74**, 5194 (1995); V. Zelevinsky, B.A. Brown, N. Frazier and M. Horoi, "Nuclear shell model as a testing ground for many–body quantum chaos", preprint MSU–1003, December 1995.

35. S. Frauendorf, in *Proc. Int. Conf. on Future of Nucl. Spectr.*, Crete, Grece 1993; *ibid*, Nucl. Phys. **A557**, 259c (1993); R. Bengtsson, Nucl. Phys. **A557**, 277c (1993); S. Frauendorf, O. Vogel, A. Gelberg and P. von Bretano, Nucl. Phys. **A584**, 241 (1995); J.R.B. Oliveira *et al.*, Phys. Rev. **C 50**, 1360 (1994).

36. A.A. Gribakina, V.V. Flambaum, G.F. Gribakin, Phys. Rev. **52 E**, 5667 (1995); A. Bulgac, unpublished; D. Kusnezov unpublished; M. Matsuo, T. Dóssing, E. Vigezzi and R.A. Broglia, Phys. Rev. Lett. **70**, 2694 (1993).

37. D.M. Brink, J. Neto and H.A. Weidenmüller, Phys. Lett. **80B**, 170 (1979).

38. V. Strutinsky, Sov. J. Nucl. Phys. **3**, 449 (1966); Nucl. Phys. **A 95**, 420 (1967); *ibid* **A 122**, 1 (1968); V.M. Strutinsky and A.G. Magner, Sov. J. Part. Nucl. Phys. **7**, 138 (1976).

39. R. Balian and C. Bloch, Ann. Phys. **67**, 229 (1972).

40. H. Nishioka, K. Hansen and B.R. Mottelson, Phys. Rev. **B 42**, 9377 (1990).

41. S.M. Reimann, S. Frauendorf and M. Brack, Zeit. f. Phys. **D 34**, 125 (1995); S.M. Reimann, K. Hanse and M. Brack, Zeit. f. Phys. **D 28**, 235 (1993).

42. D. Cline, Nucl. Phys. **A557**, 615c (1993); P.A. Butler and W. Nazarewicz, preprint (1995), submitted to Rev. Mod. Phys.

43. I. Hamamoto, B. Mottelson, H. Xie and X.Z. Zhang, Zeisch. F. Phys. **D 21**, 163 (1991); I. Hamamoto and B. Mottelson, Nucl. Phys. **A507**, 65 (1990);

44. W.D. Heiss, R.G. Nazmitdinov and S. Radu, Phys. Rev. **C 52**, 3032 (1995); *ibid*, Phys. Scipta **T56**, 182 (1995); *ibid*, Phys. Rev. **B 51**, 1874 (1995); *ibid* Phys. Rev. Lett. **52**, 2351 (1994); B. Montag, T. Hirschmann, J. Meyer, P.–G. Reinhard and M. Brack, Phys. Rev. **B 52**, 4775 (1995).

45. J.W. Negele, Nucl. Phys. **A 502**, 371c (1989) and earlier references therein.

46. G.F. Burgio, M. Baldo, A. Rapisarda and P. Schuck, Phys. Rev. **C 52**, 2475 (1995); W. Bauer, D. McGrew, V. Zelevinsky and P. Schuck, Phys. Rev. Lett. **72**, 3771 (1994); J. Blocki, C. Jarzynski and W.J. Swiatecki, Nucl. Phys. **A**, in press (1996); M. Baldo, G.F. Burgio, A. Rapisarda and P. Schuck, nucl-th/9602030, 20 Feb. 1996.

47. W.E. Frahn and R.H. Lemmer, Nouvo Cimento, **5**, 1564 (1957); F. Perey and B. Buck, Nucl. Phys. **32**, 353 (1962); A. Bulgac, Nucl. Phys. **A 487**, 251 (1988).

48. J.W. Negele and D. Vautherin, Phys. Rev. C **5**, 1472 (1972) and C **11**, 1031 (1975); X. Campi and D.W. Sprung, Nucl. Phys. **A 194**, 401 (1972); X. Campi and A. Bouyssy, Phys. Lett. **73B**, 263 (1978).

49. M. Durand, V.S. Ramamurthy and P. Schuck, Phys. Lett. **B 113**, 116 (1982).

50. V.A. Khodel, V.R. Shaginyan, and V.V. Khodel, Phys. Rep. **249**, 1 (1994).

**E.M. Henley**

**PROGRESS 1993-96**

The focus of my work continues to be related to symmetries, the connection of quark-gluons to nucleons-mesons, and the changes which occur to hadrons when placed in a nuclear medium. The motivations are to study the restrictions placed by symmetries on theories and models, to use symmetries to study structure, to learn of the connection of QCD to nucleon-meson degrees of freedom, and to study the effect of density on nucleons and mesons.

## 1. Symmetries

### A. The Electroweak Theory; Parity Nonconservation

(1.) The Weak Parity-Violating $\pi - N$ Coupling Constant

Experiments agree reasonably well with the "best" values of the weak parity-violating (pv) $\rho - N$ and $\omega - N$ coupling constants obtained from a quark model.[1] However, the weak pv $\pi - N$ coupling is found to be at least three times smaller than given by this model. W-Y.P. Hwang, L.S. Kisslinger and I have used QCD sum rules to determine this coupling and find a value an order of magnitude smaller than that of the quark model[1] due to a cancellation between a standard term and one not included in the model. If correct, our work indicates that it will not be possible to find neutral currents in nuclei. This work has been published recently.[2]

(2.) The Anapole Moment

Sporadically, M. Musolf, W. Haxton and I are examining corrections to our earlier work[3] by including $\rho$- and $\omega$-exchanges.

### B. Time Reversal Invariance

Since CP- or T-noninvariance has only been seen in one system, experimental and theoretical investigations on this topic are continuing to be of interest.

(1.) T-tests in the $\beta$-Decay of $^8$Li and $^8$B

An ongoing experiment at the Nuclear Physics Laboratory will test time reversal invariance (TRI) in these $\beta$-decays by seeking a T-odd axial current which could contribute. The intent is to measure a $2^+ \to 2^+$ decay and to use a correlation involving one of the $\alpha$ -particles in the decay of the unstable $^8$Be. S. Ying and I have examined the TRI test, have included final state electromagnetic corrections, and have studied the sensitivity of the experiment to TRI failure. This work has been published.[4]

(2.) The Neutron Electric Dipole Moment

C-T. Chan, T. Meissner and I are using QCD sum rules to study the neutron electric dipole moment in the presence of the $\theta$-term in the QCD Lagrangian. This turns out to be subtle, because both quark mass terms and the UA(1) anomaly are required to obtain a non-zero value. At present, good progress in being made and we hope to complete this work before the end of Summer, 1996.

### C. General

(1.) W. Haxton and I have edited a book on Symmetries and Fundamental Interactions in Nuclei, published by World Scientific, 1996.

(2.) I. Halpern and I have begun collaborating on a book on symmetries in nature and the arts.

### D. Charge Symmetry and Charge Independence

(1.) $\rho - \omega$ Mixing

T. Hatsuda, T. Meissner and I investigated the momentum ($q^2$) dependence of $\rho - \omega$ mixing. This mixing for $q^2 < 0$ is important to understand charge symmetry-breaking in nuclear forces and nuclei. It has been measured for $q^2 \approx m_\rho^2 \approx m_\omega^2 > 0$. Thus, the $q^2$ dependence is important. Our work and that of others has been followed by considerable discussion in the literature, because the prediction of a large $q^2$ dependence has important experimental ramifications. Our work has been published[5].

(2.) $\pi - \eta$ Mixing

Following the above work, C-T. Chan, T. Meissner and I also investigated the $q^2$ dependence of $\pi - \eta$ mixing and found it to be small[6].

(3.) Charge Symmetry in Hyperons

G. Miller and I suggested improved measurements of the semi-leptonic decays of the $\Sigma^\pm$ to test charge symmetry in this system[7].

(4.) Charge Dependence of the $\pi - N$ Coupling Constant

T. Meissner and I have used QCD sum rules to investigate the charge dependence of the pion-nucleon coupling constant. This has become of particular interest because of a recent experiment and analysis of pion-deuteron scattering. Our work has been submitted for publication.

## 2. Connection of QCD (Partons) and Mesons-Nucleons

### A. $\bar{\text{d}}$ vs. $\bar{\text{u}}$ in the Baryonic Sea

QCD based quark models of the nucleon which include couplings to mesons or mesonic degrees of freedom predict an excess of $\bar{\text{d}}$ over $\bar{\text{u}}$ in the proton (and the reverse in the neutron). M. Alberg and I have proposed Drell-Yan measurements $(\Sigma^+ p, \Sigma^- p, \Sigma^+ d, \Sigma^- d)$ to test this model. Meson models suggest an even larger excess of $\bar{\text{d}}$ in the $\Sigma^+$ (and $\bar{\text{u}}$ in the $\Sigma^-$) which can be measured in ratios of Drell-Yan cross sections, e.g., $\Sigma^+ p \to l^+ l^- X$, where $l$ is a lepton $(\mu, e)$ and $X$ stands for everything else. SU(3) predicts the opposite. This work is about to be submitted for publication.

### B. The $\bar{\text{N}}$ System

The annihilation of an antiproton on a proton should be able to give information of quark degrees of freedom. M. Alberg, L. Wilets, D. Kunz and I have continued to examine quark-based $^3P_0$ and $^3S_1$ annihilation into strange baryons $(\Lambda\bar{\Lambda}, \Sigma\bar{\Lambda}, \Lambda\bar{\Sigma}, \Sigma\bar{\Sigma})$ to test this model. It appears that spin degrees of freedom are required to differentiate quark- and meson-based models. We are examining depolarization measurements in $\Lambda\bar{\Lambda}$ because they appear to be most sensitive to model predictions and spin degrees of freedom in $\Sigma\bar{\Lambda}, \Lambda\bar{\Sigma}$, and $\Sigma\bar{\Sigma}$ production. Together with W. Hazelton, we are calculating the polarization of sea quarks in a shell-model type of description for the quarks in the nucleon, including strange quarks.

### C. Off-Mass Shell Electromagnetic Vertices

M. Frank and I are making slow progress on a quark-based field theoretic investigation of off-mass shell photon-nucleon couplings.

## 3. Nucleons in a Nuclear Medium

Magnetic Moments

One of the puzzles in nuclear physics is why the properties of nucleons change so little when placed in a nucleus. QCD sum rules offer an opportunity to investigate these changes. The magnetic moments of the $n$ and $p$ have been calculated with this technique and found to agree with experiment. The calculation of these moments in nuclei offers an opportunity to test the use of QCD sum rules for hadrons at finite densities. It is for this reason that this investigation has been undertaken.

References

1. B. Desplanques, J.F. Donoguue, and B.R. Holstein, Ann. Phys. (NY) 124, 4491 (1980).

2. E.M. Henley, W-Y.P. Hwang and L.S. Kisslinger, Phys. Lett. B367, 21 (1996).

3. W.C. Haxton, E.M. Henley and M. Musolf, Phys. Rev. Lett. 63, 949 (1989).

4. S. Ying and E.M. Henley, Nucl. Phys. A585, 463 (1995).

5. T. Hatsuda, E.M. Henley, Th. Meissner, and G. Krein, Phys. Rev. C49, 452 (1994).

6. C-T. Chan, E.M. Henley, and Th. Meissner, Phys. Lett. B3434, 7 (1995).

7. E.M. Henley and G.A. Miller, Phys. Rev. D50, 7077 (1994).

## G. A. Miller

## PROGRESS 1993-96

The relation between quantum chromodynamics (QCD) and nuclear physics is my focus. The non-perturbative nature of the theory is expected to be responsible for the existence and properties of nuclei. But the predictions for high momentum transfer processes, especially color transparency, seemed easier to test using nuclear reactions. As discussed below, it turned out that color transparency physics is sensitive to some non-perturbative aspects of QCD. Indeed, color transparency physics and high momentum transfer nuclear reactions may have implications for diverse aspects of nuclear physics including: short range correlations in nucleons, dense nuclear matter, nuclear modification of properties of bound hadrons, and even the convergence of calculations of nucleon-nucleon potentials and effective nuclear interactions.

Another favorite topic involves fundamental symmetries, which can provide relevant information about how QCD is manifest in nuclei, and are often of high intrinsic interest.

These interests led me to investigate the following areas: (1) color transparency physics; (2) fundamental symmetries; (3) physics of confinement and hadronic wave functions and, (4) quark models of nuclei and nuclear matter.

The above areas are closely related to relativistic aspects of nuclei. Many of these can be addressed using light front techniques. I have previously applied these techniques to certain problems, but much of my future work will be devoted to extending the existing methods to encompass a broad range of topics in nuclear reactions related to planned studies at CEBAF, HERA and RHIC.

### 1. Background

Much of the proposed research is based on using fundamental ideas about nucleon structure to motivate new relevant experiments using nuclei. Concern with stimulating experiments has been a long-standing interest, so I introduce the present proposal with a summary of past DOE work.

I began my career by studying pion-nucleus interactions. One suggestion was that short and medium ranged two-nucleon correlations[1] and six-quark bag effects[2] could have an important effect on $(\pi^+, \pi^-)$ nuclear reactions. In response, experiments were performed at LAMPF and TRIUMF[3]. The measured cross sections were not large enough to support the novel quark mechanism, but this stimulated other theorists[3] to successfully explain the data using two-nucleon correlation effects. Moreover, our calculations[4] on the related process of $\pi^-$ absorption of a pair of protons bound in $^3He$ led to new experiments at TRIUMF[5]. These confirmed that the absorption reaction was dominated by physics at small nucleon-nucleon separations.

Colleagues and I also suggested and explained[6] the first experiments to detect charge symmetry breaking in a system which has no Coulomb force. We found that specific spin-dependent neutron-proton scattering measurements are necessary. Experiments at TRIUMF[7] and the IUCF[8] have successfully observed this effect.

The EMC observation that the structure function $F_2$ of a bound nucleon is different from a free nucleon generated many different explanations. Our response was to show[9] that measurements of the production of high momentum $\mu^+\mu^-$ pairs in proton-nucleus reactions (nuclear Drell-Yan process) could disentangle explanations of the EMC effect. A Fermilab experiment to measure the predicted nuclear dependence was undertaken by LAMPF physicists[10]. The results placed very severe limitations on the mesonic content of nuclei, which remain puzzling[11].

I also need to mention our Cloudy Bag Model treatment[12] of the baryon as three quarks in a bag surrounded by a cloud of pions. Computations of many observables gave excellent agreement with experimental results, especially in providing a reasonable pionic cloud explanation of the charge radius of the neutron. We also applied the Cloudy Bag Model[12] to systems of heavy (s,c, or b) quarks bound to light (anti-) quarks, and strong and electromagnetic decay rates were predicted[13]. Those for the decays of the D* mesons were confirmed by recent experiments[14].

## 2. Physics of Color Transparency

Color transparency[15] is the vanishing of initial and final state interactions in high momentum transfer ($Q^2$) nuclear reactions in which the resolution is good enough to ensure that no extra pions are created in the fundamental hadronic two-body reaction. Examples of such reactions are the (e,e'p), (p,pp) and $(e, e'\Delta)$ processes involving nuclear targets. Several experiments searching for color transparency have been planned and are underway.

The color transparency postulate is based on three main points: (i) small objects (ejected wave packets (ejectiles) which, if very small, are point-like configurations PLC) are produced in high $Q^2$ exclusive processes, (ii) the interactions of such small color singlet objects are suppressed due to the effects of cancellation of gluonic emission (color screening or color neutrality), (iii) if the small object remains small for long enough it can escape the nucleus without further interactions. For experiments at Brookhaven, CEBAF and SLAC the kinematics are such that expansion must take place. The observational evidence for (ii) is discussed in many references. But points (i) and (iii) required serious investigation, which we summarize.

### A. Ejectile Propagation Through the Nucleus

B.K. Jennings (TRIUMF) and I developed the approach of treating the ejectile as a coherent superposition of baryonic states[16]. In electron reactions the ejectile wave function depends on proton-baryon electromagnetic transition form factors, and the ejectile-nucleon interaction depends on baryon-nucleon interactions. These inputs were initially modeled[16−18] and later constrained by data[19]. The expansion of the ejectile depends on the masses of its baryonic components, and determines the energy dependence of the reactions. Thus, our approach allows us to show how the ordinary low momentum transfer nuclear black disk becomes transparent at large values of the momentum transfer. The data do not completely determine the ejectile nucleon interaction, so that there will be unavoidable uncertainty until definitive evidence for color transparency is found in several different reactions. Our results for the propagation are similar to those of Strikman and Frankfurt's quantum diffusion approach[20].

Another effect is the that the degree of color transparency depends strongly on the (Fermi) momentum of the initially bound nucleon[21]. Thus we proposed to include all of the known effects, e.g. (1) PLC expansion, (2) quantum interference between the PLC and the BlC and (3) momentum of the bound nucleon. The resulting calculations obtained a very good description of the existing (p,pp) data. We found[22] that color transparency was required to reproduce the size of the cross section of the (p,pp) reaction[23]. A good description of the observed dependence on the "momentum of the struck nucleon" was also achieved. The calculations were made using assuming that the experimental resolution was good, so that it will be important to compare this theory with the expected new, more precisely determined data. We also note that the model which predicts significant color transparency effects for the (p,pp) experiment is also consistent with the NE18 data[24] for the (e,e'p) reaction, which shows little, if any, evidence for color transparency.

**B. Is the ejectile a small object?**

L. Frankfurt (Tel Aviv), M. Strikman (PSU) and I studied the question of small-sized wavepacket or point-like configuration (PLC) formation, a high $Q^2$ process by constructing operators which measure the transverse size, $b^2(Q^2)$ of a wave packet[25]. For systems of three quarks, mean field models leads to no PLC formation, but if inter-quark correlations are present, PLC is obtained. Most realistic models give PLC for momentum transfers as low as $\mathrm{Q}^2 = 1\ (\mathrm{GeV/c})^2$. Even with this result, which favors the existence of color transparency, there is a significant problem in looking for CT effects in experiments at $Q^2$ from about one to a few $\mathrm{GeV}^2$. The assumed $PLC$ would expand rapidly while propagating through the nucleus. This expansion of the wavepacket is important up to rather large values of $Q^2$ because of the relatively small Lorentz factor of the struck nucleon. This brings us to the next subsection, which concerns an effort to handle this difficulty.

**C. Double Scattering Processes and Intermediate $Q^2$ Color Transparency**

This project started as a collaboration between K.Egiyan(Erevan PI) W.R. Greenberg, L.Frankfurt(Tel Aviv), M.Sargsyan(Erevan PI), M.Strikman(PSU) and myself[26], which defined and supports an experiment 94-019 proposed to and accepted by CEBAF.

The effects of wavepacket expansion must be suppressed if one is to observe color transparency CT at intermediate values of $Q^2$. This can be achieved by using the lightest nuclear targets, where the propagation distances are small. In this case, the transparency is close to unity, so the effects of CT in $(e,e'p)$ reactions are small. However, if we select a process where the produced system can **only** be produced by an interaction in the final state, a double scattering event, then the color transparency effects would be manifest as a decrease of the probability for final-state interactions with increasing $Q^2$. An advantage of looking for such processes is that it is possible to observe an effect decreasing from the value expected without CT (Glauber-value) to zero. Thus, the measured cross section is to be compared with a vanishing quantity so that the relevant ratio of cross sections runs from 1 to infinity.

Therefore, we studied the reactions $^3He(e,e'pp)$[26] and $D(e,e'pn)$[27]. These experiments involve triggering on a fast proton which carries almost all of the virtual photon's three-momentum, and also detecting another "spectator" proton or neutron of momentum between 100 and 400 MeV/c. This value is small compared with the fast proton's momentum and large compared with a proton's Fermi motion inside the target.

The scattering amplitude $\mathcal{M}$, including the $np$ final state interaction, can be written as a sum of Born and scattering terms ($ST$) with $\mathcal{M} =< p_z, \vec{p}_t|d> +ST$, where $\vec{p}_t$ ($p_z$) is the component of the spectator's momentum that is perpendicular (parallel) to the direction of the virtual photon. The conventional theory without CT predicts that the two terms of $\mathcal{M}$ have a very different $\vec{p}_t$ dependence for reactions occuring near the quasielastic peak. For $\vec{p}_t \approx 0$, the ratio of the second term to the first is of the order of $-\sigma_{tot}^{pn}/16\pi R_d^2$ and is small and negative. Thus, at low $p_t$, final state interactions reduce (shadowing effect) the value of the computed cross section. But the first term falls more rapidly than the second as the magnitude of $\vec{p}_t$ increases. This is because the fall off is controlled by the large deuteron size in the first term and by the small range of the $np$ interaction in the second term. As $p_t$ increases from zero, the relative importance of the shadowing grows. However, if $p_t$ is further increased, the value of the ratio $|\frac{\mathcal{M}}{<\vec{p}_t|d>}|^2$ increases due to the rapid vanishing of the denominator! Thus one may observe the effects of color transparency by performing the experiments with successive values of $Q^2$, starting at low values where the conventional theory is expected to work. For values of $Q^2$ large enough to support color transparency, the term $ST$ is reduced and the $\vec{p}_t$ dependence is predicted to be completely different.

**D. Spin dependence of color transparency**

Calculations of color transparency effects in electron scattering typically used scalar photons. Student W. Greenberg (his thesis) took the vector nature of the photon into account[28]. Thus both the $\gamma_\mu$ and $\sigma_{\mu\nu}$ forms of photon-baryon coupling are included. The initial bound wave function [29,30] and ejected baryonic wave packet are described as four-component Dirac spinors. We studied the spin dependence of color transparency in $(e, e', p)$ reactions. In particular, the polarization of the outgoing proton is caused by the final state spin orbit interaction and therefore vanishes if color transparency occurs. We studied all of the observables, and found that the expected polarization does vanish, but at $Q^2$ too high to be interesting. This project included a detailed account of the conventional effects, especially an analysis of the nucleon nucleon scattering amplitudes needed to obtain the final state interactions.

## 3. Charge Symmetry Breaking

Charge symmetry is a fundamental symmetry which occurs if the Lagrangian is invariant with respect to rotating the u into d quarks (or d→ u) quarks. Slaus (Zagreb), Nefkens (UCLA) and I reviewed Charge Symmetry Breaking (CSB)[31], introducing the quark-based definition. This review was updated by W. van Oers(TRIUMF) and myself[32]. CSB in systems ranging from mesons to heavy nuclei was studied, with the result that all observed CSB can be explained in terms of the difference between the down and up quark masses $\delta m$ and electromagnetic interactions between quarks. It has long been known that $\delta m$ can account for the observed value of the isospin mixing between the $\rho^0$ and $\omega$ mesons. Furthermore, one can compute the CSB-potential between two nucleons arising from the exchange of a mixed $\rho^0$-$\omega$ meson. The resulting CSB potential is large enough to explain the Nolen Schiffer anomaly and provides a spin-dependent potential which makes a significant contribution to the IUCF 183 MeV experiment.

However, Goldman and Thomas[33] claimed that the $\rho^0 - \omega$ mixing matrix element has a significant off-mass shell dependence which renders its effects negligible in nucleon-nucleon scattering. This conclusion was obtained by several other authors[34], but others do not have the same conclusion[35]. My approach[32] was to consider the effects of these theories on the $q^2$ (square of the $\rho$ four momentum) dependence of the $\gamma\rho$ coupling constant which is measured at $q^2 =$ in photoproduction experiments and has essentially the same value as at $q^2 = M_\rho^2$. Several of the above theories predict a large $q^2$ variation, in contrast with the data. In the meantime, significant evidence that $\rho - \omega$ mixing has little variation with $q^2$ has emerged.

Another approach was to investigate the off-shell dependence of $\rho - \omega$ mixing in the charge symmetry breaking nucleon-nucleon potential by examining the complete process (e.g., $\rho^0$ emission, propagation, conversion to an $\omega$, propagation and absorption). T. Cohen (Maryland) and I found[36] that present models describing the off-shell dependence of $\rho^0 - \omega$ mixing are not sufficient to determine the charge symmetry breaking nucleon-nucleon potential because one needs to compute the vertex from the theory that supplied the propagator. None of the present treatments of the off-shell propagator does this.

E.M. Henley and I also found[37] a large charge symmetry breaking effect in the semi-leptonic decays of $\Sigma^\pm$. The two decay rates differ by about 6%, because the baryons are related by the replacement of two $u$ quarks by $d$ quarks. We proposed that present experimental data be improved to search for this effect.

## 4. Physics of Confinement and Hadronic Wave Functions

The issues of color transparency are closely related to those of hadronic wave functions, so our attention was drawn to this area.

### A. Lattice QCD study of the time dependence of a wave packet's transverse size

The opportunity to observe color transparency (CT) is determined by how rapidly a small-sized hadronic wave packet expands. D. Makovoz and I used SU(2) lattice gauge theory with Wilson fermions in the quenched approximation to investigate the expansion[38]. The wave packet is modeled by a point hadronic source, often used as an interpolating field in lattice calculations (not a point-like configuration). The procedure is to determine the Euclidean time (t), pion channel, Bethe-Salpeter amplitude $\Psi(r,t)$, and then evaluate $b^2(t) = \int d^3r \Psi(r,t) r^2 sin^2\theta \Psi_\pi(r)$. This quantity represents the soft interaction of a small-sized wave packet with a pion. The time dependence of $b^2(t)$ is fit as a superposition of three states, which is found sufficient to reproduce a reduced size wave packet. Using this superposition allows us to make the analytic continuation required to study the wave packet expansion in real time. We find that the matrix elements of the soft interaction $\hat{b}^2$ between the excited and ground state decrease rapidly with the energy of the excited state, $E_n$. This result favors color transparency, because it places a lower limit on the rest frame expansion time, $1/(E_n\text{-}E_{gs})$.

A second investigation[39] concerned a detailed investigation of the spectral density in the pseudoscalar and vector channels. These quantities were extracted from the SU(2) lattice quenched data. We found that within the energy range accessible on the lattice, the spectral density consists of three sharp poles. The implication is that color transparency will occur when the energies involved are large enough to produce the states at the third pole. This conclusion must be shown to hold for unquenched SU(3) QCD before one can have confidence in this conclusion about color transparency.

**B. QCD Sum Rule Approach to the mesonic wave function $\phi(x, \kappa_t^2)$**

The usual light-cone "wave function" $\phi(x)$ is really $\phi(x, \mu^2) \equiv \int^{\mu^2} d^2\kappa_t \phi(x, \kappa_t)$. But color transparency effects are controlled by the $\kappa_t$ dependence of $\phi(x, \kappa_t)$. T. Hatsuda, S. Lee and I used QCD sum rules to investigate this dependence[40]. We determined moments (within an estimated error of $\pm 50\%$ ) of the form $\int_0^1 dx\ x^{n-l} \int^{\mu^2} d^2\kappa_t \kappa_t^l \phi(x, \kappa_t)$ for $n$ and $l$ equal to 0, 2 or 4. Furthermore we showed that the transverse size of the pion is dictated by the gluon condensate, even though the mass and longitudinal distributions are dominated by the quark condensate. Our results indicated that fluctuations are large. This favors the existence of point like configurations. Our moments can be used to constrain first-principles calculations of the pion form factor.

**C. Role of meson exchange in baryon spectra**

This work was stimulated by talks by D.O. Riska at the INT. His work with Glozman[41] stressed the importance of explaining baryon spectra using meson exchange between quarks, instead of the popular gluon exchange mechanism. Therefore Z. Dziembowski (Temple U), Fabre de la Rapelle (Orsay, IPN) and I began an investigation of a non-perturbative treatment of gluons and pseudoscalar mesons in baryon spectroscopy. We studied baryon spectroscopy including the effects of pseudoscalar meson exchange and one gluon exchange potentials between quarks, using non-perturbative, hyperspherical method calculations. We find[42] that a model which includes only gluon exchange can not simultaneously describe the Roper and P-wave excitation energies. Using only pseudoscalar meson exchange partially cures this problem, but at the cost of using a relatively large pion quark coupling constant. However, one gets a similar agreement with data in a model with both effects by using a quark-meson coupling constant compatible with the measured pion-nucleon coupling constant, and a value of $\alpha_s \approx 0.35$.

## 5. Quark Models of Nuclei

**A. The Role of Color Neutrality in Nuclear Physics – Modifications of Nucleonic Wave Functions**

M.R. Frank (INT), B.K. Jennings (TRIUMF) and I investigated[43] the influence of the nuclear medium upon the internal structure of a composite nucleon. The interaction with the medium is assumed to depend on the relative distances between the quarks in the nucleon consistent with the notion of color neutrality: when all of the three quarks are in the same place, the interaction with the surrounding medium vanishes. As a result, the nucleon in matter is a superposition of the ground state (free nucleon) and radial excitations. The effects of the nuclear medium on the electromagnetic and weak nucleon form factors and the nucleon structure function were computed using a light-front constituent quark model. Our approach is to compute the medium-modified wave function and obtain predictions for many observables. One of our results is that the nucleon's mean radius is increased compared to the value in free space. But we can compute any of the effects of the medium on any observable. The effects of color neutrality supply small but significant corrections to predictions of many observables. These results are similar to earlier work using the same idea$^{FS}$, but our formalism can be applied to both low and high momentum transfer reactions.

**B. Quark-Meson Coupling Model For Finite Nuclei**

Quantum chromodynamics (QCD), a theory of quarks and gluons, is the current paradigm for the strong interaction. Nuclei are bound by the strong interaction, but hadronic degrees of freedom account for the most of the physical properties. This contrast suggests both questions and opportunities. One might ask: how and why does this standard picture of nuclear physics as a system of clustered color-singlet objects emerge from the fundamental theory? One possible answer has been suggested[44], based on the strong coupling limit. The opportunities arise from the challenge of discovering small (at normal nuclear densities) but interesting corrections to the standard picture which arise from the underlying constituents.

Thus the need for a theory of nuclei that incorporates quark-gluon degrees of freedom, but also respects the vast body of information substantiating the standard picture, is apparent. There are many possibilities, and here we wish to focus on the quark-meson coupling model[45] in which nuclear matter consists of color-singlet clusters of quarks and also mesons. The quarks are assumed to be bound in non-overlapping nucleon bags, and the interaction between nucleons arises from a coupling of meson fields to the quarks. The ultra-relativistic quarks are described by a mean-field Dirac equation. The nucleons are assumed to be also described by the Dirac equation in the effective mean fields arising from meson fields coupling to the quarks in the nucleon. The model is computationally similar to the familiar QHD model[30], in which the meson fields couple to point-like nucleons. However, the value of the $\sigma$ and $\omega$ mean fields is smaller here, and the effects of the nucleon Dirac sea are therefore reduced.

P. Blunden and I extended this model to finite nuclei[46]. See also Ref. 47. Most of the previous calculations involved nuclear matter or a local density approximation. In finite nuclei, it is necessary to treat the the spatial non-uniformity of the meson fields over the volume of the nucleon as well as the volume of the nucleus. We developed a perturbative scheme for treating these variations. Our procedure is to define the potentials that act on the nucleons in terms of averages of the true potential over the volume of the nucleon. The perturbation is then the true potential minus the average. This procedure is more convergent than simply using the value of the true potential at the center of the nucleon, and with this definition, the leading order term is dominant.

References

These references are included only as a possible aid to the reader, and are not intended as a definitive review of the literature. Many excellent papers are not listed here.

1. G.A. Miller and J.E. Spencer, Annals of Physics (N.Y.) 100, 562 (1975).

2. G.A. Miller, Phys. Rev. Lett. 53, 2008 (1984).

3. See the reviews in "Proceedings of the Lampf Workshop on Pion Double Charge Exchange", AIPCP 163.

4. G.A. Miller and A. Gal, Phys. Rev. C36, 2, 450 (1987); E. Piasetzky, D. Ashery, M.A. Moinester, G.A. Miller and A. Gal, Phys. Rev. Lett. 57, 2135 (1986).

5. S. May Tal-Beck *et al.*, Phys. Rev. Lett. 68, 3012 (1992); L.C. Smith *et al.*, Phys. Rev. C40, 1347 (1989); D. Ashery, Nucl. Phys. A478, 603C (1988).

6. E.M. Henley and G.A. Miller, in *Mesons in Nuclei*, Ed. by M. Rho and D. Wilkinson (North-Holland, Amsterdam, 1979), p. 405; C.Y. Cheung et al., Phys. Rev. Lett. 43, 1215 (1979); Nucl. Phys. A348, 365 (1980); G.A. Miller, A.W. Thomas and A.G. Williams, Phys. Rev. Lett. 56, 2567 (1986); Phys. Rev. C36, 1956 (1987).

7. R. Abegg *et al.*, Phys. Rev. D39, 2464 (1989); Phys. Rev. Lett. 56, 2571 (1986); Phys. Rev. Lett. 75, 1711 (1995).

8. S.E. Vigdor *et al.*, Phys. Rev. C 46, 410 (1992); L.D. Knutson *et al.*, Phys. Rev. Lett. 66, 1410 (1991).

9. R.P. Bickerstaff, M.C. Birse and G.A. Miller, Phys. Rev. Lett. 53, 2532 (1984); Phys. Rev. D33, 3228 (1986).

10. D. M. Alde *et al.*, Phys. Rev. Lett. 64, 2479 (1990).

11. G.F. Bertsch, L. Frankfurt and M. Strikman, Science 259, 773 (1993); G.A. Miller, Phys. Rev. Lett. 69, 2449 (1992).

12. G.A. Miller, A.W. Thomas and S. Théberge, Phys. Lett. B91, 192 (1980); Phys. Rev. D22, 2838 (1980); Phys. Rev. D24, 216 (1981) Can. J. Phys. 60, 59 (1982).

13. G.A. Miller and P. Singer, Phys. Rev. D37, 2564 (1988); Phys. Rev. D39, 825 (1989).

14. A.N. Kamal and Q.P. Xu, Phys. Lett. B284, 421 (1992), and the references therein.

15. A. Mueller in Proc. of Seventeenth Rencontre de Moriond, 1982, ed. J Tran Thanh Van (Editions Frontiéres, Gif-sur-Yvette, France, 1982), p. 13; S.J. Brodsky, in Proc. of the Thirteenth Int'l Symposium on Multiparticle Dynamics, ed. W. Kittel, W. Metzger and A. Stergiou (World Scientific, Singapore, 1982), p. 963. A recent review is P. Jain, B. Pire and J.P. Ralston, hep-ph 950113.

16. B.K. Jennings and G.A. Miller, Phys. Lett. B236, 209 (1990); Phys. Rev. D44, 692 (1991).

17. B.K. Jennings and G.A. Miller, Phys. Lett. B274, 442 (1992).

18. L. Frankfurt, *et al.*, Phys. Rev. C 46, 2547 (1992).

19. B.K. Jennings and G. A. Miller, Phys. Rev. Lett. 69, 3619 (1992).

20. L. Frankfurt and M. Strikman, Physics Reports 160, 237 (1988).

21. See e.g. B. Kopeliovich and B.K. Jennings, Phys. Rev. Lett. 70, 3384 (1993).

22. B.K. Jennings and G.A. Miller, Phys. Lett. B318, 7 (1993)

23. A.S. Carroll *et al.*, Phys. Rev. Lett. 61, 1698 (1988); BNL expt. 850.

24. N.C.R. Makins *et al.*, Phys. Rev. Lett. 72, 1986 (1994); T.G. O'Neill, *et al.*, Phys. Lett. B351, 87 (195).

25. L. Frankfurt, G.A. Miller, and M. Strikman, Comm. Nucl. Part. Phys. 21, 1 (1992); Nucl. Phys. A555, 752 (1993).

26. K.S. Egiyan *et al.*, Nucl. Phys. A580, 365 (1994).

27. L.L. Frankfurt *et al.*, Phys. Lett. B369, 201 (1996); Z. Phys. A352, 97 (1995).

28. W.R. Greenberg and G.A. Miller, Phys. Rev. C49, 2747 (1994); E50, 2643 (1995).

29. C.J. Horowitz and B.D. Serot, Nucl. Phys. A368, 503 (1981).

30. B.D. Serot and J.D. Walecka, Adv. in Nucl. Physics 16, (1986).

31. G.A. Miller, B.M.K. Nefkens and I. Slaus, Phys. Rpts. 194, 1 (1990).

32. G.A. Miller and W.T.H. Van Oers, in "Symmetries and Fundamental Interactions in Nuclei" edited by W.C. Haxton and E.M. Henley (World Scientific, Singapore, 1995), p. 127; G.A. Miller, Chin. Journ. Phys. 32, 1075 (1994).

33. T. Goldman, J.A. Henderson and A. W. Thomas, Few Body Systems 12, 123 (1992).

34. J. Piekarewicz and A.G. Williams, Phys. Rev. C47, A2462 (1993); G. Krein, A.W. Thomas, and A.G. Williams, Phys. Lett. B317, 293 (1993); K.L. Mitchell *et al.*, Phys. Lett. B335 282, (1994); H.B. O'Connell, *et al.*, Phys. Lett. B336, 1 (1994); T. Hatsuda, *et al.*, Phys. Rev. C49, 452 (1994).

35. M.J. Iqbal, X-m Jin, D.B. Leinweber, Phys. Lett. B367, 45 (1996); R. Urech, Phys. Lett. B355, 308 (1995).

36. T.D. Cohen, G.A. Miller, Phys. Rev. C52, 3428 (1995).

37. E.M. Henley, G.A. Miller, Phys. Rev. D50, 7077 (1994).

38. D. Makovoz, G.A. Miller, Nucl. Phys. B451, 622 (1995).

39. Spectral Density on the Lattice D. Makovoz, G.A. Miller, OSU-95-117, Nov 1995. hep-lat/9511011, in press Nucl. Phys. B.

40. Su H. Lee, T. Hatsuda, G.A. Miller, Phys. Rev. Lett. 72, 2345 (1994).

41. Ya. Glozman and D. O. Riska, The Spectrum of the Nucleons and the Strange Hyperons and Chiral Dynamics, Preprint DOE/ER/40561-187-INT95-16-01 [LANL hep-ph 9505422], Physics Reports (1995) - in press.

42. Non-perturbative treatment of Gluons and Pseudoscalar Mesons in Baryon Spectroscopy", Z. Dziembowski, M. Fabre de la Ripelle, G. A. Miller, Phys. Rev. C. Rapid Communication, in press.

43. The Role of Color Neutrality in Nuclear Physics; Modifications of Nucleonic Wave Functions. By M.R. Frank, B.K. Jennings (TRIUMF), G.A. Miller, DOE-ER-40561-217, Sept. 1995. e-Print Archive: nucl-th/9509030 accepted by Phys. Rev. C. [hep-ph 9505422],

44. G.A. Miller, Phys. Rev. C39, 1563 (1989).

45. P.A.M. Guichon, Phys. Lett. B200, 235 (1988). S. Fleck, W. Bentz, K. Shimizu and K. Yazaki, Nucl. Phys. A510, 731 (1990); K. Saito and A.W. Thomas, Phys. Lett. B327, 9 (1994); K. Saito and A.W. Thomas, Phys. Rev. C51, 2757 (1995).

46. Quark-Meson Coupling Model For Finite Nuclei, P. G. Blunden, Gerald A. Miller DOE-ER-40427-04-N96, Feb 1996. nucl-th/9602031. Accepted by Phys. Rev. C.

47. P.A.M. Guichon, K. Saito, E. Rodionov and A.W. Thomas, ADP-95-45-T-194, Sept. 1995. nucl-th/9509034

48. L.L. Frankfurt, G.A. Miller and M. Strikman, Ann.Rev.Nucl.Part.Sci.44, 501 (1994)

49. J. de Kam and H. Pirner, Nucl. Phys. A389, 640 (1982).

50. T-S.H. Lee, Phys. Rev. C29, 195 (1983).

51. L. Frankfurt, G.A. Miller and M. Strikman, Phys. Lett. B304, 1 (1993).

52. G.F. Bertsch, S.J. Brodsky, A.S. Goldhaber and J. Gunion, Phys. Rev. Lett. 47, 297 (1981).

53. B.K. Jennings (TRIUMF), G.A. Miller Phys. Rev. C50, 3018 (1994).

54. C. Ordonez, L. Ray and U. van Kolck, Phys. Rev. Lett. 72, 1982 (1994).

55. H.O. Meyer *et al.*, Nucl. Phys. A539, 633 (1992); A. Bondar *et al.*, Phys. Lett. B356, 8 (1995); G.A. Miller and P.U. Sauer, Phys. Rev. C44, R1725 (1991); J.A. Niskanen, Phys. Lett. B289, 227 (1992); T.-S.H. Lee and D.O. Riska, Phys. Rev. Lett. 70, 2237 (1992); C.J. Horowitz, *et al.*, Phys. Rev. C49, 1337 (1994); E. Hernández and E. Oset, Phys. Lett. B350, 158 (1995); C. Hanhart it et al., Phys. Lett. B358, 21 (1995).

56. "The pp$\rightarrow$ pp $\pi^0$ Reaction Near Threshold: A Chiral Power Counting Approach" T.D. Cohen, et al., Phys. Rev. C, in press. [nucl-th/9512036]

57. R.A. Krauss, et al. Phys. Rev. C46, 655 (1992); Y. Mardor, *et al.*, Phys. Rev. Lett. 65, 2110 (1990).

58. "$K^+$ Elastic Scattering From C and $^6$Li at 715 MeV/c", R. Michael *et al.*, 1996 BNL preprint.

59. See the review, I. Sick, Comm. Nucl. Part. Phys. A18, 109 (1988).

60. CEBAF and the Baryon Physics Program, V. D. Burkert, CEBAF-PR-96-001, Jan 1996. 9pp. Invited talk at 7th Int. Conf. on the Structure of Baryons, Santa Fe, NM, 3-7 Oct 1995.

61. P.A.M. Dirac, Rev. Mod. Phys. 21, 392 (1949).

62. S. Weinberg, Phys. Rev. 150, 1313 (1966).

63. See e.g. the reviews, M. Burkardt, "Light Front Quantization", Adv. Nucl. Phys. 1995, hep-ph 9505259; S.J. Brodsky and G.P. Lepage in "Perturbative Quantum Chromodynamics" ed. by A.H. Mueller (World Scientific, Singapore, 1989).

64 See the reviews, B.D. Keister and W.N. Polyzou, Advances in Nuclear Physics 20, 225 (1991); L.L. Frankfurt and M.I. Strikman, Phys. Rep. 76, 215 (1981).

65. F.Coester in *The Three-body Force in the Three Nucleon System*, edited by B.L. Berman and B.F. Gibson (Springer, New York, 1986), p.472.

66. L. Frankfurt and M. Strikman, in *Modern topics in electron scattering*, edited by B. Frois and I. Sick (Illinois U., Urbana, 1992), p. 645.

67. P.L. Chung, F.Coester, B.D.Keister, and W.N. Polyzou, Phys. Rev. C37, 2000 (1988).

68. R. Dashen and M. Gell-Mann, 1966, in Proceedings of the $3^{rd}$ Coral Gables Conference on Symmetry Principles at High-Energy (Freeman).

69. W.R. Gibbs, L. Ai, W.B. Kaufmann, Phys. Rev. Lett. 74, 3740 (1995).

69. D.H. Beck, talk at national INT, March 1996.

70. V. Dmitrasinovic, S.J. Pollock, Phys. Rev. C52 1061 (1995).

## U. van Kolck

My research plan is oriented towards the use of effective theories in the non–perturbative regime of QCD. During the past few years, the theory of effective chiral Lagrangians has emerged as a promising tool to systematically describe QCD at low energies. The aim is an understanding of long-known nuclear features in a framework consistent with QCD, other hadronic processes, and pion production reactions for which facilities such as Mainz, Saskatoon, IUCF and Uppsala have recently produced very good threshold data.

In this program, the starting point is the most general Lagrangian involving the relevant low-energy degrees of freedom (pions, slow nucleons and possibly Delta isobars, photon) that incorporates the symmetries of QCD. Short-range physics (comparable to the Compton wavelength of the $\rho$ meson) is accounted for in a derivative expansion; it is thus represented by an infinite number of parameters analogous to moments of charge distributions. Long-range effects are accounted for explicitly in a loop expansion. As a result, to some desired accuracy only a finite number of interactions and diagrams needs to be considered. At the current level of understanding of QCD, the parameters of the Lagrangian cannot be derived from known QCD parameters and we are limited to fitting and thus relating the various hadronic processes.

Chiral perturbation theory ($\chi PT$) has been applied with great success to mesonic interactions, but the most interesting problems lie now in the baryonic sector. My main interest is in systems with several nucleons. Such systems present challenges because $\chi PT$ breaks down and bound states arise; but because this breakdown is due to infrared quasi–divergencies, $\chi PT$ can still be employed for nucleon–irreducible amplitudes, such as the nuclear potential or the kernel where external bosons are attached to. Iteration of the nuclear potential generates wavefunctions, and the cross-section for any scattering process on a nucleus is obtained by calculating the expectation value of the kernel between the relevant wavefunctions.

## PROGRESS 1993-96

### 1. Nucleon-nucleon (NN) force

An NN potential was constructed to third order in chiral perturbation theory[1], neglecting isospin violation. This potential has a leading component consisting of static one-pion exchange and contact (short-range) terms, and sub-leading pieces that involve one-loop diagrams and two-derivative contact terms. Further one-loop diagrams show up when the Delta isobar is included explicitly, and first results of a fit to scattering phase shifts and deuteron data – using a gaussian cut-off of 770 MeV – appeared some time ago[2]. A more completed analysis was completed recently[3]. Most data could be fit within about 10% through laboratory energies of a 100 MeV; the quality of the fit was roughly the same for cut-offs of 500 and 1000 MeV, as well as the original 770 MeV cut-off.

### 2. Isospin Violation

Isospin violation can be systematically studied in $\chi PT$, by constructing all the operators that transform under chiral symmetry in the same way as either quark mass terms or photon exchange interactions. A simple yet remarkable result[4] is that no isospin violating operators appear in the lowest order chiral Lagrangian: isospin is therefore an accidental symmetry. As a consequence, except for processes – such as $\pi^0 N$ scattering – that vanish in lowest order, isospin violation is suppressed by powers of (small momentum or pion mass/ QCD scale). Furthermore, the interplay of "indirect" electromagnetic effects and quark mass effects explains the hierarchy of isospin violating nuclear forces[4]. A phenomenological analysis of the resulting isospin violating potential was carried out recently[5,6]. In particular, isospin violation in the $\pi N$ coupling constants was studied at one-loop level, and the relevant counterterm extracted from the Nijmegen phase shift analysis. Meson-mixing models were also discussed from the point-of-view of naturalness[6].

## 3. Pion photoproduction

Pion photoproduction on nuclei was also considered in the framework of $\chi PT$ [7]. The case of neutral pion photoproduction is particularly interesting in that the leading, single-nucleon contributions vanish, so the role of two-nucleon contributions is enhanced. The leading remaining contributions come from the so-called $O(Q^3)$ single-nucleon process and from a few two-nucleon diagrams. The free $O(Q^3)$ single-nucleon process was evaluated before (see, e.g. Ref. 8) without an explicit inclusion of the Delta, and is known to fail for neutral pion photoproduction on the proton; we therefore used also an alternative estimate based on the old low-energy theorem[9]. The two-nucleon diagrams were calculated for an isoscalar target. We further computed the threshold amplitude for the deuteron, obtaining similar results when using the fully consistent deuteron wavefunction of Ref. 3 and the Bonn wavefunction. As expected, two-nucleon contributions were found to be comparable to the single-nucleon process. The overall result is in agreement with data when the old low-energy theorem estimate is employed.

## 4. Pion production in the $pp \to pp\pi^0$ reaction

The reaction $pp \to pp\pi^0$ was discussed from the point-of-view of a modified chiral power counting[10]. The role of the Delta was stressed and the s-wave pion rescattering contribution evaluated with the general chiral Lagrangian; both contributions were found to interfere destructively with the standard impulse contribution. We further modeled short-range contributions using $\sigma$ and $\omega$ pair diagrams as in Ref. 11. The final result is a theoretical cross-section a factor 3-5 smaller than threshold data.

References

1. C. Ordóñez and U. van Kolck, Phys. Lett. B291, 459 (1992).

2. C. Ordóñez, L. Ray, and U. van Kolck, Phys. Rev. Lett. 72, 1982 (1994).

3. C. Ordóñez, L. Ray, and U. van Kolck, Phys. Rev. C, in press.

4. U. van Kolck, *Few-Body Systems Suppl.*9, 444 (1995); and preprint DOE/ER/40427-13-N94 (in preparation).

5. U. van Kolck, to be published in the *Proceedings of the 7th International Conference on the Structure of Baryons*, Santa Fe, October 1995.

6. U. van Kolck, J. Friar, and T. Goldman, Phys. Lett. B, in press.

7. S.R. Beane, C.Y. Lee, and U. van Kolck, Phys. Rev. C 52, 2914 (1995).

8. V. Bernard, N. Kaiser, and U.-G. Meissner, Int. J. Mod. Phys. E4, 193 (1995).

9. I.A. Vainshtein and V.I. Zakharov, Sov. J. Nucl. Phys. 12, 333 (1971); Nucl. Phys. B 36, 589 (1972); P. de Baenst, Nucl. Phys. B24, 633 (1970).

10. T. Cohen, J. Friar, G. Miller, and U. van Kolck, Phys. Rev. C, in press.

11. T.-S.H. Lee and D.O. Riska, Phys. Rev. Lett. 70, 2237 (1992) ; C.J. Horowitz, D.K. Griegel, and H.O. Meyer, Phys. Rev. C49, 1337 (1994).

12. W.E. Caswell and G.P. Lepage, Phys. Lett. B167, 437 (1986).

13. U. van Kolck, Phys. Rev. C49, 2932 (1994).

14. W.W. Daehnick *et al.*, Phys. Rev. Lett. 74, 2913 (1995).

## M. Alberg

### PROGRESS 1993-96

A dynamical mechanism for the negative polarization of the strange sea of the proton has been proposed (with J. Ellis and D. Kharzeev). Our model of polarized, intrinsic strangeness is based on correlations between light valence quarks and vacuum strange antiquarks. It provides a consistent explanation of the state-dependence of OZI violations in low energy $\bar{p}p$ reactions, and is tested in the measurement of target spin depolarization $D_{nn}$ in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at LEAR in FY96-FY97.

A flavor asymmetry in the light quark sea of $\Sigma^{\pm}$ has been proposed (with E.M. Henley). The asymmetry appears naturally in the meson cloud model for baryons. Drell-Yan experiments using $\Sigma^{\pm}$ beams on proton and deuteron targets could measure the asymmetry. Existing beam intensities appear to be adequate for the measurement.

A long-standing apparent discrepancy between charge distributions extracted from experiment and theoretical calculations for $^3$He and $^4$He has been addressed (with L. Wilets, J. Carlson, W. Koepf, S. Pepin and Fl. Stancu). The significant depression in central density derived from experimental data is not reproduced in detailed theoretical calculations. Our preliminary results show that a variation of the proton form factor as a function of density, or of proton-nucleon separation, can explain the experimental results without invoking the "hole" in the central density.

Spin observables in antihyperon-hyperon production have been studied (with E.M. Henley, P.D. Kunz and L. Wilets). We have extended our earlier work on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ to include $\bar{\Sigma}\Lambda + \bar{\Lambda}\Sigma$ and $\bar{\Sigma}\Sigma$ production. We find a significant reduction in the singlet fraction for $\bar{\Sigma}\Lambda + \bar{\Lambda}\Sigma$ due to initial and final state interactions.

**Publications: April, 1993 to April, 1996**

1. I. Aitchison and M. Klein-Kreisler, "Effect of Wavefunction Renormalization in N-flavour $QED_3$ at Finite Temperature," Phys. Rev. D50, 1068 (1994).

2. I.J.R. Aitchison and J.A. Zuk, "The Non-Local Odd-Parity $0(e^2)$ Effective Action of $QED_3$ at Finite Temperature," Ann. Phys. 242, 77 (1995).

3. M.A. Alberg, J. Ellis, and D. Kharzeev, "The Proton Spin Puzzle and Depolarization in $\bar{p}p$ - $\bar{\Lambda}\Lambda$ Phys. Lett. B356, 113 (1995).

4. M.A. Alberg, E.M. Henley, and L. Wilets, "A Quark Model of $\bar{\Lambda}\Lambda$ Production in $\bar{p}p$ Interactions," Nucl. Phys. A560, 365 (1993).

5. M.A. Alberg, E.M. Henley, L. Wilets, and P.D. Kunz, "A Quark Model of $\bar{\Lambda}\Lambda$ Production in $\bar{p}p$ Interactions, " Nuovo Cimento 107A, 2483 (1994).

6. M. A. Alberg, E.M. Henley, L. Wilets, and P. D. Kunz, "A Quark Model of Antihyperon-Hyperon Production in Antiproton-Proton Interactions," Physics of Atomic Nuclei 57, 1608 (1994).

7. M.A. Alberg, E.M. Henley, L. Wilets, and P.D. Kunz, "A Quark Model of $\bar{\Lambda}\Lambda$ Production in $\bar{p}p$ Interactions:, " Phys. Rev. C50, 614 (1994).

8. A. Ayala, J. Jalilian-Marian, L. McLerran, and R. Venugopalan, "Quantum Corrections to the Weizäcker-Williams Gluon Distribution Function at Small *x*," Phys. Rev. D53, 458 (1996).

9. S.R. Beane, C.Y. Lee, and U. van Kolck, "Neutral Pion Photoproduction on Nuclei in Baryon Chiral Perturbatiion Theory," Phys. Rev. C52, 2914 (1995).

10. S.R. Beane and U. van Kolck, "The Dilated Chiral Quark Model," Phys. Lett. B328, 137 (1994).

11. W.A. Beck, L. Wilets, and M.A. Alberg, "Semi-Classical Description of Antiproton Capture on Atomic Helium," Phys. Rev. A48, 2779 (1993).

12. M.E. Bracco, A. Eiras, G. Krein, and L. Wilets, "Self-Consistent Solution of the Schwinger-Dyson Equations for the Nucleon and Meson Propagators," Phys. Rev. C49, 1299 (1994).

13. W. Broniowski, M. Lutz, and A. Steiner, "$N_c$-counting Rules and the Axial Vector Coupling Constant of the Constituent Quark," Phys. Rev. Lett. 71, 1787 (1993).

14. A. Bulgac, G. Do Dang, and D. Kusnezov, "Coupling Between Slow and Fast Degrees of Freedom in Systems with Complex Spectra: Driven Systems," Ann. Phys. 242, 1 (1995).

15. A. Bulgac and D. Kusnezov, "Dynamics beyond the Adiabatic Approximation," Chaos, Solitons and Fractals 5, 1051 (1995).

16. A. Bulgac and L. Frankfurt, "Coherence Effects, Parton Distributions and Baryon Rich Matter in Central High Energy Heavy Ion Collisions," Phys. Rev. D48, 1894 (1993).

17. A. Bulgac and C. Lewenkopf, "A Generalized Local Approximation to the Exchange Potential," Phys. Rev. B52, 16476 (1995).

18. A. Bulgac and C. Lewenkopf, "Stable Deformations in Large Metallic Clusters," Phys. Rev. Lett. 71, 4130 (1993).

19. A. Bulgac and C. Lewenkopf, "Temperature Dependence of the Optical Response of Small Sodium Clusters," Europhys. Lett. 31, 519 (1995).

20. A. Bulgac, C. Lewenkopf, and V. Mickrjukov, "Generalized Local Approximation to the Exchange Potential," Phys. Rev. B52, 16476 (1995).

21. A. Bulgac and V.R. Shaginyan, "A Systematic Surface Contribution to the Ground State Binding Energies," JEPT Letters 62, 833 (1995).

22. C-T. Chan, E.M. Henley, and Th. Meissner, "$\pi$-$\eta$ Mixing from QCD Sum Rules," Phys. Lett. B343, 7 (1995).

23. S. Choi, T. Hatsuda, Y. Koike, and S.H. Lee, "Twist-4 Matrix Elements of the Nucleon from Recent DIS Data at CERN and SLAC," Phys. Lett. B312, 351 (1993).

24. M-C. Chu, J.M. Grandy, S. Huang, and J.W. Negele, "Correlation Functions of Hadron Currents in the QCD Vacuum Calculated in Lattice QCD," Phys. Rev. D48, 3340 (1993); Phys. Rev. Lett. 70, 255 (1993).

25. M.-C. Chu, J.M. Grandy, S. Huang, and J.W. Negele, "Evidence for the Role of Instantons in Hadron Structure from Lattice QCD," Phys. Rev. D49, 6039 (1994).

26. T.D. Cohen, "Baryon Isovector Electric Properties in the Large $N_c$ and Chiral Limits," Phys. Lett. B359, 23 (1995).

27. T.D. Cohen and W. Broniowski, "Pseudogoldstone Modes in Isospin Asymmetric Nuclear Matter," Phys. Lett. B 348, 12 (1995).

28. T.D. Cohen and W. Broniowski, "Vanishing Condensates and Anomalously Light Goldstone Modes in Medium," Phys. Lett. B 342, 25 (1995).

29. T.D. Cohen, R. J. Furnstahl, D. K. Griegel, and X. Jin, "QCD Sum Rules And Applications To Nuclear Physics," Prog. Part. Nucl. Phys. 35, 221 (1995).

30. T.D. Cohen and G.A. Miller, "Rho-Omega Mixing and Off-Shell Charge Symmetry Breaking in the *N-N* Potential," Phys. Rev. C52, 3428 (1995).

31. J. Cooperstein, "Supernovae, the Equation of State, and Phase Transitions," Nucl. Phys. A556, 237 (1993).

32. V. Efimov, "Effective Interaction of Three Resonantly Interacting Particles and the Force Range," Phys. Rev. C47, 1876 (1993).

33. K.S. Egiyan, L.L. Frankfurt, W.R. Greenberg, G.A. Miller, M.M. Sargsyan, and M.I. Strikman, "Searching for Color Coherent Effects at Intermediate $Q^2$ via Double Scattering Processes," Nucl. Phys. A580, 365 (1994).

34. M. Fosmire and A. Bulgac, "Neutron and X-ray Scattering Off Atomic Clusters," Phys. Rev. B52, 17509 (1995).

35. L.L. Frankfurt, W.R. Greenberg, G.A. Miller, M.M. Sargsyan, and M.I. Strikman, "Color Transparency Effects in Electron Deuteron Interactions at Intermediate $Q^2$," Zeit. f. Phys. A352, 97 (1995).

36. L.L. Frankfurt, W. Greenberg, G.A. Miller, M. Sargsyan, and M. Strikman,"Color Transparency and the Vanishing Deuterium Shadow," Phys. Lett. B369, 201 (1996).

37. L. Frankfurt, G.A. Miller, and M. Strikman, "Coherent Nuclear Diffractive Production of Minijets-Illuminating Color Transparency," Phys. Lett. B304, 1 (1993).

38. L. Frankfurt, G.A. Miller, and M. Strikman, "Evidence for Color Fluctuations in Hadrons from Coherent Nuclear Diffraction," Phys. Rev. Lett. 71, 2859 (1993).

39. L.L. Frankfurt, G.A. Miller, and M. Strikman, "The Geometrical Color Optics of Coherent High Energy Processes," Ann. Rev. Nucl. Part. Sci. 45, 501 (1994).

40. L. Frankfurt, G.A. Miller, and M. Strikman, "Precocious Dominance of Point-like Configurations in Hadronic Form Factors," Nucl. Phys. A555, 752 (1993).

41. T. Frederico and G.A. Miller, "Deep Inelastic Structure Function of the Pion in the Null-plane Phenomenology," Phys. Rev. D50, 210 (1994).

42. J.N. Ginocchio and C.W. Johnson, "Unified Theory of Fermion Pair to Boson Mapping in Full and Truncated Spaces," Phys. Rev. C. 51, 1861 (1995).

43. W.R. Greenberg and E.L. Lomon, "The $\Lambda N - \Sigma N$ Interaction with Isobar Coupling," Phys. Rev. D47, 2703 (1993).

44. W. Greenberg and G.A. Miller, "Color Transparency and Dirac-based Spin Effects in (e,e'p) Reactions," Phys. Rev. C49, 2747 (1994).

45. T. Hatsuda, E.M. Henley, Th. Meissner, and G. Krein, "The Off Shell $\rho-\omega$ Mixing in the QCD Sum Rules," Phys. Rev. C49, 452 (1994).

46. E.M. Henley, "Discrete Space-Time Symmetries," Czechoslovak Journal of Physics 43, 289 (1993), No. 3/4.

47. E.M. Henley, "Measuring Strangeness in the Nucleon," Revista Mexicana de Fisica 40, 31 (1994).

48. E.M. Henley, W-Y.P. Hwang, and L.S. Kisslinger, "The Weak Parity-Violating Pion-Nucleon Coupling," Phys. Rev. B367, 21 (1996).

49. E.M. Henley and G.A. Miller, "A Proposed Test of Charge Symmetry in $\Sigma$ Decay," Phys. Rev. D50, 7077 (1994).

50. E.M. Henley and J. Pasupathy, "QCD Sum Rules for Nucleon Current in a Nucleus," Nucl. Phys. A556, 467 (1993).

51. S. Huang, "Real-time Hadron Properties at Finite Temperature from an Euclidean Lattice," Phys. Rev. D47, 653 (1993).

52. S. Huang and A.R. Levi, "A Non-Abelian Variation on the Savvidy Vacuum of the Yang-Mills Gauge Theory," Phys. Rev. D49, 6849 (1994).

53. S. Huang and W. Lin, "The Role of Anomalous Singularity in Hadronic Form Factors," Nucl. Phys. B402, 251 (1993).

54. S. Huang and W. Lin, "On the Zero Mode Problem of the Light-Cone Quantization," Ann. Phys. 226, 248 (1993).

55. S. Huang and M. Lissia, "Constraining Spectral Functions at Finite Temperature and Chemical Potential with Exact Sum Rules in Asymptotically Free Theories," Phys. Rev. D52, 1134 (1995).

56. S. Huang and M. Lissia, "Exact Sum Rules at Finite Temperature and Chemical Potential and Their Application to QCD," Phys. Lett. B 348, 571 (1995).

57. S. Huang and M. Lissia, "Dimensional Reduction at High Temperature for Fermions," Phys. Lett. B 349, 484 (1995).

58. S. Huang and M. Lissia, "The Relevant Scale Parameter in the High Temperature Phase of QCD," Nucl. Phys. B438, 54 (1995).

59. S. Huang and T. Tjon, "Nucleon Solution of the Faddeev Equation in the Nambu-Jona-Lasinio Model," Phys. Rev. C49, 1702 (1994).

60. S. Huang and B. Schreiber, "Statistical Mechanics of Relativistic Anyon-like Systems," Nucl. Phys. B426, 644 (1994).

61. M.J. Iqbal, X-M. Jin, and D.B. Leinweber, "Mesonic Width Effects on the Momentum Dependence of the $\rho-\omega$ Mixing Matrix Element," Phys. Lett. B367, 45 (1996).

62. B.K. Jennings and G.A. Miller, "Color Transparency (p,pp) Reactions," Phys. Lett. B318, 7 (1993).

63. B.K. Jennings and G.A. Miller, "Orthogonality Effects in the Coherent Nuclear Production of Jets," Phys. Rev. C50, 3018 (1994).

64. B. Jennings and G.A. Miller, "Total Neutron-Nucleus Cross-Sections and Color Transparency," Phys. Rev. C49, 2637 (1994).

65. X. Jin and T.D. Cohen, "Relations Among Zero Momentum Correlators for Heavy-Light Systems in QCD," Phys. Rev. D 51 5316 (1995).

66. N. Ju and A. Bulgac, "Finite Temperature Properties of Sodium Clusters," Phys. Rev. B48, 2721 (1993).

67. N. Ju, A. Bulgac, and J.W. Keller, "Excitation of Collective States in Fullerenes," Comp. Mater. Sci. 2, 615 (1994).

68. N. Ju, A. Bulgac, and J.W. Keller, "Excitation of Collective States in Fullerenes," Phys. Rev. B48, 9071 (1993).

69. W. Koepf and E.M. Henley, "Electromagnetic Gauge Invariance of Chiral Hybrid Quark Models," Phys. Rev. C49, 2219 (1994).

70. W. Koepf, E.M. Henley, and M. Alberg, "Mesons and the Structure of Nucleons," in *A Gift of Prophecy, Essays in Celebration of the Life of Robert Eugene Marshak*, ed. E.C.G. Sudarshan (World Scientific, 1995).

71. W. Koepf and L. Wilets, "Quark Model Description of the N-N System: Momentum Distributions, Structure Functions and the EMC Effect," Phys. Rev. C51, 3445 (1995).

72. W. Koepf, L. Wilets, S. Pepin, and Fl. Stancu, "Nucleon-Nucleon Potential in the Chromodielectric Soliton Model: Statics," Phys. Rev. C50, 614 (1994).

73. G. Krein, M. Nielsen, R.D. Puff, and L. Wilets, "Ghost Poles in the Nucleon Propagator: Vertex Corrections and Form Factors," Phys. Rev. C47, 2485 (1993).

74. D. Kusnezov and C.H. Lewenkopf, "Lévy Diffusion and Clases of Universal Parametric Correlations," Phys. Rev. C53, 2283 (1996).

75. S.H. Lee, "Contribution of Quark-Mass-Dependent Operators to Higher Twist Effects in DIS," Phys. Rev. D49, 2242 (1994).

76. S.H. Lee, S. Choe, T.D. Cohen, and D.K. Griegel, "QCD Sum Rules and Chiral Logarithms," Phys. Lett. B, 263 (1995).

77. S.H. Lee, T. Hatsuda, and G.A. Miller, "Transverse Quark Distribution in Mesons - QCD Sum Rule Approach," Phys. Rev. Lett. 72, 2345 (1994).

78. S.H. Lee, C. Song, and H. Yabu, "Photon Vector-Meson Coupling and Vector Meson Properties at Low Temperature Pion Gas," Phys. Lett. B341, 407 (1995).

79. C. Lewenkopf, "New Aspects of Stochastic Phenomena Related to Nuclear Physics," Braz. J. Physics 24, 630 (1994).

80. M. Lutz, A. Steiner, and W. Weise, "Kaons in Baryonic Matter," Nucl. Phys. A574, 755 (1994).

81. D. Makovoz and G.A. Miller, "Color Transparency Assumptions," Phys. Rev. C51, 2716 (1995).

82. D. Makovoz and G.A. Miller, "Expansion Aspect of Color Transparency on the Lattice," Nucl. Phys. B451, 622 (1995).

83. G.A. Miller, "Charge Independence and Symmetry of Nuclear Forces," Chinese Journal of Physics 32, 1075 (1994).

84. G.A. Miller, L. Frankfurt, W. Greenberg, M. Sargsyan, and M. Strikman, "Color Transparency and the Vanishing Deuterium Shadow," Phys. Lett. B369, 201 (1996).

85. G.A. Miller and J. Pasupathy, "Higher Twist and Higher Order Contributions to the Pion Electromagnetic Form Factor," Z. Phys. A348, 123 (1994).

86. G.A. Miller and W.T.H. van Oers, "Charge Independence and Charge Symmetry," in *Symmetries and Fundamental Interactions in Nuclei*, eds. E.M. Henley and W. Haxton, Singapore: World Scientific, pp. 127-168 (1995).

87. C. Ordonez, L. Ray, and U. van Kolck, "Nucleon-Nucleon Potential from an Effective Chiral Lagrangian," Phys. Rev. Lett. 72, 1982 (1994).

88. V.R. Pandharipande, C.J. Pethick, and V. Thorsson, "Kaon Energies in Dense Matter," Phys. Rev. Lett. 75, 4567 (1995).

89. S. Pepin, Fl. Stancu, W. Koepf and L. Wilets, "The Nucleon-Nucleon Potential in the Chiral Chromodielectric Soliton Model: Dynamics," Phys. Rev. C53, 1368 (1996).

90. Z. Pluhar, H.A. Weidenmuller, J.A. Zuk and C.H. Lewenkopf, "Crossover from Orthogonal to Unitary Symmetry for Ballistic Electron Transport in Chaotic Microstructures,"Annal. Phys. 243, 1 (1995).

91. Z. Pluhar, H.A. Weidenmuller, J.A. Zuk and C.H. Lewenkopf, "Suppression of Weak Localization Due to Magnetic Flux in Few-Channel Ballistic Microstructures," Phys. Rev. Lett 73, 2115 (1994).

92. L. Wilets, "Nuclear Structure Effects in Atomic Parity Nonconservation," Chinese Journal of Physics 32, 1271 (1994).

93. U. van Kolck, "Few-Nucleon Forces from Chiral Lagrangians," Phys. Rev. C 49, 2932 (1994).

94. U. van Kolck, J. Friar, and T. Goldman, "Phenomenological Aspects of Isospin Violation in the Nuclear Force," Phys. Lett. B371, 169 (1996).

95. L. Wilets and R.D. Puff, "Collapse of Flux Tubes," Phys. Rev. C51, 339 (1995).

96. K-C. Yang, W-Y.P. Hwang, E.M. Henley, and L.S. Kisslinger, "QCD Sum Rules and Neutron-Proton Mass Difference," Phys. Rev. D47, 3001 (1993).

97. S. Ying, "The Induced Pseudoscalar Axial Current in Polarized Nuclear β Decay," Phys. Rev. C47, 833 (1993).

98. S. Ying and E.M. Henley, "Time-Reveral Invariance in the β-Decays of A = 8 Nuclei," Nucl. Phys. A585, 463 (1995).

99. D.C. Zheng, B.R. Barrett, J.P. Vary, W.C. Haxton, and C-L. Song, "Large-basis Shell Model Studies of Light Nuclei with a Multi-valued G-matrix Interaction," Phys. Rev. C52, 2488 (1995).

**Accepted for Publication**

1. P.B. Blunden and G.A. Miller, "Quark-Meson Coupling Model for Finite Nuclei," (accepted for publication by Phys. Rev. D).

2. A. Bulgac and V.R. Shaginyan, "A Systematic Coulomb Contribution to the Ground State Binding Energies and the Okamoto-Nolen-Schiffer Anomaly," (accepted for publication by Nucl. Phys. A)

3. A. Bulgac and M. Adamuti-Trache, "Molecular Dynamics of Rigid Molecules," (accepted for publication by J. Chem. Phys.).

4. T.D. Cohen, J.L. Friar, G.A. Miller, and U. van Kolck, "The $pp \rightarrow pp\pi^0$ Reaction Near Threshold: A Chiral Power Counting Approach," (accepted for publication by Phys. Rev. C).

5. Z. Dziembowski, M. Fabre de la Ripelle, and G.A. Miller, "Nonperturbative Gluons and Pseudoscalar Mesons in Baryon Spectroscopy, " (accepted for publication by Phys. Rev. C).

6. M. Frank, B.K. Jennings, and G.A. Miller, "The Role of Color Neutrality in Nuclear Physics - Modifications of Nucleonic Wave Functions," (accepted for publication by Phys. Rev. C).

7. S. Huang and M. Lissia, "Contrasting Real Time Dynamics With Screening Phenomena at Finite Temperatures," (accepted for publication by Phys. Rev. D).

8. S. Huang and M. Lissia, "The Dimensionally Reduced Effective Theory for Quarks in High Temperature QCD," (accepted for publication by Nucl. Phys. B).

9. D.B. Leinweber, "QCD Equalities for Baryon Current Matrix Elements," (accepted for publication by Phys. Rev. D).

10. D. Makovoz and G.A. Miller, "Spectral Density on the Lattice," (accepted for publication by Nucl. Phys. B).

11. C. Ordonez, L. Ray, and U. van Kolck, "The Two-Nucleon Potential from Chiral Lagrangians," (accepted for publication by Phys. Rev. C).

**Submitted for Publication**

1. A. Bulgac and J.M. Thompson, "The Shape of the Fermi Surface," (submitted to Phys. Lett. B).

2. C.A. da Rocha, G. Krein, and L. Wilets, "Ghost Poles and Chiral Symmetry in $\pi N$ Scattering," (submitted to Phys. Rev. C).

3. M.J. Iqbal, X-M. Jin, and D.B. Leinweber, "$\rho-\omega$ Mixing Via QCD Sum Rules With Finite Mesonic Widths," (submitted to Phys. Lett. B).

4. D.B. Leinweber, "QCD Sum Rules for Skeptics," (submitted to Ann. Phys.).

**Conference Proceedings**

1. A. Bulgac, G.D. Dang, A. Klein, D. Kusnezov, and N.R. Walet, "Decoupling and Dissipation of Collective Modes in Complex Systems," in *Perspectives of Nuclear Physics in the late Nineties,* pp. 156-64, eds. N-D. Dang, D-H. Feng, N-V Giai, D-D Tu (World Scientific, Singapore, 1995).

2. A. Bulgac, G. Do Dang, and D. Kusnezov, "Stochastic Aspects of Large Amplitude Collective Motion," Phys. Rep. 264, 67 (1996) .

3. A. Bulgac, G. Do Dang, and D. Kusnezov, "Coupling Between Slow and Fast Degrees of Freedom in Systems with Complex Spectra,"in *Recent Progress in Many Body Theories* 4, eds. E. Schachinger, H. Mitter and H. Sorman, Plenum, New York (1995).

4. A. Bulgac, G. Do Dang, and D. Kusnezov, "Stochastic Aspects of Large Amplitude Collective Motion" in *Collective Nuclear Dynamics*, ed. F.A. Ivanyuk, Nat. Acad. Scien., Ukraine, Kiev (1994).

5. L. Frankfurt, "Diffraction at Collider Energies," AIP Conf. Proc. 272, 943 (1993).

6. W.R. Greenberg and G.A. Miller, "Color Transparency and Spin Effects in (e,e'p) Reactions," in *Few-Body Problems in Physics,* AIP Conf. Proc. 334, pp. 733-6 (1995).

7. W.C. Haxton, "Nuclear Astrophysics," Nucl. Phys. A553, 397c (1993).

8. W.C. Haxton, "Shape Coexistence, Lanczos Techniques, and Large-Basis Shell-Model Calculation," in *Proc. Intl. Conf. on Nuclear Structure at High Angular Momentum*, 2, p. 294 (AECL publication 10613).

9. W.C. Haxton, "Double Beta Decay: Comparison of Theory to Experiment," Nucl. Phys. B Proc. Suppl. 31, 88 (1993).

10. E. Henley, "Aspects of Symmetry Violation," in *Frontiers of High Energy Spin Physics*, eds. T. Hasegawa, N. Horikawa, A. Masaike, and S. Sawada (Universal Academy Press, Inc., Tokyo, 1993), pp. 59-68.

11. E.M. Henley, "Symmetry Problems in Low Energy Physics," in *Weak and Electromagnetic Interactions in Nuclei,* eds. H. Ejiri, T. Kishimoto and T. Sato (World Scientific, Singapore, 1995), pp. 697-713.

12. B.K. Jennings and G.A. Miller, "Color Transparency," in *Exclusive Reactions Of High Momentum Transfers: Proceedings*, eds. C. Carlson, P. Stoler, M. Taiuti. (World Scientific, 1994).

13. W. Koepf, L. Wilets, S. Pepin, and Fl. Stancu, "The Nucleon-Nucleon Potential in the Chromodielectric Soliton Model," in *Many-Body Physics*, eds. C. Fiolhais, M. Fiolhais, C. Sousa, and J.N. Urbano (World Scientific, 1994), p. 141.

14. T. Meissner, E.M. Henley, T. Hatsuda, and C. Chan, "Meson Mixing in the QCD Sum Rules and Its Application to the Charge Symmetry Breaking *N-N* Force," in *Few-Body Problems in Physics,* AIP Conf. Proc. 334, 809 (1995).

15. G.A. Miller, "Charge Independence and Charge Symmetry," Pion-Nucleon Newsletter 11, 90 (1995).

16. G.A. Miller, "Chiral Transparency," in *Chiral Dynamics in Hadrons & Nuclei,* Proc. Intl. Workshop on Nuclear and Particle Physics, Seoul, Korea (1995).

17. G.A. Miller, "Color Transparency Effects in Quasi-Elastic Nuclear Reactions," *Workshop on CEBAF at Higher Energies*, Newport News, Virginia (1994).

18. G.A. Miller, "Overview of Charge Symmetry," Proc. *SPIN '94*, Indiana University (1994).

19. G.A. Miller and B.K. Jennings, "Color Transparency: Enchantment and Effort," in *Perspectives in Nuclear Physics at Intermediate Energies,* eds. S. Boffi, C.C. deli Atti, and M. Giannini (World Scientific, 1992), p. 25.

20. S. Pepin, Fl. Stancu, W. Koepf, and L. Wilets, "The Nucleon-Nucleon Interaction in the Chromo-Dielectric Soliton Model," Proc. Belgium Phys. Soc. (1994).

21. U. van Kolck, "Chiral Lagrangians and Few-Nucleon Forces," AIP Conf. Proc. 334, 863 (1995).

22. U. van Kolck, "Effective Chiral Theory of Nuclear Forces," in *Low Energy Effective Theories and QCD,"* ed. D.-O. Min (Han Lim Won Printing Co., Seoul, 1995), pp. 1-69.

23. U. van Kolck, "Isospin Violation in Low-Energy Hadronic Physics," Few-Body Systems Suppl. 9, 444 (1995).

24. L. Wilets, "Collapse of Flux Tubes, "in *Hot and Dense Nuclear Matter,* eds.W. Greiner, H. Stoecker, and A. Gallmann, NATO ASI Series B 335, pp. 485- (1994).

25. L. Wilets, "Nuclear Physics: An Historic Overview," *Recent Progress in Many-Body Theories 4,* eds. E. Schachinger, H. Mitter, and H. Sormann, New York: Plenum Press, 153-161 (1995).

26. L. Wilets, "Nuclear Structure Effects in Atomic PNC," Proc. Intl. Conf. Symmetries in Subatomic Systems, Taipei (1994).

27. L. Wilets, S. Pepin, and Fl. Stancu, "The N-N Potential in the Chromo-Dielectric Soliton Model: Statics," Bull. Am. Phys. Soc. 39, 1091 (1994).

28. L. Wilets, S. Pepin, and Fl. Stancu, "Quark Model Description of the Two Nucleon System: The Short Range Repulsion and the EMC Effect," Proc. Few Body XIV, Williamsburg, VA, (1994).

**Conference Proceedings, accepted for publication**

1. E.M. Henley, "Symmetries and Nuclei," Proc. Conf. "Physics in the 21st Century," Shantou, China, August, 1995.

2. D.B. Leinweber, X-M. Jin, and R.J. Furnstahl, "New QCD Sum Rules for In-Medium Nucleons," Proc. 7th Int'l. Conf. on the Structure of Baryons, Santa Fe, NM, October, 1995.

3. U. van Kolck, "Isospin Violation: $\pi N$ Coupling and $\pi\gamma$ Exchange Potential," Proc. 7th Int'l Conf on the Structure of Baryons, Santa Fe, NM, October, 1995.

4. L. Wilets and M.A. Alberg, "The "Hole" in Helium," Proc. Int'l. Conf. on Nuclear Physics at the Turn of the Millennium, George, South Africa, March, 1996.

5. L. Wilets and R.D. Puff, "From Flux Tube to Plasma Tube to Break-up," in *Relativistic Aspects of Nuclear Physics III,* eds. T. Kodama, Y. Hama, K.C. Chung, S.U.B. Duarte and M.C. Nemes, World Scientific.

## Nuclear Theory Group

**Faculty in 1988**
**Haxton**
**Henley**
**Miller**
**Wilets**

**Faculty in 1996**
**Bulgac**
**Miller**
**Savage**

| Research Asst Prof'rs | RAP Yrs |
|---|---|
| Jerry Cooperstein | 1990 |
| Suzhou Huang | 1991-95 |
| *Ubirajara **van Kolck** | 1996- |

*** = now faculty :**

| Students | Ph.D. Yr | Postdocs | Pdoc Yrs |
|---|---|---|---|
| Achtzehnter, J. | 1988 | ***Beyer**, Michael | 1986-88 |
| Benesh, C. | 1988 | ***Williams**, Anthony G. | 1986-89 |
| ***Jung**, H. | 1989 | Raskin, A. | 1987-89 |
| Wampler, D. | 1989 | ***Pang**, Y. | 1988-90 |
| | | ***Zhang**, W-M. | 1989-91 |
| Driscoll, D. | 1990 | | |
| ***Johnson**, C. | 1990 | Ritschel, Uwe | 1990-91 |
| ***Musolf**, M. | 1990 | Frederico, Tobias | 1990-92 |
| Szczepaniak, A. | 1990 | Lin, Wei | 1990-93 |
| ***Ying**, S. | 1992 | ***Bass**, Steven | 1992-93 |
| Tang, P. | 1993 | ***Lee**, S-H. | 1992-93 |
| Greenberg, W. | 1993 | | |
| | | Koepf, Werner | 1993-95 |
| Lee, K. | 1995 | Lutz, Matthias | 1993-95 |
| Makovoz, D. | 1995 | ***Lewenkopf,** Caio | 1993-95 |
| | | ***van Kolck**, Ubirajara | 1993-96 |
| Chan, C-T. | 1997 | | |
| Beck, W. | 1997 | ***Johnson**, Calvin | 1994-95 |
| | | Leinweber, Derek | 1995-96 |
| Song, C-L. | (1997?) | | |
| Hazelton, W. | (1997?) | Thorsson, Vesteinn | 1995-97 |
| Watrous, M. | (1997?) | da Rocha, Carlos | 1995-97 |
| Walden, J. | (1997?) | Venugopalan, Raju | 1996 |

| Long-term Visitors (from DOE summaries) | Grant FY | DOE $ avail | Indir Cost |
|---|---|---|---|
| Beck, Griffin, Ji, Krein, McKellar, Rosen | N88 | $600,000 | $170,500 |
| Kunz, Hwang, Mosel, Herczeg | N89 | $580,000 | $179,200 |
| Dieperink, Sorensen, Pendrill, Rosina | N90 | $610,000 | $204,500 |
| Ginocchio, Sauer, Herczeg, Frederico | N91 | $585,000 | $187,700 |
| Efimov, Frankfurt, Horowitz, Mosel, Noack, Norenberg, Pasupathy, Weidenmuller | N92 | $600,000 | $219,700 |
| Frankfurt, Horowitz, Ishii | N93 | $620,000 * | $201,200 |
| Aitchison, Frankfurt, Mosel, Efimov, Lipkin | N94 | $620,000 | $192,700 |
| | N95 | $620,000 | $192,200 |
| Blunden, Cohen, Cavalcante, DoDang, Jung, Pepin, Robilotta, Rosina, Trache | N96 | $620,000** | $183,300 |

* plus $15,000 for computer for new Asst Prof Bulgac

** included $21,000 for computer for new Asst Prof Savage

**Papers written, numbered in the Grant publications register:**

**N88** (11/1/87-10/31/88) : **40**, including 11 conference proceedings

**N89** (11/1/88-10/31/89) : **35**, including 10 conference proceedings

**N90** (11/1/89-10/31/90) : **35**, including 5 conference proceedings

**N91** (11/1/90-10/31/91) : **40**, including 10 conference proceedings

**N92** (11/1/91-10/31/92) : **39**, including 7 conference proceedings

**N93** (11/1/92-10/31/93) : **33**, including 3 conference proceedings

**N94** (11/1/93-10/31/94) : **32**, including 4 conference proceedings

**N95** (11/1/94-10/31/95) : **41**, including 9 conference proceedings

**N96** (11/1/95-10/31/96) : **34**, including 4 conference proceedings