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Recent and Planned Research

Wick Haxton

Most of my recent research has focused on nuclear and atomic tests of symmetry principles, on various aspects of nuclear astrophysics, and on nuclear structure physics.

1. Symmetry Tests

Henley, Musolf and I have recently studied a class of weak radiative corrections important to electron scattering experiments with nucleon or nuclear targets. The nuclear “anapole moment” is strongly enhanced in heavy nuclei, growing like $A^{7/3}$, and can exceed the tree-level neutral current amplitude for experiments probing axial hadronic couplings. Our work provided new insights into the importance of current conservation in constraining the form of the anapole moment, and into the important role played by exchange currents. We are currently extending our earlier work, in which pion contributions were evaluated, to include the effects of heavy mesons.

Our work of the past several years on nuclear parity nonconservation (PNC) has demonstrated that the isovector weak $NN$ interaction, which should be dominated by neutral currents, is at least three times weaker than expected from standard current-algebra/sum-rule/quark-model calculations. The demonstration that nuclear PNC matrix elements could be derived in special cases from axial-charge beta decay rates was important to this conclusion. It appears, in close analogy with strangeness-changing hadronic decays, that existing techniques for evaluating hadronic corrections to weak meson-nucleon couplings are inadequate. C. Johnson, V. Zeps, and I are presently studying some of the nuclear physics issues effecting PNC matrix elements for nuclei near $A=16$.

Studies of double beta decay continue to provide our best constraints on lepton number conservation and on the masses and right-handed couplings of Majorana neutrinos. Recent measurements of the two-neutrino process in $^{82}$Se and $^{76}$Ge have yielded rates in excellent agreement with the shell model predictions made eight years ago. Williams and I have recently evaluated forbidden corrections to the two-neutrino process that arise from the double axial-charge operator and the double $E1$ operator. These operators test the admixture of double giant resonance amplitudes into nuclear ground states, a topic also of interest in double charge exchange.

There exists an interactive procedure based on the Lanczos algorithm for evaluating the effect of a Green's function operating on an arbitrary state vector. I first implemented this technique in the anapole study discussed above, and found very rapid convergence. This technique will now allow one to evaluate the full $1/E$-weighted sum appearing in double beta decay matrix elements, thereby avoiding the closure approximation that had been necessary in very large basis calculations. This has motivated my renewed interest in the nuclear structure aspects of this problem. New calculations
for $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{100}$Mo, and $^{130}$Te will appear in an Annual Reviews article now in preparation.

I have also been involved in a number of studies of CPNC in atomic nuclei. Henley and I have a continuing interest in deriving nuclear electric dipole moments given some underlying CPNC Lagrangian. Musolf and I are working out the corrections to Schiff's theorem, the screening of the nuclear edm by atomic electrons, that arise from the finite nuclear size, nuclear penetration terms, M2 CPNC nuclear moments, and the Breit interaction. [Schiff, Feinberg, Khriplovich, and others have discussed these corrections, but we believe the full result has not yet appeared.] Other group members and visitors (Henley, Wilets, Pang, Martensson) all have interest in these results. I am also quite interested in an analogous screening problem in $^{229}$Pa, a nucleus that exhibits a remarkable E1 ground-state doublet with a separation of only 200 eV. I've shown that the ordinary E1 transition in this nucleus should be similarly screened: this is the only experimentally accessible transition where the E1 transition energy is small compared to the inverse of the atom size.

Various experimentalists are interested in tests of CP-odd but P-even hadronic interactions. While such interactions are theoretically exotic, existing experimental limits are only at the level of $10^{-3}$ of the strong interaction. I believe that the atomic edm induced by this interaction in combination with the neutral-current electron-nucleus interaction allows one to derive much tighter constraints. This work is being done in collaboration with Andreas Schäfer.

Johnson and I recently studied the celebrated $0^{-}$ to $0^{+}$ axial-charge transition in $^{16}$O. In contrast to most earlier work, we concluded that the muon capture rate demands a value for the pseudoscalar coupling in good agreement with the Goldhaber-Treiman relation. We are troubled that the corresponding beta decay rate is somewhat smaller than experiment. We are in the process of a more careful calculation of corrections due to Coulomb effects on the electron wave function.

Other recent work included studies of the tritium beta decay endpoint spectrum, the extended Siegert's theorem, experimental signals for hyperphotons, and axion emission by nuclei (see publication list).

2. Nuclear Astrophysics

One great success of the past two years has been the demonstration that neutrino reactions in the mantle of a collapsing star are responsible for important nucleosynthesis. Some 10-15 light nuclei appear to owe their existence in the galaxy to this process. Several long-standing astrophysical puzzles have been resolved, including the origin of $^7$Li and $^{19}$F and the explanation of the isotopic ratios of Li and B. The $^7$Li result is very important cosmologically as it provides a natural mechanism for synthesizing most of the galactic abundance, thereby explaining why the big-bang production accounts for only 10% of the $^7$Li we see about us. My collaborators and I (Woosley, Hartmann, Hoffman, Colgate, Epstein) have much work to do, including extending our network calculations to heavier nuclei, exploring the dependence of the synthesis on the supernova progenitor, etc.
We are continuing work on a neutrino-induced classical r-process, with the hope that we can finally explain the origin of many neutron-rich isotopes. On initial investigations in the He zone came very close to success (producing neutron concentrations of $10^{17}/\text{cm}^3$), but still failed by at least an order of magnitude. My collaborator, R. Hoffman is now much closer to success.

I am also pursuing a radical idea that some r-process nuclei may in fact be synthesized by a new process. The “neutrino process” discussed above involves neutral current neutrino spallation reactions. It is possible for neutrinos to resonantly capture on nuclei by annihilating an electron, thereby changing one nuclear proton to a neutron while leaving the nucleus intact. This cross section increases very rapidly with Z, with the result that its phase space exceeds that for $(\nu, e)$ on a bare nucleon for heavy nuclei. In a supernova the neutrino fluences are so high near the star’s core that a single heavy nucleus has a good probability of resonantly absorbing neutrinos twice, thereby yielding a stable neutron-rich daughter (e.g., within the silicon shell). Thus we are exploring the possibility that some r-process nuclei can be synthesized in this way from s-process seeds. Of course, an important consideration is the survival of the daughters during peak shock-wave heating.

All of the above work involves parallel studies of neutrino contributions to the explosion mechanism. I showed that neutral current neutrino scattering leads to increased lepton-number loss during the infall stage (which will inhibit the explosion), but also “preheats” iron in front of the shock wave after bounce (which lessens losses by the shock wave, thereby helping the explosion)\textsuperscript{15}. Detailed calculations are being done in collaboration with Steve Bruenn.

Several new ideas have recently emerged. During infall hot nuclei can cool by radiating $\nu-\bar{\nu}$ pairs, which conserves the star’s lepton number. This could inhibit beta decay rates at very early times, thereby leading to a larger trapped lepton number. Brad Meyer, George Fuller, Kar Lee, and I are performing detailed calculations.

The inverse resonant process, the charged-current resonant process discussed above, and inelastic neutrino “up-scattering” off a hot nucleus all have the interesting property that the cross sections remain nonzero as the neutrino energy goes to zero. This demonstrates, in contrast to all the standard codes, that coherent scattering does not dominate the neutrino opacity at sufficiently low energies. Is it possible that the large lepton number losses due to radiation of low-energy neutrinos during infall are an artifact of these omissions? Kar Lee and I are exploring this possibility and its effect on the prompt explosion model.

Several years ago I provided the first analytic treatment of the MSW\textsuperscript{16} mechanism that was correct in both the adiabatic and non-adiabatic limits\textsuperscript{17}. I have extended this work to provide an analytic treatment of solar neutrino oscillations that is virtually exact for all masses and mixing angles\textsuperscript{12}, and this result was used by Bahcall and me to determine the implications of the Cl, Kamioka II, and possible Ga experiments while taking into account all uncertainties in the standard solar model. (Full Monte Carlo calculations were performed using the results of 1000 solar models.) We are improving
this code further in anticipation of the Ga and new Kamioka II results that will be
announced at Neutrino 90.

Ray Davis has claimed that his signal is varying with time, and this conclusion
has been strongly supported by Bahcall and Press and less strongly by Fillipone and
Vogel. The variation appears to anticorrerate with the solar cycle. Lim and Marciano
have offered the most plausible theoretical explanation, but their model requires both
a very large and extensive magnetic field (at least 1000 times the average surface field
of 10 Gauss) and a huge off-diagonal neutrino magnetic moment (a million times the
naive upper bound of 10^{-17} Bohr magnetons). I am currently pursuing another tact
that introduces two new ideas: the effective mass of the neutrino can vary due to solar
currents over the scale of any turbulence in the sun, and this can lead to sharp changes
in the neutrino survival probability if the scale of the current eddies matches the local
oscillation frequency of the neutrinos. This is quite distinct from the Russian work on
parametric resonances: the solar density need not change, and the interesting effects
are not linear in the perturbation.

I recently demonstrated that there was one theoretical possibility for testing the
standard solar model prediction of significant long-term luminosity increase (40%), a
result that has greatly troubled paleoclimatologists.

Johnson and I developed a model of the galactic neutrino luminosity and its impli-
cations for geochemical neutrino flux integrations.

I'm preparing a review paper on particle physics solutions to the solar neutrino
problem.

Other recent work included a reinterpretation of the 37Ca beta decay experiment of
the 37Cl neutrino capture cross section, the nuclear response of water Cerenkov detectors
to neutrinos, a new idea for a radiochemical neutrino detector now being pursued by
Davis and Lande, the feasibility of a 37Ar neutrino source, and nuclear cross sections
for the SNO experiment (see publication list).

3. Many-body Physics

Johnson and I recently completed the first \( 4\hbar \omega \) shell model calculation of the struc-
ture of \( ^{16}\text{O} \). We were motivated by interest in weak interaction rates and in technical
aspects of the Lanczos algorithm, as well as a desire to better understand the micro-
cosmic origin of superdeformation in the second \( 0^+ \) state. We also demonstrated the
power of the Lanczos algorithm by generating an inclusive response function, the \( B(\text{GT}) \)
spectrum.

Zhang and I are exploring the fractal patterns of \( 0^+ \) ground states that emerge from
diagonalization of a single-shell shell model, as the fractional filling goes from 0 to 1,
with successive increases in \( (2J+1) \). The original motivation for this is the fractional
quantum Hall effect, which can be mapped into the shell model problem described
above, with the continuum limit being \( J \) going to infinity. The observed glitches in the
conductivity uniquely correspond to \( J=0 \) ground states.
References


W. C. Haxton

Publications in Refereed Journals (1985-present)


Conference Proceedings (1985-present)


E. M. Henley

My main areas of interest continue to be related to symmetries and the connection of the quark-gluon description of nucleons and nuclei with the nucleon-meson degrees of freedom. The motivation is to gain insight into QCD and to probe weak and electromagnetic interactions, particularly at short distances or high momentum transfers.

1. The Electroweak Theory; Parity Nonconservation

(a) Electron scattering

With the advent of CEBAF, some of my interests focused on parity non-conservation (PNC) in electron scattering. The production of Δ's via a weak interaction and strange baryon production were studied in a meson-nucleon picture. These initial studies were at lower momentum transfers to make certain that structural features were understood. In the future, I intend to apply light-cone techniques to such studies with high energy electrons. This work has begun (see 6(b), below).

(b) Nucleon-nucleon scattering

Because nucleon-nucleon phase shifts became available up to momenta of 6 GeV/c, I decided to re-examine the puzzle of the large PNC observed at this incident momentum. The spin-dependent distortions are not the answer; only a small PNC asymmetry was obtained.

(c) The Anapole Moment

Mike Musolf, Wick Haxton, and I developed a nucleon-meson calculation of the anapole moment of the nucleon and of nuclei. This is an interesting and novel effect due to PNC in the electromagnetic interaction. In addition, we find that the dominant effect is a nuclear many-body one, and that the anapole moment can be measured in heavy nuclei or atoms, but not for single nucleons. We are continuing to improve our model. At present, we are working on including other mesons than the pion. Further work on inelastic scattering and off-mass shell effects remains to be carried out and is on our agenda. Atomic calculations have also been started.

(d) Neutrino interactions

A fundamental process of the weak interactions is the charged- and neutral-neutrino disintegration of the deuteron. W. Haxton, S. Ying, and I examined this process in connection with the proposed SNO detector.

2. Time Reversal Invariance

In connection with invited talks, I had to review the status of time reversal invariance; this has led to a renewed interest and I am presently investigating effects of time reversal invariance (TRI) in the beta decay of the mass 8 system, where the final state is in the continuum. In addition, with Wick Haxton, Yang Pang, Larry Wilets and Ann-Marie Martensson-Pendrill I am looking at tests of TRI in atoms; these are
measurements of an electric dipole moment or magnetic quadrupole moment. The Schiff screening effect is an important constraint on the electric dipole moment. Mike Musolf, Wick Haxton, and I have examined this effect in some detail. This work is ongoing and will continue.

3. Chiral Symmetry and Charge Symmetry

The Nambu-Jona-Lasinio model of chiral symmetry and its breaking is a very useful one for mimicking part of the long-range effects of non-perturbative QCD. Together with G. Krein, I have investigated the effects of the up and down quark mass differences on nucleon and mirror nuclei, as well as on quasi-elastic electron scattering. The effects and their dependence on nuclear density are revealing and help to explain the Nolan-Schiffer anomaly and some problems in quasi-elastic electron scattering not easily understood in terms of standard nuclear theory.\textsuperscript{17,19} With Herbert Muether, I examined some other nuclear medium effects on chiral symmetry and a crude model for including confinement in the NJL model.\textsuperscript{24} Confinement is an important feature of QCD. I intend to examine more realistic and better ways of adding confinement to the NJL Model during the next grant period.

4. Isospin, Charge Independence

One of the problems of understanding isospin invariance breaking effects, such as the difference of the pp,np, and nn scattering lengths and effective ranges at low energies, is the model dependence of the removal of the Coulomb effects, e.g., from the measured low energy pp cross section. The solution to this problem depends on a knowledge of the short-range behavior of two nucleons. This is a problem I intend to probe during the next grant period. In the meantime, Jerry Miller and I examined the one-body problem. We used the measured form factors of the proton to extract the Coulomb energy difference of the proton and neutron in a relatively model-independent manner.\textsuperscript{22}

5. Aspects of the quark-gluon to nucleon-meson transition

(a) The NN System:

The annihilation of antinucleons on nucleons occurs when the two particles overlap, so that this phenomenon is likely to involve quark degrees of freedom, even at low energies. We (Mary Alberg, Larry Wilets, and I) have advanced the idea that one should not discuss the superiority of the so-called $^3P_0$ over the $^3S_1$ model, but that both of these models should be used together, as they represent different aspects of QCD. This idea was first tested in the two meson annihilation channel\textsuperscript{15} and is now being tested by us in the theoretical analysis of $p\bar{p} \to \Lambda\bar{\Lambda}$, where polarizations can be measured. We are examining angular distributions, polarization of the $\Lambda$ and $\bar{\Lambda}$, and spin correlation coefficients.\textsuperscript{14,35,39} We intend to extend this work to other strange baryons, e.g., $\Lambda\bar{\Sigma}$. 
(b) Other aspects

There are many puzzling aspects and problems in the description of nucleons, nuclei, and mesons in terms of quarks. One of these problems is the proper description of the pion. Is it a Goldstone boson, a quark-antiquark object, or a combination of the two? In the quark-antiquark picture, one of the problems has been the mass splitting between the vector and pseudoscalar mesons, e.g., the rho and pi. I attacked this problem with a self-consistent technique and obtained some improved results.29

Quark exchange effects between particles could also show up at low energies. One place to look would be in very light nuclei. We (G.A. Miller, S. Ying, and I) examined the photodisintegration of the deuteron with this feature in mind. Before the work was completed, others had published results similar to our endeavor. We next examined higher energies, where we thought that the smaller D-state of the Bonn potential might explain the discrepancy between theory and experiment in the forward photodisintegration cross section. Careful work showed that this was not the case.29

An effective one vector colored object (taken to be a massive gluon to represent one and more gluons) exchange among quarks leads to the $^3S_1$ model. This model was first studied for $NN$ annihilation to two mesons, extended to meson decays10, and lastly, applied to meson-nucleon coupling constants.21 Although the model has problems, it was more successful than anticipated.

7. Use of the Light Cone for Exclusive Reactions

(a) Heavy Meson Decays

The light cone frame, or light cone algebra, seems to me to be a powerful technique for examining exclusive reactions in the GeV energy range. In order to learn it we (a student, Adam Szczepaniak and I) used it to examine heavy meson decays. Together with Stan Brodsky, we analyzed the decay of $B \rightarrow \pi\pi$ and other light mesons.23 More recently, Adam and I have examined CP violation in the decays of the B-mesons to two-body CP eigenstates for which no penguin diagrams contribute.24 This work is continuing; we are extending it to other decays.

(b) Electron scattering at Several GeV and the Weak Interaction

The light cone technique is also being employed by Jerry Miller, Tobias Frederico and me to study electron scattering from very light nuclei in the several GeV region. We are studying the interference of the weak and electromagnetic interactions as a possible way to test the separability of the hard and soft parts of the reaction in the light cone analysis. I hope to extend this work further to a six quark structure of the deuteron.

(c) Weak coupling constants of mesons to nucleons

Together with W-Y. P. Hwang, I hope to apply light cone techniques to calculate the weak meson-nucleon coupling constants. Such a calculation would serve as a check of the model dependence of the quark model calculation of the same constants.
8. Strangeness in Nucleons

Together with G. Krein, and A. Williams, I am investigating methods of testing the strangeness content, or strangeness matrix elements, of the nucleon. To this end, we have examined electro- and neutrino-production of $\phi$ mesons and are also examining other reactions, such as neutrino elastic scattering on nucleons and isospin zero targets. (Abstract submitted to PANIC)

9. Subatomic Physics

I have completed the revision of "Subatomic Physics" and it is presently in press.
E. M. Henley

Publications in Refereed Journals (1985-present)


Conference Proceedings (1985-present)


G. A. Miller

My principal interest is to use nuclear properties to test and probe Quantum Chromodynamics (QCD). This requires examinations of low and high momentum transfer properties. In addition, processes involving fundamental symmetries can provide relevant information about how QCD is manifest in nuclei, and are often of high intrinsic interest. I therefore plan investigations in four different areas: physics of confinement; relativistic, chirally invariant field theory of nuclei; fundamental symmetries; and, high energy probes of nuclear properties.

In the descriptions below I motivate the need to solve these problems. Previous efforts are discussed, and the proposed work is described.

Much of the work will be performed in collaboration with other members of the group, especially students and post-docs. There are also collaborations planned with members of outside institutions. Indeed, some of the projects have their origin in the first INT workshop on "Quarks in Nuclei".

1. Physics of Confinement

   A. Using the Nucleus to learn about quantum chromodynamics (QCD)

   The nucleus, under ordinary conditions, can be regarded as a collection of baryons and mesons. These features of the strong interaction must originate from QCD. But how? Presumably, the existence of nuclei is related to long-distance, non-perturbative, large coupling constant features of QCD. Thus I examine the strong-coupling limit of QCD (SCQCD). The essential feature of SCQCD is that gluonic degrees of freedom are needed to maintain local gauge invariance LGI. Here the gluons are represented by lines of color electric flux. A consequence of this approach is that in nuclei the Pauli principle is obeyed at the hadronic level. This is important in understanding the origin of the shell model. I have also found that the gluonic effects of flux line rearrangement provide negligible contributions to interactions. A more significant mechanism in SCQCD is the breaking of electric flux lines. According to LGI, this happens only if a quark-antiquark pair is emitted or absorbed. This is meson emission from baryons, the basis of conventional nuclear dynamics. I computed meson-baryon coupling constants, with results in qualitative agreement with experiment. SCQCD seems to reproduce the salient features of the meson-baryon picture of low momentum transfer nuclear physics.

   Another tractable limit of QCD is the perturbative limit, which leads to the MIT bag model. The simplest bag models would lead to significant quark percolation and perhaps complete deconfinement of quarks throughout the nuclear volume. This is not observed.

   Thus the known properties of nuclei at low momentum transfer suggest that the strong coupling limit of QCD is closer to reality than the perturbative limit.

   Future work is aimed at making the above conclusion more solid and then using it as a guide to future experiments. The first step is to incorporate the chiral invariance of
SCQCD. I found that the use of so-called staggered fermions leads to a vacuum quark condensate and a result that quarks cannot move without developing a meson cloud. The properties of the vacuum, the pion and a sigma meson (first excited state of the vacuum) are then closely related. I intend to obtain a model of the above three systems and to improve the calculations mentioned above by incorporating chiral invariance.

If enough qualitative features of SCQCD are found to be true then one can use SCQCD as a guide for knowing the experiments to avoid and to pursue. I list a few possible examples. There are no strong interaction “Van der Waals” forces in SCQCD. A nuclear hyperon occupies the lowest energy shell model orbitals. Quark deconfinement at low momentum transfer is suppressed. To probe the structure of the pion is essentially to probe the structure of the QCD vacuum.

B. Searching for the pentaquark

The observation of exotic states such as the doubly strange six-quark H-dibaryon or the pentaquark (c̅s, +nucleon) would provide significant information about confinement. We (new student W. Greenberg and I) are starting a project on this topic. Most of our attention will be devoted to the pentaquark, since much work has been done on the H particle. We hope to learn how to compute the cross sections for formation of such states in nuclear reactions. New calculations of the masses to see if such states really are bound are also planned. We will extend earlier calculations by including the effects of the finite value of the charmed quark mass and coupling to meson-baryon channels.

2. Relativistic, Chirally Invariant Field Theory of Nuclei

Understanding the saturation properties of normal nuclear matter is still an important problem. Recently, it has become popular to study nuclear matter with relativistic quantum field theories. However, pionic effects are not important in the commonly used mean field approximation to such theories. This is surprising since pions mediate the nucleon-nucleon interaction at all but the shortest ranges. Furthermore, chiral symmetry is an important approximate symmetry of strongly interacting systems which requires pionic degrees of freedom. Hong Jung and I obtained a relativistic chiral treatment of nuclear matter. We use Weinberg’s pseudovector representation of the linear sigma model with vector omega mesons and delta isobars also included. To obtain a result that maintains chiral symmetry and achieves nuclear matter saturation it is necessary to include the relativistic pion ring series which we derive and sum. The calculations reproduce the observed binding energy, density and incompressibility of normal nuclear matter. A qualitative feature that distinguishes our results from others is that the effects of the scalar meson are very small. Instead the attraction comes from pion exchanges.

Future work is aimed at improving the calculations and expanding the range of applications. The first step is to compute the pion ring series contribution to the nucleon self-energy, Σ. Jung’s thesis work indicates that this contribution to Σ gives large attractive scalar and vector potentials. Furthermore, the nucleon spectroscopic factor at the Fermi surface, Z, is about 0.5, which is significantly smaller than typical
values of 0.8. This is an indication that the nuclear shell model is not obtained with the approximations employed so far. We plan to search for a remedy. There are two options. The first and simplest is to see if different coupling constants and form factors yield a larger value of $Z$. The second is to make a self-consistent calculation by computing the ring series with nucleon propagators as modified by the ring series. I hope that the new post-doc, Wei Lin (IUCF Ph.D. '90) and/or G. Krein will be involved in these projects.

If our current results survive the necessary improvements in the theory, we will have obtained a different treatment than those of other relativistic approaches. Therefore we seek experiments to distinguish the various ideas. We predict the existence of a pion condensate for values of the Fermi momentum greater than about twice that of normal nuclear matter. We may examine proton-nucleus scattering in the framework of this theory. The number density of excess pions is also computed. This is of interest in understanding deep inelastic scattering and nuclear Drell-Yan experiments, see below.

3. Fundamental Symmetries

A. Charge Symmetry Breaking

Slaus (Zagreb), Nefkens (UCLA) and I have just completed a Physics Report on Charge Symmetry Breaking (CSB)\(^7\). CSB in systems ranging from mesons to heavy nuclei is studied. We find that ALL observed CSB can be explained in terms of quark mass differences and electromagnetic interactions between quarks. The down quark is more massive than the up quark at momentum scales corresponding to confined systems. A recent paper with E. Henley showed\(^8\) how to incorporate the experimentally measured charge form factors into determinations of the up-down quark mass difference from the neutron-proton mass difference.

We have made simple calculations\(^7,9\) which show that the model dependence of removing the Coulomb force from the proton-proton interaction is limited to 0.4 fm. The idea was to use the three-body nuclei to rule out nucleon-nucleon interactions with unusual off-shell dependence. The claim can be confirmed by making calculations using more detailed three-body wave functions. To make progress it is necessary to collaborate with someone with a program that solves the Fadeev equation. R. Machleidt, Idaho, may be interested in this effort.

Future work on CSB may include a calculation of the gamma-pion exchange potential (with M. J. Iqbal, TRIUMF). A definitive calculation has never been done. This effect could be important to understand the recent TRIUMF and IUCF experiments that observe CSB class-IV forces in neutron-proton scattering. (The background information is discussed in the review\(^7\).)

B. CP Violation (CPV) and Time Reversal Violation

The existence of CPV effects has important implications for many areas of physics. But so far, has been observed only in the neutral kaon system. It is clear that future progress in understanding the origins of CPV depends on a new experimental observation. Therefore, I have been investigating possible CPV violations in processes involving baryons.
In this work (begun with M.J. Iqbal at TRIUMF) a new technique to calculate CPV observables is developed. The idea is to use the hadronic CPV matrix elements measured in the neutral kaon system. Thus the calculation is strongly constrained by experimental measurements. We compute the neutron electric dipole moment and the CPV meson-nucleon coupling constants $G_{CPV}$. The nuclear consequences of the CPV pion-nucleon coupling constant seem very small. However we find that CPV may be observable in the decays of hyperons because the CPV coupling constant for the decay of the lambda hyperon to the pion and nucleon is about six orders of magnitude larger than $G_{CPV}$. Experimentalists are interested in pursuing this by comparing the decays of hyperons and anti-hyperons produced in proton-antiproton collisions. This work is now published\textsuperscript{10}.

Future efforts will be in collaboration with A. Gersten, Beersheba. We will use some of the above ideas to develop theories of TRV in hyperon-nucleon scattering and other processes involving hyperons.

C. Parity Violation (PV) in Nucleon-Nucleon Scattering

The ultimate goal of such studies is to determine the weak parity-violating interactions in the presence of the strong force. D. Driscoll, (Ph.D. 1989) and I plan to finish our investigations of proton-proton scattering. We developed a formalism in which the computed parity violating asymmetries are essentially independent of the strong interaction potential\textsuperscript{11}. Then the PV nucleon-nucleon potential is constructed without making the usual non-relativistic approximations\textsuperscript{12}. This requires the use of the momentum space representation. The next step is to include the effect of PV in inelastic channels. We believe this is necessary to understand the LAMPF data\textsuperscript{13} at 800 MeV. The dominant inelasticity pion production via delta decay. Thus we will compute the box diagram with an intermediate delta-nucleon state.

4. High Energy Probes of Nuclear Properties

A. Nuclear Dependence of the Drell-Yan Process

High momentum transfer electron-nucleus scattering experiments have shown that the structure function of the nucleon is modified when the nucleon is immersed in the nuclear environment. Several reasonably successful models to explain this "EMC effect" were developed\textsuperscript{14}. Our response was to search for other experiments to distinguish the diverse models. We proposed\textsuperscript{15} that new measurements of the process of lepton-pair production in high energy proton-nucleus scattering can separate the different models. In this Drell-Yan process a quark in the projectile (target) combines with an anti-quark in the target (projectile) to form a pair of leptons. If nuclear effects, such as excess pions, give an enhancement of the nucleon sea, the number of available anti-quarks is increased, and the Drell-Yan process is enhanced. The first high-precision data have just been published\textsuperscript{16} and no nuclear enhancements are observed. We (A. W. Thomas Adelaide and H. Jung (CMU) are studying the experiment to convince ourselves of its validity. We also plan to determine the constraints that these data impose on nuclear models.
B. Deep Inelastic Scattering from the deuteron

The discovery of the EMC effect has caused many people\textsuperscript{14} to improve the computations of nuclear contributions to lepton-nucleus deep inelastic scattering (DIS). We apply this new theoretical knowledge to the problem of extracting the neutron structure function from a DIS on deuterium. The new feature is that the deuteron spectral function can be evaluated without making a closure approximation commonly used for heavier nuclei. This simplifies the evaluation of DIS from the deuteron. I have used the 4-dimensional nature of the spectral function to obtain a gauge invariant (GI) formalism. The original extraction\textsuperscript{17} did not use a GI procedure.

There are other reasons for examining DIS from the deuteron. The calculations are simpler than for heavier nuclei and one may be able to examine the validity of some of the approximations. Furthermore, the spin-1 nature of the deuteron allows the measurement of a new quantity the $b_1$ structure function\textsuperscript{18}. A student B. Lopez and I plan to check and publish my earlier computation\textsuperscript{19}.

C. On Color Transparency

B. Jennings, TRIUMF, and I study a class of high momentum transfer (greater than about 2 GeV/c) nuclear processes which proceed by the emission of a single fast nucleon from the nucleus. Examples are the semi-exclusive $(e,e'p)$ and $(p,pp)$ reactions.

It has been argued\textsuperscript{20} that a phenomenon called color transparency occurs for sufficiently large values of the momentum transfer. These arguments are summarized here: To obtain an appreciable amplitude for a high momentum transfer reaction on a nucleon leading to a nucleon, the colored constituents must be close together. If the constituents are close together, their color electric dipole moment is small and the soft interactions with the medium are suppressed. If the particle remains small, it can escape the medium without further interaction and absorption. This possibility of reduced nuclear opacity (RINO) has been called "color transparency". Color transparency or RINO is expected to hold even when the projectile-nucleus optical potential is not small.

The idea of color transparency has generated much interest\textsuperscript{21-25} because of the arguments\textsuperscript{20} that the existence of color transparency is a testable prediction of quantum chromodynamics (QCD). Moreover, if color transparency holds, one obtains a new way to study the high-momentum tails of nuclear wave functions.

Previous derivations\textsuperscript{20} of color transparency used a time-dependent approach, classical arguments, and a Fock state decomposition. Here we clarify the arguments using a time-independent, quantum mechanical approach with physical states. Color transparency is shown to arise from using the closure approximation. A new set of conditions necessary for the appearance and eventual measurement of color transparency effects are determined\textsuperscript{26}. We found that the conditions for color transparency to occur are satisfied if $E \gg 1.2A^{1/3}$ or $E \gg 3.6$ GeV for $^{27}$Al. For an $(e,e'p)$ experiment $E = E(q)$ where $q$ is the three-momentum transfer to the outgoing nucleon of energy $E$. Thus to see color transparency in the $(e,e'p)$ reaction one needs $q \gg 6$ GeV.

The early work was based on using limits of expressions. Future work on RINO involves explicit evaluations of the energy dependence of the approach to color trans-
D. Has color transparency already been found?

The above section 4D describes our efforts to see if color transparency can in principle be observed. But there has already been an experiment aimed at observing color transparency. These are the particularly intriguing data of Carroll et al., Ref. 25. In that work the highest momentum transfer \((p, 2p)\) cross sections were measured for incident proton momentum of 6, 10 and 12 GeV/c. The nuclear transparency was defined in Ref. 25 as the ratio of the nuclear \((p, 2p)\) cross section (per nucleon) to the free \(pp\) cross section at the same momentum-transfer squared. The interesting finding was that the nuclear transparencies measured for \(^{12}\text{C}\) and \(^{27}\text{Al}\) increase by a factor of about 2 as the incident momentum increases from 6 to 9.5 GeV/c. But the transparency falls significantly when the beam momentum is increased to 12 GeV/c.

This observation of so-called "oscillating color transparency" led to interesting explanations\(^{21-23}\). However, if Sudakov form-factor effects\(^{24}\) are computed the Landshoff diagrams may not involve well-separated quarks.

T. S-H Lee (Argonne) and I propose to examine the influence of conventional effects on the computed \(p, 2p\) reaction cross sections. Such effects include: using realistic nuclear wavefunctions with modern treatments of nucleon-nucleon correlations, an improved Glauber calculation of the distortion without using the "factorization" approximation. These effects might be important in giving struck nucleons a higher momentum than that assumed by Carroll et al. in making their analysis of the data. It is necessary to rule out the possibility that conventional effects yield the oscillations before concluding that color transparency has indeed been observed.

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July 1989.

L. Wilets

My research interests in the past have covered a broad range of topics. I list below some which I consider significant and pioneering. (The terminology in some cases is more modern than used in the papers.)

1. The role of nuclear deformation in atomic isotope shifts.
2. Nuclear deformation and excitation in muonic atoms.
3. A numerical method for solving nonlinear differential equations with boundary conditions. This pioneering work is the basis of such well-known schemes as COLSYS.
4. Theory of nuclear fission (including Coulomb fission).
5. Gamma-unstable collective excitations in nuclei.
6. The energy density formalism for nuclear matter distribution.
7. Inelastic scattering from rotational nuclei—close coupling (the first) and other approximations.
8. Surface coupling as a mechanism for viscosity.
9. Pairing in nuclei.
10. Eikonal method for atomic collisions; P-H calculations.
11. Non-relativistic many body calculations, especially using Green's function techniques.
12. Relativistic nucleon-meson field theory for few and many-body systems; N-N scattering.
13. Vacuum polarization in high-Z atoms.
15. Parity nonconservation in atoms.
17. A classical many-body model of nuclear and atomic collisions incorporating the Pauli and Heisenberg principles.
18. Modeling QCD with nontopological solitons.

The total number of papers published or accepted in refereed journals is 155.

Recent research topics and plans for the future include:
1. Chirally-invariant Chromodielectric Soliton Model

Recently, G. Fai, R. Perry and I proposed a chirally invariant version of the Friedberg-Lee soliton model, where quarks are coupled only to the gluonic field, not to the scalar $\sigma$-field. Along with P. Tang, G. Krein and A. Williams, we have demonstrated, in the local approximation, how confinement is effected and how the pion emerges as a Nambu-Goldstone boson. Work is continuing (as Tang’s thesis) to solve the problem with its full nonlocality and to construct the pion explicitly.

2. The Need for a Non-local Dielectric Function (with U. Ritschel)

In classical electrostatics, as well as chromodielectric models, renormalization of a massive charged particle self-energy is not possible in a spatially varying local dielectric. The concept of a local dielectric has meaning (in electrostatics) only as an average over many atoms or molecules, whereas the divergence in the self-energy comes at short distances. We propose setting $\kappa(\vec{r}, \vec{r}') = \delta(\vec{r} - \vec{r}') + \kappa_1(\vec{r}, \vec{r}')$ where $\kappa_1$ is smooth. In the chromodielectric model, one still preserves color confinement and we find an effective scalar potential $\sim \kappa^{-1/2}$. Consequences are being pursued.


In a series of three papers, Fl. Stancu (University of Liège) and I have presented the classification and construction of six-quark systems appropriate for N-N scattering and bound state systems. The scheme is based on orthogonal parity (molecular) eigenstates, as distinct from the popular cluster states, which omit certain important configurations. The algebra is actually easier using these orthogonal functions rather than the non-orthogonal cluster model functions. We have performed calculations of the short range (actually, spherical) interaction energy for both current and constituent quark models and find a dramatic lowering of the energy relative to the separated 3-quark clusters. This calls into serious question previous calculations, which generally neglect these configurations. The neglected configurations are actually constructed from the same spatial functions as the ones used in common cluster models. We supply the algebra for practitioners in the field in order to facilitate the inclusion of these states in their work.

4. The Gluon Propagator in Medium

P. Tang and I have finished a paper on the linear gluon (or Maxwell) propagator in inhomogeneous dielectric media, in various gauges. Errors in previous works on the subject have been corrected. The results have wide ranging application in models of QCD and in E & M.

5. Many-bag Systems

In previous papers, M. Birse, J.J. Rehr, J. Achtzehnter, W. Scheid and I proposed a preliminary “crystalline” approximation for many-bag systems. This was then further approximated by the Wigner-Seitz cell method which is actually more realistic.
(i.e. less unrealistic). An important problem is the filling of the Bloch bands. This problem is not serious in solid state physics because there the residual two-body interactions are weak. In QCD they are strong and are responsible for color confinement and (for example) $N$-$\Delta$ splitting. M. Birse (Manchester), Fl. Stancu (Liège) and I have embarked on a renewed program to study intra-band configuration mixing using the chromo-dielectric model and the numerical methods developed for 6-quark systems. The goal is to extract nucleon form factors (with A. Dieperink and M. Rosina) as a function of density, as well as to study the hadron-plasma phase transition. Alternative approaches, beginning with pseudo-Wanier states, are being studied with M. Rosina (Ljubljana) and J.J. Rehr.

6. Atomic Structure and Symmetry Violation

Atomic symmetry violation experiments by the Fortson group at the University of Washington and elsewhere now demand more precise atomic calculations in order to interpret the results. I have a continuing interest in such calculations. Working in the context of soliton bags, M. Li, R. Perry and I developed very accurate techniques for constructing Dirac propagators in external, one-body (local) potentials; from this can be constructed projection operators. Y. Pang and I have produced a program to construct Dirac propagators and projection operators for local and non-local potentials, such as relativistic Hartree-Fock potentials. Although this has not been done before, it is generally recognized as an excellent way of handling the "continuum dissolution" problem. A perturbation theory built on RHF states should converge more rapidly than one built on plane waves, especially for heavy atoms. Techniques developed earlier (with E.M. Henley) should now be very appropriate for correlation calculations.

7. Nuclear Structure Effects in Atomic PNC (with Y. Pang and E.N. Fortson)

Because of uncertainties in atomic calculations, several researchers have suggested studying ratios of PNC observables in strings of isotopes. Specific atomic many-body effects cancel in the ratios. Nevertheless, we find that the ability to deduce weak parameters, such as the Weinberg angle, depend sensitively on the neutron distribution, which cannot be determined accurately or in a model-independent way from experiment. While this limits the utility of determining weak parameters from such experiments, it does provide a unique measure of changes in the neutronic rms radius, and a good test of theory. Similarly, if nuclear calculations can be shown to be predictive for both charge and neutron distributions, one can then use theoretical neutron calculations to help extract the weak parameters.

8. Semi-classical Atomic and Nuclear Collisions

W. Beck and I have been continuing a study of atomic and nuclear collisions. The work is based on a model introduced earlier, which simulates the Pauli and Heisenberg principles by a momentum-dependent potential. The model has come to be known under the general heading "quantum molecular dynamics." An essential feature of the potential is the length-momentum scaling in order to reproduce the Fermi sea for non-interacting particles. An interesting variation has been proposed by H. Feldmeier which
is based on a variational principle utilizing Gaussian packets. We are studying the properties and utility of the model.

9. (Anti-) Cold Fusion Limits, and Related Real Physics

M. Alberg (Seattle University), J.J. Rehr, J. Mustre de Leon and placed realistic limits on cold fusion, which are well beyond the range of reported experiments. A screened potential for charged particles in an electron gas was used for the $d-d$ or $p-d$ potential and the $d$ or $p$ interaction with the crystal was calculated using a spherical average of the Matteiss muffin-tin approximation. Inclusion of higher angular modes would only further decrease the calculated rate. Thus an overly optimistic estimate of the $p-d$ rate in the small tetrahedral site yields $10^{-49}$/sec, far below the "experimental" report of $10^{-(19-23)}$/sec. The paper is to be published in Phys. Rev. C.

Our investigations suggest interesting physics problems which have been left unsolved before. For example, two point charges in a degenerate electron gas using (a) Thomas-Fermi or (b) Hartree-Fock. Even the full, non-linear single charge Thomas-Fermi calculations have not been uncovered in the literature, but we have now calculated the problem and find that it reduces the screened potential (increases screening) by 17% from the usually quoted linear result. (This is like charge renormalization.) We have the tools to tackle the two-center problem for both T-F and H-F.

10. Numerical Techniques

The numerical work on cold fusion led M. Alberg and me to discover a class of analytic solutions to the Coulomb plus oscillator potential. Such exact solutions have practical applications beyond their amusement.

In Hartree-Fock calculations, the exchange term makes the eigenvalue problem an integral-differential equation (in configuration space). I have developed a method for solving the problem as a set of coupled differential equations. I have tested it in limited cases, and now K. Vigeland is studying it more generally to test its speed relative to conventional methods.

11. A Model of $\bar{p}p \rightarrow \Lambda\Lambda$

In collaboration with M. Alberg (Seattle University), E.M. Henley and D. Kunz (University of Colorado), we are studying $\bar{N}-N$ rare processes, especially $\bar{p}p \rightarrow \Lambda\Lambda$, in the context of simple quark models. A linear combination of $^3P_0$ and $^3S_1$ interactions are found to significantly improve the fits to cross section and polarization LEAR data over previous models built on only one of these forms. The fits are quite sensitive to the $\Lambda\Lambda$ potential, and thus provide a handle on determining this function.

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L. Wilets

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