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Nuclear Theory Group
University of Washington

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This document is a summary of the physics research carried out by the Nuclear Theory Group at the University of Washington during the last twelve-month period.

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1Joint Position with Jefferson Laboratory.
## Effective Field Theories in Multi-Nucleon Systems

A. \( np \rightarrow d\gamma \) for Big-Bang Nucleosynthesis ........................................ 4  
B. Photonic Interactions with the Deuteron in Chiral Perturbation Theory ........ 5  
C. Pion-Deuteron Scattering in Chiral Perturbation Theory .......................... 6  
D. Improving the Convergence of NN Effective Field Theory ......................... 6  
E. Neutrino-Deuteron Interactions ................................................................. 7  
F. Three-Body Processes .................................................................................. 8  
G. \( NN \rightarrow NN\pi \) from the Effective Field Theory Point of View and the Three  
   Nucleon System ......................................................................................... 8  
H. Pion Production in Low Energy Two-Nucleon Interactions ......................... 9  
I. Effective Field Theory for \( \bar{NN} \) Scattering ............................................. 9  

## Light-Front Nuclear Physics

A. Heavy Nuclei ................................................................................................. 11  
B. HERMES Effect .......................................................................................... 11  
C. Relativistic Corrections to Nuclear Charge Radii ...................................... 12  
D. Relativistic Quarks in Relativistic Nucleons ............................................. 12  
E. Light Nuclei .................................................................................................. 13  
F. Nucleon Structure Functions ....................................................................... 14  
G. Quantization of Spin \( \frac{3}{2} \) Particles on the Light Front ......................... 14  

## Color Transparency and High Momentum Transfer Reactions

A. The High Energy \( \gamma d \rightarrow np \) Reaction ............................................. 15  

## Astrophysics

A. Neutrino and Axion Radiation from Neutron-Star Cooling and Supernovae  16  
B. SN1987A Bounds on Large Compact Extra Dimensions ............................ 16  
C. Shielding of Nuclei in a Finite Temperature Plasma ................................... 17  

## QCD at High Density



## Fundamental Symmetries

A. Charge Symmetry Breaking .......................................................................... 18  
B. Parity Violating Proton-Proton Scattering at High Energy ......................... 18  
C. Time Reversal and CP Violation .................................................................. 19  
D. Deuteron Anapole Form Factor ................................................................... 19  
E. Parity Violation in \( \gamma N \) Compton Scattering ......................................... 19  
F. Book on Symmetries ..................................................................................... 19  

## Finite-Temperature QCD

A. Scalar Field Theory - Screened Perturbation Theory .................................. 21  
B. Quantum Chromodynamics - Hard Thermal Loop Perturbation Theory .... 21
| Section | Title | Page |
|---------|-------|------|
| VIII | Many-Body Physics | |
| A | Inhomogeneous Nuclear Matter | 22 |
| B | Dissipative Collective Motion | 24 |
| C | Nuclear Energy Density Functional | 24 |
| D | New Gaussian Single–Particle Wave Function Basis | 24 |
| IX | Hadronic Interactions and Structure | 25 |
| A | Strangeness Content of the Nucleon | 25 |
| B | Influence of Kaon-loops on \( \phi \) Photoproduction | 25 |
| C | Production of Heavy Mesons in Nucleon-Nucleon Collisions | 26 |
| D | A Meson-Exchange Model for Pion Production in Nucleon-Nucleon Collisions | 26 |
| E | \( pp \rightarrow p\Lambda K^+ \) and \( pp \rightarrow p\Sigma^+ K^+ \) Near Threshold | 26 |
| F | The Structure of the Roper Resonance | 27 |
| G | Pion-Baryon Couplings and SU(3) | 27 |
| H | Electron-Deuteron Scattering in a Relativistic Current-Conserving Frame- work | 27 |
| X | Large-\( N \) QCD and Nuclei | 28 |
| A | High Energy Theorems at Large-\( N \) | 28 |
| B | Low Energy Constants from High Energy Theorems | 28 |
| XI | Other | 29 |
| A | Dimensional Regularization of Integral Equations | 29 |
| B | Exact Solutions to the Schroedinger Equation for Coulomb-Plus-Oscillator Potential | 29 |
I. EFFECTIVE FIELD THEORIES IN MULTI-NUCLEON SYSTEMS

Since Weinberg’s pioneering efforts to describe nuclear systems with effective field theory (EFT) \(^{[1]}\), nuclear physicists have spent the last decade attempting to realize this dream. Beane, Chen\(^{[2]}\), Grießhammer\(^{[3]}\), Phillips\(^{[4]}\), Rupak\(^{[5]}\) and Savage at the University of Washington have on-going programs to develop a systematic and perturbative theory to describe multi-nucleon systems. During the last year, important progress has been made in our ability to calculate observables in the two- and three-nucleon sectors. Techniques have been developed that enable precision calculations of low-energy observables, particularly those involving the deuteron.

A. \(np \rightarrow d\gamma\) for Big-Bang Nucleosynthesis

\[J.-W. \text{ Chen, G. Rupak and M. J. Savage}\]

The recent revelation by Burles, Nollet, Truran and Turner \(^{[2]}\) that the theoretical uncertainty in the cross section for \(np \rightarrow d\gamma\) at low-energies (which they estimated to be \(\sim 5\%\)) made a significant contribution to the uncertainties of elemental abundances computed in the Big-Bang, motivated Jiun-Wei Chen, Gautam Rupak and Martin Savage to examine this process with EFT. Chen and Savage \(^{[3]}\) were able to derive expressions for the cross section that had an associated error of \(\sim 3\%\) over the energy region of interest. This amplitude involves one constant that is not determined by nucleon-nucleon scattering data, however, it is determined by the precisely measured cross section for thermal neutron capture. The predicted cross section for \(\gamma d \rightarrow np\) is shown in Figure \[4\]. Rupak \(^{[4]}\) was able to extend this calculation to one higher order in the EFT expansion and so obtain a cross section with an associated uncertainty of \(\sim 1\%\). An additional constant appears at this order and is determined by the cross section for \(\gamma d \rightarrow np\) at higher energies. Consequently, the theoretical uncertainty for this process that enters nucleosynthesis codes is reduced by a factor of \(\sim 5\), thereby eliminating this process as a significant source of uncertainty.

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\(^{2}\)PhD student of Savage who graduated in 1999 and is currently a Postdoctoral Fellow at the University of Maryland

\(^{3}\)A Postdoctoral Fellow in our group during 1997-1999, and currently a researcher at Munich.

\(^{4}\)Currently a Research Assistant Professor in our group, and who will assume a tenure-track Assistant Professor position at Ohio University in the fall of 2000.

\(^{5}\)Currently a PhD student of Savage, who will assume a Postdoctoral position at TRIUMF in the fall of 2000.
FIG. 1. The cross section for $\gamma d \to np$ versus photon energy. The solid curve corresponds to the theoretical cross section computed with EFT. The two dotted curves correspond to the $\sim 3\%$ uncertainty in the calculation of Chen and Savage [3]. Rupak’s calculation reduced this uncertainty further, to below $\sim 1\%$ [4].

B. Photonic Interactions with the Deuteron in Chiral Perturbation Theory

S. R. Beane, M. Malheiro (Brazil), J. McGovern (Manchester), D. R. Phillips, and U. van Kolck[6] (Caltech)

The electric and magnetic polarizabilities of the neutron and proton provide great insight into the structure of the nucleon. Due to the absence of pure neutron targets, efforts to extract neutron polarizabilities from processes involving nuclei continue. The reactions

\[
\gamma + d \to \gamma + d \\
\gamma + d \to \gamma + p + n
\]

are of particular interest because, provided suitable kinematics are chosen, they may allow the extraction of electromagnetic polarizabilities of the neutron. In baryon chiral perturbation theory hadronic effects can be included systematically, order-by-order in the chiral expansion. Consequently, the hadronic part of the reactions (1) can be calculated in a controlled way, and effects due to electromagnetic polarizabilities of the neutron can be reliably extracted from the data.

We have recently computed the elastic photon-deuteron scattering to next-to-leading order using Weinberg’s power counting [1]. The results appeared in [5], and are in reasonable agreement with the data from Illinois [6], although they differ from the recent SAL data [7]—as do all reasonable extant theoretical calculations. During the fall of 1999 Dr. Malheiro visited our group, and considerable progress was made towards performing the calculation to next order. This higher-order calculation has the advantage that the neutron polarizabilities appear as the only free parameter at this order in chiral perturbation theory. It also allows for a test of the convergence of the chiral expansion for this reaction. In Figure 2 the

6Former Research Assistant Professor in our group who will assume a tenure track Assistant Professor position at the University of Arizona in the fall of 2000.
results of three orders for this calculation are compared to the data at a photon energy of 69 MeV \[6\].

C. Pion-Deuteron Scattering in Chiral Perturbation Theory

S. R. Beane, U.-G. Meißner (Julich), and D. R. Phillips

The recent complete one-loop calculation of pion-nucleon scattering in chiral perturbation theory \[8\] has greatly improved the description of pion-nucleon scattering. In fact, the agreement with the low-energy pion-nucleon scattering data is now quite good. The logical next step is to apply the recently developed techniques to describe the deuteron in EFT to pion-deuteron scattering. This is of particular interest because the pion-deuteron scattering experiment constrains the isoscalar combination of $\pi - N$ scattering lengths, $a^+$. However, as in the case of the neutron polarizability, if one is to extract this quantity reliably one must employ a formalism in which the two-body corrections to the reaction mechanism are under control. We have had preliminary discussions regarding this calculation.

D. Improving the Convergence of NN Effective Field Theory

D. R. Phillips, G. Rupak, and M. J. Savage

At energies well below the pion mass the only relevant degrees of freedom in few-hadron systems are the nucleons themselves. This led to the formulation of an effective theory of $NN$ interactions which is akin to effective range theory. Indeed, for two-nucleon processes this effective field theory uniquely reproduces the results of effective range theory. However, its predictions differ for processes in which external probes couple to the $NN$ system, in that one can systematically include the effect of operators which are not constrained by $NN$ phase shifts, or related to $NN$ processes by current conservation. There have been a number of very accurate calculations pursued in the last year in this “$NN$ EFT”, but one persistent problem was that the series for elastic processes on the deuteron converged somewhat slowly.
Last summer we realized that this could be resolved by using an alternative fitting procedure in the $NN$ EFT. This procedure, called the Z-parameterization, involves reproducing the tail of the deuteron wave function correctly in the $NN$ EFT at next-to-leading order. For many observables this results in excellent convergence of the expansion. Indeed, it means that in elastic scattering the first corrections to the NLO result come from two-body operators and relativistic effects. The Z-parameterization significantly improves the convergence of inelastic deuteron processes, such as $np \rightarrow d\gamma$ as described previously, and is no worse for ordinary $NN$ scattering than the original fitting procedure [9].

E. Neutrino-Deuteron Interactions

J.-W. Chen and M. N. Butler (Halifax)

Nuclear physics is playing a central role in the present discovery of neutrino masses, the first experimental evidence for physics beyond that standard model. The SNO detector will measure both the neutral and charged current interactions of neutrinos from the sun thereby measuring, to some accuracy, their flavor composition (electron verses muon, tau or sterile). Both the production of $pp$ neutrinos, and the subsequent flavor discrimination involve inelastic deuteron processes. Thus it is of the utmost importance to understand the electroweak interactions of the deuteron.

![Inelastic $\nu(\bar{\nu})d$ cross-sections versus incident $\nu(\bar{\nu})$ energy.](image)

FIG. 3. Inelastic $\nu(\bar{\nu})d$ cross-sections versus incident $\nu(\bar{\nu})$ energy. The solid curves in the left graph are results of [14] while the dot-dashed curves, which lie on top of the solid curves, are NLO in EFT with $L_{1,A} = 6.3$ fm$^3$. The solid curves in the right graph are the results of [13] while the dashed curves, which also lie on top of the solid curves, are NLO in EFT with $L_{1,A} = 1.0$ fm$^3$.

Existing potential model calculations [13,14] of the $\nu - d$ breakup processes disagree at the 5% level due to different assertions about meson exchange currents. Effective field theory calculations by Butler and Chen [11,12] of $\nu - d$ breakup processes have clarified this ambiguity. A local, gauge invariant operator contributes to the matrix element of the axial current at next-to-leading order, with coefficient $L_{1,A}$. Different potential model results correspond to different choices of this counterterm, as can be seen in Figure 3. This counterterm can be fixed in two possible ways. Firstly, an experimental measurement of $\nu_e d \rightarrow pe^-$ at low-energies at the 1%-level, would determine the counterterm, enabling 1% predictions of the processes utilized by the SNO experiment (a higher precision prediction would require knowledge of additional counterterms). Secondly, a theoretical calculation of the rate of tritium $\beta$-decay would also fix the counterterm. This is being considered by Paulo Bedaque, a Research Assistant Professor at the INT. In fact, sophisticated potential
model calculations \cite{10} have implemented the later approach to predict \( pp \rightarrow de^+\nu_e \). Butler and Chen have recently included the Coulomb corrections for \( pp \rightarrow de^+\nu_e \).

\section*{F. Three-Body Processes}

\textit{P. F. Bedaque (INT), F. Gabbiani (Duke) and H. Grießhammer}

During the last twelve months, Bedaque, Gabbiani and Grießhammer completed interesting work (that was underway while Grießhammer was a Postdoctoral Fellow in our group) in three-body systems with effective field theory. Phase shifts for \( n-d \) scattering in the spin quartet channel and in several partial waves have been calculated both above and below the deuteron breakup threshold, solely in terms of two-nucleon scattering parameters \cite{15}. The agreement with data is impressive, and agrees well with the few predictions that have been made using sophisticated nuclear potentials.

\section*{G. \( NN \rightarrow NN\pi \) from the Effective Field Theory Point of View and the Three Nucleon System}

\textit{C. Hanhart, G. A. Miller and U. van Kolck (Caltech)}

For almost a decade high quality data available for the near-threshold pion production in nucleon–nucleon collisions has been available. However, the reaction is still not fully understood. As pion dynamics are controlled by chiral symmetry constraints it was hoped that chiral perturbation theory could resolve the uncertainties. Until recently, however, there was significant disagreement between the chiral perturbation theory calculations and data. Our work \cite{16} highlighted the reason for that: once a proper counting scheme is employed it becomes clear that loops enter at next-to-leading order and thus the tree level calculations carried out thus far were incomplete. In addition we were able to demonstrate that p-wave pion production is better behaved: loops enter only at next-to-next-to leading order. The convergence of the chiral expansion was demonstrated with a spin observable for \( \pi^0 \) production, where a parameter-free prediction is in agreement with the data. At the order to which we worked there were two unknown coefficients in the chiral Lagrangian. The respective interaction terms not only influence observables in pion production but might provide a solution to the long standing problem in few body physics, the so called \( A_y \) puzzle in \( pd \) scattering. Thus our work demonstrated the close connection between pion production and the three nucleon system. This provides a deeper understanding of low and medium energy nuclear physics.
H. Pion Production in Low Energy Two-Nucleon Interactions

C. Hanhart, G. A. Miller, F. Myhrer (South Carolina), T. Sato (Osaka), and U. van Kolck (Caltech)

Chiral perturbation theory (or effective field theory) is a relatively new way to derive nuclear forces and cross sections in terms of parameters that carry information about QCD dynamics. Chiral power-counting arguments are expected to supply an organizing principle.

Understanding threshold pion production reactions in nucleon-nucleon collisions provides an interesting challenge to any such approach because the relevant momentum scale is $p \sim \sqrt{m_N m_\pi}$, so $\frac{p}{m_N}$ is not very small and the usual low momentum expansion is slowly convergent. The acquisition of excellent data \[35\] for the $pp \rightarrow pp\pi^0$ reaction heightened the interest in studying these reactions. Our first paper on this subject found that the seemingly mandated (by chiral symmetry) treatment of the off-shell pion-nucleon scattering amplitude caused the term arising from the pion rescattering to interfere destructively with other amplitudes, leading to a computed cross section was considerably smaller than the measured one \[36\]. To be specific, consider the effect of a term $\pi^2 \bar{N}N$. Evaluation of this term, for threshold kinematics, in the rescattering graph (without including initial or final state interactions between the nucleons) gives a factor of $m_\pi m_\pi/2$, in which the first factor arises from the final energy of the pion and the second from the energy of the intermediate pion which carries half of the initial center of mass energy. But another group, Sato et al. \[37\] treated this same factor as $m_\pi (E(p) - E(p'))$ in which $p, (p')$ is the relative momentum in the initial (final) state, and $E(p) = \sqrt{p^2 + m_N^2}$. This is evaluated by multiplying by the initial and final state $pp$ wave functions and integrating over the momenta. Their result is that the low momentum tail of the initial high energy $pp$ wave function and the high momentum tail of the final threshold wave function turn out to be dominant, so that this difference in energies turns out on average to be much larger than $m_\pi$ in magnitude and negative. Our discussions at the joint INT/ANL August 1998 workshop led us to try to understand better the differences between the calculations. Both methods of calculation employ a three-dimensional integral to the evaluation of a Feynman diagram which is a four-dimensional integral. This led us to originate a semi-realistic toy model in which one may evaluate the four-dimensional integral exactly, and determine which (if any) of the two approximations are accurate. We proposed to evaluate the relevant Feynman graphs. The preliminary results of the toy model calculations are that the procedure of Ref. \[36\] is a good approximation to the exact toy model answer.

I. Effective Field Theory for $\bar{N}N$ Scattering

M. Alberg (Seattle U.), E. M. Henley

An effective field theory for nucleon-anti-nucleon low energy scattering is being developed. The aim is obtain phase shifts which can better fit the scattering data, so as to extend

\footnote{Former PhD student of Wilets and currently a faculty member at Seattle University.}
previous work on various nucleon-anti-nucleon interactions. The case of a large effective range and a small scattering length has been examined.

II. LIGHT-FRONT NUCLEAR PHYSICS

The aim is to develop a relativistic treatment of nucleons in nuclei which can be used in a variety of high-energy, high-momentum transfer processes, and which incorporates fully the present knowledge of nuclear physics. A method that yields covariant results is needed to properly interpret a host of new electron-nuclear scattering experiments performed at Jefferson Laboratory and at HERA in Hamburg. Relevant reactions include deep inelastic lepton-nucleus scattering, the related Drell-Yan ($\mu^+\mu^-$ production) experiments, and nuclear quasi-elastic reactions such as ($e,e'$), ($e,e'p$), and ($p,2p$). Our choice has been to use light-front variables. For example, in the parton model the Bjorken variable $x = k^+/p^+$ where $k^+ = k^0 + k^3$ is the plus-momentum of the struck quark and $p^+$ is the plus-momentum of the target. Quark distributions represent the probability that a quark has a plus-momentum fraction $x$. One of our main interests is in computing the distribution functions $f(k^+)$ which give the probability for nuclear nucleons and mesons to have a given plus-momentum $k^+$.

In the light-front technique the $f(k^+)$ are determined by the ground-state wave function, while in the usual equal-time formulation obtaining the $f(k^+)$ requires computing the response function which involves matrix elements between the ground and all excited states. Thus the use of the light front dynamics engenders vast simplicities, if one is able to compute the ground-state wave function using those light-front dynamics. Our previous work included substantial progress towards computing realistic wave functions, which is described below. The light-front quantization for a chiral Lagrangian is performed by obtaining the appropriate Hamiltonian and energy momentum tensor $[17,18]$. The mean field approximation was defined and applied to infinite, isospin symmetric, nuclear matter $[17]$. The one boson exchange treatment of nucleon-nucleon scattering was studied and a close connection with the on-shell T-matrix of the usual equal time formalism is obtained $[17]$. A new light-front one-boson exchange nucleon-nucleon potential, which achieves a reasonably good representation of the phase shifts has been obtained $[18]$. The tree-level pion-nucleon scattering amplitude was shown to reproduce soft pion theorems $[17]$. Meson distribution functions for finite nuclei have been obtained, using a simple model $[19]$. Calculations of properties of finite nuclei are well underway. One of the problems in using the light-front formalism is the lack of manifest rotational invariance. We have recovered the $2j + 1$ single-nucleon degeneracy characteristic of the shell model of spherical nuclei. This is accomplished by deriving and solving a new light-front equation for the nucleon wave functions $[20]$. Nucleon-nucleon correlations are often treated using Brueckner theory. A light front version of this has been derived and successfully applied to infinite nuclear matter. The simplicity of the vacuum allows us to derive the theory from a set of integral equations which maintains the necessary connection between the mesonic components of the Fock space and the nucleon-nucleon potential $[18]$. Good saturation properties are obtained $[21]$, including a compressibility of 180 MeV. The nuclear medium is found to enhance the average number of pions per nucleon by about 5%.
A. Heavy Nuclei

P. Blunden (Winnipeg), M. Burkardt (New Mexico), G. Krein (IFT),
R. Machleidt (Idaho), G. A. Miller

We have made progress in using light-front dynamics to compute nuclear wave functions. The implementation of rotational invariance should ultimately allow a widespread use of light-front dynamics in any calculation in which relativistic aspects of nuclei are expected to be relevant. A necessary condition for this to occur is that the computed momentum distributions \( f(k^+) \) be at least roughly consistent with the experimental data for deep inelastic lepton-nucleus scattering, as well that of the \((e,e'p)\) reaction. It is interesting to note that achieving even a vague resemblance to the data requires a very high level of nuclear structure theory. To explain this, we review the history of this problem. The mean field calculation for infinite nuclear matter \[18\] found that the nucleons carry only about 65\% of the nuclear plus-momentum, with the remainder carried by the \(\omega\) meson. This fraction should be about 90\% in infinite nuclear matter \[38\].

These results are specific to the use of mean field theory and infinite nuclear matter. Thus it was necessary to make calculations for finite nuclei and to go beyond the mean field approximation. Our finite nucleus result \[20\], obtained using the mean field approximation for \(^{40}\text{Ca}\), is that the nucleons carry only 73\% of the plus momentum, with the \(\omega\) carrying almost all of the remainder. Thus a substantial problem remains.

We have done calculations beyond mean field theory by including correlations between two nucleons. This is a light-front version of Bruckner theory. Our calculations \[18,21\] reproduce the saturation properties, but including correlations allows much weaker scalar and vector potentials. One consequence is that the nucleons carry at least 84\% of the plus momentum, which is much closer to the desired value of 90\%.

B. HERMES Effect

S. J. Brodsky (SLAC), M. Karliner (Tel Aviv), and G. A. Miller

We have emphasized the need to reduce the computed value of the plus-momentum carried by the \(\omega\) mesons. But it is clear that any future versions of the present calculations will predict some significant enhancement of the nuclear \(\omega\) content. The proposal stated that “We shall try to find experimental signals for this presence. This may be difficult, but it seems worthwhile to try.” In June 1999 the HERMES collaboration announced \[25\] that the ratio \(R = \sigma_L/\sigma_T\) was enhanced in nuclear deep inelastic scattering. A small value of \(R\) is a signature that the struck partons have spin 1/2 \[26\], so a very large value indicates the strong presence of nuclear mesons.

This HERMES discovery led us to search for the influence of vector and scalar mesons. We showed \[27\] that nuclear \(\sigma\), and \(\omega\), mesons can contribute coherently to enhance the

\[8\] Former Research Assistant Professor at the UW.

\[9\] Former Postdoctoral Fellow in our group and long-term visitor during the past academic year.
FIG. 4. Ratio of $R = \frac{\sigma_{L}}{\sigma_{T}}$, $R(A)/R(D)$, $A=14$. IG and dipole refer to the form factor used.

electroproduction cross section on nuclei for longitudinal virtual photons at low $Q^2$ while depleting the cross section for transverse photons. We described recent HERMES inelastic lepton-nucleus scattering data at low $Q^2$ and small $x$ using photon-meson and meson-nucleus couplings which are consistent with (but not determined by) existing constraints from meson decay widths, nuclear structure, deep inelastic scattering, and lepton pair production data. We find that while pion currents are not important for the present data, they could be observed at different kinematics. Thus our model is very easy to test and is being tested by an experiment at Jefferson Lab. The results of our calculation for $^{14}N$ are shown in Figure 4.

C. Relativistic Corrections to Nuclear Charge Radii

P. Blunden (Winnipeg), M. Burkardt (New Mexico), and G. A. Miller

R. Michaels and P.A. Souder (of the TJNAF HAPPEX collaboration) have proposed [29] an experiment (see also [30]) intended to measure the neutron density of $^{208}$Pb using parity violating electron scattering. The stated aim is to determine the neutron radius to about 1%. This made it relevant to pursue a new study of how relativistic effects influence the computed charge radii. We showed that these effects are very tiny [28,22].

D. Relativistic Quarks in Relativistic Nucleons

G. Krein (IFT), and G. A. Miller

There has also been progress in going beyond the nucleon-meson version of nuclear physics. There may be some processes such as DIS for which quark models can be used directly. Thus our aim is to provide a light-front calculation in which the nucleons are treated as moving relativistically within the nucleus, and in which the the quarks (and gluons) are
moving relativistically within the nucleon. An extension of the quark-meson coupling model \cite{23} may provide the easiest path to obtaining a realistic formalism that is also tractable. In this model, 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. First calculations using a quark-di-quark model of the nucleon which is immersed in the medium give promising results. Nuclear saturation is achieved with relatively weak mesonic fields.

\textbf{E. Light Nuclei}

\textit{J. Cooke$^{10}$, G. A. Miller, and D. R. Phillips}

This is the thesis project of Jason Cooke, which is aimed at doing relativistic deuteron physics. We started by examining the bound states of the Wick-Cutkosky model in which two-heavy scalar particles ("nucleons") interact by exchanging another scalar particle. This is a good testing ground for such calculations, because essentially exact solutions exist \cite{39}. As a starting point we studied bound states \cite{31} using the Hamiltonian formalism on the light-front. In this approach manifest rotational invariance is broken when the Fock space is truncated. By considering an effective Hamiltonian that takes into account two meson exchanges, we find that this breaking of rotational invariance is decreased from that which occurs when only one meson exchange is included. The best improvement occurs when the states are weakly bound.

We also made a more detailed study \cite{32} of the Wick-Cutkosky model in which light-front potentials for two-nucleon bound states are calculated using two approaches. First, light-front time-ordered perturbation theory is used to calculate one- and two-meson-exchange potentials. These potentials give results that agree well with the ladder and ladder plus crossed box Bethe-Salpeter spectra. Secondly, approximations that incorporate non-perturbative physics are used to calculate alternative one-meson-exchange potentials. These non-perturbative potentials give better agreement with the spectra of the full non-perturbative ground-state calculation than the perturbative potentials. For lightly-bound states, all of the approaches appear to agree with each other.

The above results indicate that the detailed Fock-space wave function of the deuteron could be obtained using light-front techniques. The deuteron is the nucleus that has been the subject of almost all light front calculations of nuclei, and will be studied intensively at Jefferson Lab. The previously mentioned papers can be considered as a warm-up for a realistic calculation, which includes meson degrees of freedom of the deuteron.

$^{10}$PhD student of Miller.
F. Nucleon Structure Functions

M. Alberg (Seattle U.), E. M. Henley, and G. A. Miller

The nuclear calculations, mentioned above, which predict a significant $\omega$ content of the nucleus lead us to consider the effects of the $\omega$ content of the nucleon. Recent Drell-Yan studies \[10\] of the proton and deuteron have allowed the extraction of the $\bar{d}(x)/\bar{u}(x)$, and $\bar{d}(x) - \bar{u}(x)$, which is equivalent to the isovector and isoscalar anti-quark distributions of the nucleon. Calculations using the effects of a pion cloud seem to successfully reproduce the isovector $\bar{q}$ distributions \[10\], but provide isoscalar distributions that are smaller than the observed ones. The proposal said “we expect that including the effects of the $\omega$ should supply the missing strength, and propose to make the necessary calculations. This subject is related to a project of Henley & Alberg and we plan to join forces.” The result \[11\] was that we were able to use the meson cloud model of the nucleon to calculate distribution functions for $(\bar{d} - \bar{u})$ and $\bar{d}/\bar{u}$ in the proton. Including the effect of the omega meson cloud, with a coupling constant $g_\omega^2/4\pi \approx 8$, allows a reasonably good description of the data. We are also trying to understand how the ratio $\bar{d}(x)/\bar{u}(x)$ can fall below unity at large values of $x$. The only effects that can give such a result involve the breaking of charge symmetry.

G. Quantization of Spin $\frac{3}{2}$ Particles on the Light Front

C. Hanhart and G. A. Miller

Up to now there is no consistent procedure available to quantize higher-spin baryons on the light-front. However, quantization is a necessary step if light-front dynamics is to be used for nuclear applications. So far we are able to quantize the free spin-$\frac{3}{2}$ field on the light-front.

III. COLOR TRANSPARENCY AND HIGH MOMENTUM TRANSFER REACTIONS

M. Frankfurt (Tel Aviv), G. A. Miller, M. Sargsian\[12\] (FIU), and M. Strikman (Penn. State)

Color transparency \[33\] is the unusual 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 are the $(e,e'p)$ $(p,pp)$ and $(e,e'\Delta)$ reactions involving nuclear targets. Several experiments searching for color transparency are underway. Much of the theory of the three fundamental aspects of color transparency has been done as well as possible, any future progress in the theory rests on the ability to interpret the findings of future experiments.

\[11\]Former Postdoctoral Fellow in our group and currently an Assistant Professor at Florida International University.
Our main recent progress is in understanding coherent pion diffraction into minijets. Consider the process of coherent disintegration of a high energy (500 GeV) pion beam into two jets on a nuclear target. We found \cite{24} in 1993 that if each of the jets has a very large transverse momentum \( \kappa_t > 4 \text{ GeV/c} \), but the sum of their momentum is very close to that of the beam, the forward cross section is predicted to vary with nucleon number \( A \) approximately as \( A^2 \), a very striking prediction of color transparency. If one integrates the angular distribution to obtain the cross section for this coherent process, the power of 2 is changed to 4/3. We encouraged experimentalists to search for this process, and the challenge was taken up by the Tel Aviv group as part of Fermilab E791. They compared data taken on \(^{195}\text{Pt}\) and \(^{12}\text{C}\) targets and found \cite{42} a power of 1.55 ± 0.05 in rough but striking agreement (in the sense that the ratio of the cross sections for Pt and C targets was about 70 times bigger than the prediction of the usual diffractive treatment) with our prediction.

We proposed to use perturbative quantum chromodynamics to input the perturbative part of the pion wave function into the calculation, to include the final state \( q\bar{q} \) interaction and, to specify the quantum numbers of the different final two-jet states. We intend also to use an updated version of the soft \( q\bar{q}\)-nuclear final state interaction and to include the effects of the skewed gluonic distribution of the nucleon and the effects of electromagnetic disintegration of the pion. Much of the work has been done and some appears in a paper accepted for publication \cite{43}. We are preparing a more detailed calculation.

A. The High Energy \( \gamma d \rightarrow np \) Reaction

We have studied \( \gamma d \rightarrow np \), which has been the subject of a recent TJNAF experiment \cite{44}. A new mechanism is introduced in which photon absorption by a quark in one nucleon followed by a high momentum transfer interaction with a quark in the other may produce two nucleons with high relative momentum. In this mechanism the amplitude depends on the well-known, low-momentum, two-nucleon component of the deuteron wave function. Other diagrams are smaller by orders of magnitude. We intend to determine how much of the observed cross section can be accounted for in this way. We study the absolute value, energy, and angular dependence of the recently measured cross sections. According to the literature, two competing mechanisms account for the high momentum transfer nucleon-nucleon scattering amplitude. These are the Feynman mechanism and the use of the minimal Fock space components. We studied the role of each of these mechanisms in determining the \( np \) final state interaction that occurs in the photoabsorption process. It is possible that the careful analysis of this data could lead to the resolution of a long-standing question about which mechanism is most important. Our first calculation is now published \cite{45}.
IV. ASTROPHYSICS

A. Neutrino and Axion Radiation from Neutron-Star Cooling and Supernovae

C. Hanhart, D. R. Phillips, and S. Reddy (INT)

Neutrino-nucleon processes are important sources of cooling and heating in several astrophysical phenomena. Neutrino cooling in neutron stars, for example, is driven by reactions of the type $nn \rightarrow nn\bar{\nu}$ and $nn \rightarrow npe^{-}\bar{\nu}_{e}$. To date, the strong interaction correlations between the two nucleons have been calculated only perturbatively, i.e. using the one-pion-exchange potential as the $NN$ amplitude [46].

Based on soft-radiation theorems we performed a model-independent calculation of the emission rates for $NN \rightarrow NN\bar{\nu}$ and $NN \rightarrow NNa$, finding that the one-pion-exchange approximation overestimated these rates by a factor of 4-5. This result will have a serious impact on the role played by neutrinos in the cooling of neutron stars. It may also affect the understanding of the role of neutrinos in supernova explosions. At this stage it is unclear how this result will change the axion mass bound, since a different neutrino rate will influence those as well. However, it is clear that previous estimates of the axion production rate in SN1987A were based on a two-body axion emission amplitude that was much too large.

B. SN1987A Bounds on Large Compact Extra Dimensions

C. Hanhart, D. R. Phillips, S. Reddy (INT), and M. J. Savage

A scenario that is emerging from string theory and effective field theory descriptions of gravity is that matter fields exist on a four-dimensional brane embedded in a higher dimensional space which gravity alone can propagate. One of the strongest constraints on the existence of large, compact, “gravity-only”, extra dimensions comes from SN1987A. If the rate of energy loss into these putative extra dimensions is too large, then the neutrino pulse from the supernova will differ from that actually seen. The dominant mechanism for graviton and dilaton production in the supernova is via gravistrahlung and dilastrohlung from the nucleon-nucleon system. Low-energy theorems of the type discussed in the previous paragraph can also be used to calculate these processes in a model-independent fashion. This relates these emissivities to the measured nucleon-nucleon cross section. This is possible because for soft gravitons and dilatons the leading contribution to the energy-loss rate is from graphs in which the gravitational radiation is produced from external nucleon legs. We have re-evaluated the bounds on extra dimensions using our low-energy theorem, and find that if there are two extra “gravity-only” dimensions then to be consistent with the SN1987A observations these dimensions must be of a radius less than 1 micron.
C. Shielding of Nuclei in a Finite Temperature Plasma

B. Giraud (Saclay), J. J. Rehr, M. J. Watrous, and L. Wilets.

A novel technique for evaluating the electron shielding of nuclei in a finite temperature plasma has been developed and applied. The physics is Hartree plus local-density approximation to account for exchange and correlation (Kohn-Sham-Mermin). This is particularly applicable to the fusion process in stellar and laboratory plasmas. Finite-temperature, finite-density electron Green’s functions are calculated. Contour integration yields a sum of residues over the complex Matsubara poles. This automatically includes discrete bound states and continuum states weighted by the finite temperature Fermi factor. The one-center problem is adequate for the calculation of fusion rates. A paper describing the method and presenting numerical comparisons with the works of others has been published [47].

A second paper including shielding due to ions and applying the method to the solar fusion problem has been published [48]. We believe the results obtained are the most reliable reported to date.

V. QCD AT HIGH DENSITY

S. R. Beane, P. F. Bedaque (INT), and M. J. Savage

The realization that high-baryon density systems can be color superconductors [49] has lead to significant progress during the past year or so. In such dense systems perturbative calculations of their properties in $\alpha_2(\mu)$ are possible. The very low-energy excitations of the dense system can be described with an effective field theory of the pseudo-Goldstone bosons associated with the spontaneous breaking of the global symmetries of the underlying theory. Previous works had attempted to determine the decay constants and masses of the pseudo-Goldstone modes, but contained errors. We determined the decay constants and masses of the excitations [50], making extensive use of effective field theory techniques.

The original analytical determinations of the superconducting gap in QCD suffer from two flaws. First, the gap equation is divergent and so must be regularized and renormalized. Most treatments have taken the baryon density as a sharp cutoff. This might cause some concern since it leads to the possibility of contaminating the low energy physics of the gap with ad hoc high energy physics. Second, the solution of the gap equation at momenta large compared to the gap has been obtained by assuming a particularly unhealthy mathematical approximation. In a recent paper, we use cutoff regularization to define a renormalized gap equation. We also find an exact asymptotic solution to this equation, thus excising the flaws contained in previous determinations. Our results confirm the original analysis by Son. The renormalized gap equation enabled us to resum the large logarithmic contributions due to the evolution of the strong coupling constant between $\mu$ and the gluon magnetic mass scale [51]. Recently, Beane and Bedaque have derived an expression for the gap with dimensional regularization [52].

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12 Former PhD student of Wilets.
VI. FUNDAMENTAL SYMMETRIES

Fundamental symmetries has long been a topic of high interest at the U.W. Recent efforts involve the use of nuclear physics to elucidate the standard model.

A. Charge Symmetry Breaking

G. A. Miller, J.A. Niskanen (Helsinki), U. van Kolck (Caltech)

Charge symmetry, CS, is a fundamental symmetry which occurs if the Lagrangian is invariant with respect to rotating the u into d quarks (or d → u) quarks \[34\]. We were able to use chiral effective field theory to make predictions, based on QCD, for the reaction np → dπ0. If charge symmetry holds, the cross section is symmetric about 90° in the cm frame. The form of the charge symmetry breaking part of the hadronic Lagrangian is determined by the symmetries of QCD \[53\]. This Weinberg term predicts a large breaking of CS in the πN scattering amplitude which is needed to compute the cross section for np → dπ0. The numerical result was that this Weinberg term provides the dominant contribution to the forward-backward asymmetry in the angular distribution for the reaction pn → dπ0, for reasonable values of the mass difference between down and up quarks, δmN. Using a value δmN ≈ 3 MeV leads to a prediction of a 10 standard deviation effect for a TRIUMF experiment.

B. Parity Violating Proton-Proton Scattering at High Energy

G. A. Miller

Lockyer et al. \[55\] found a very large parity violating asymmetry AL of about AL = 2.5 × 10⁻⁶ at a proton beam energy of 6 GeV/c. The only calculation which reproduces this result, without violating the constraints of low-energy data, is a quark-model calculation of Preston and Goldman \[56\], in which parity violation occurs as a result of a quark-quark interaction in an excited state of the proton which is formed as a result of an initial state strong interaction. This calculation also predicts a rapid rise in AL as the beam momentum increases. Interest in this topic was revitalized by the possibility of new experiments involving polarized protons at RHIC and the AGS at Brookhaven National Lab. T. Roser (BNL), speaking at the June 1998 INT workshop on parity violation, argued that it could be possible to ultimately make measurements, with an error of about 3 × 10⁻⁷, at beam momenta between 5 and 250 GeV/c. Working on understanding all of the reaction mechanisms is in progress and we have found that the physical ideas of Ref. \[56\] are very good, but that the calculation is flawed in certain ways. Plans to make a better calculation using a similar (but different) reaction mechanism are underway.
C. Time Reversal and CP Violation

E. M. Henley

Plans are underway to study time reversal and CP-violation for both heavy quarks (the B system) and in nuclear physics.

D. Deuteron Anapole Form Factor

M. J. Savage and R. P. Springer (Duke)

Stimulated by the SAMPLE experiment at Bates, Springer and Savage computed the anapole form factor of the deuteron at leading order with effective field theory [57]. Previously, they had computed the deuteron anapole moment, and were able to extend this to the full form factor using the analytic expressions for multi-loop integrals developed by Michael Binger[]. Due to the large size of the deuteron, it is possible, although very difficult, to distinguish between contributions from the nucleon strange form factor and from the deuteron anapole moment due to the different lengths scales involved in determining the scale of each form factor.

E. Parity Violation in $\gamma N$ Compton Scattering

P. F. Bedaque (INT) and M. J. Savage

It is now universally accepted that determining the single pion nucleon parity violating coupling $h^{1}_{\pi NN}$ is very difficult. Systems in which its effects are amplified do not allow for rigorous computation of observables, and systems where rigorous calculations are possible have only small parity violating effects. Experimental programs with ever-increasing sensitivity to parity violating effects are ongoing in an effort to unambiguously determine $h^{1}_{\pi NN}$.

In a somewhat speculative calculation, Bedaque and Savage [58] examined parity violation in $\gamma N \rightarrow \gamma N$ Compton scattering. The amplitude for this process is theoretically clean and is determined by the long sought after parity violating $\pi NN$ coupling $h^{1}_{\pi NN}$. Corrections to these contributions are small. While measurement of such observables will be difficult, it would provide a theoretically well-defined determination of $h^{1}_{\pi NN}$.

F. Book on Symmetries

I. Halpern and E. M. Henley

The authors are preparing a book entitled “Symmetries in Nature and Science” that is aimed at explaining the importance of symmetries to a popular audience.

13An undergraduate student with the summer 1998 REU program at the UW
FIG. 5. The free energy of a hot gluon gas normalized to that of an ideal gas of gluons. The black diamonds are lattice data for pure-glue QCD [61]. The bands enclosed by the curves labeled 2, 3, 4, and 5 are the perturbative approximations to $F_{QCD}$. The bands correspond to varying $\mu_4$ by a factor of 2. The shaded region is the HTL-improved free energy. The region corresponds to varying the renormalization scale by a factor of 2.

VII. FINITE-TEMPERATURE QCD

J.O. Andersen (OSU), E. Braaten (OSU), and M. Strickland

The current theoretical understanding of the quark-gluon plasma (QGP) phase of nuclear matter is rather limited. In particular, the supposition that the QGP phase can be described as a weakly-interacting gas of quarks and gluons has lead to a number of theoretical predictions that rely on only the lowest order of perturbation theory. In the last five years there have been some significant advances in finite-temperature perturbative calculations. Of particular interest is the perturbative expansion of the free energy of the QGP phase. This quantity has been calculated to order $g^5$ [59,60] and show that in the region of experimental interest ($T < 1$ GeV) the series shows no signs of converging. In Figure 5 the successive approximations to the free energy of a gluon plasma along with the latest lattice result are shown. This clearly illustrates that the theoretical uncertainties due to the poor convergence of the perturbative series, even at order $g^5$, are quite large and that a different approach is needed.

The origin of the large perturbative corrections seems to be plasma effects, such as the screening of interactions and the generation of quasiparticles. These effects arise from the momentum scale $gT$. Effective-field-theory methods can be used to isolate the effects of the scale $gT$ from those of the scale $T$ [60], so that the effects of the scale $gT$ can be calculated using nonperturbative methods. There has been some recent progress in solving the analogous problem for a massless scalar field theory with a $\phi^4$ interaction [62,63]. When the free energy is calculated using screened perturbation theory, the convergence of successive approximations to the free energy is dramatically improved.
A. Scalar Field Theory - Screened Perturbation Theory

At nonzero temperature, the conventional perturbative expansion of $g\phi^4$ theory generates infrared divergences. They can be removed by resumming the higher order diagrams that generate a thermal mass of order $gT$ for the scalar particle. This resummation changes the perturbative series from an expansion in powers of $g^2$ to an expansion in powers of $g$. Screened perturbation theory (SPT) is simply a reorganization of the perturbation series for thermal field theory. At nonzero temperature, SPT does not generate any infrared divergences, because the mass parameter in the free lagrangian provides an infrared cutoff.

Anderson, Braaten and Strickland have recently made a systematic three-loop calculation of the free energy, entropy, and screening mass within SPT. The previous calculation was only performed to two loops because one of the three-loop diagrams (the so-called “basketball diagram”) had not been evaluated analytically. They have been able to calculate this diagram, reducing it to expressions involving three-dimensional integrals that can be easily evaluated numerically, enabling them to calculate the thermodynamic functions for scalar field theories to three-loop order. The results of this calculation show that the convergence of the free-energy, entropy, and screening mass are dramatically improved.

B. Quantum Chromodynamics - Hard Thermal Loop Perturbation Theory

In order to apply the techniques used in scalar theories to QCD a fundamental change to the formalism must be made. Instead of using a momentum-independent thermal mass one must use the momentum-dependent thermal gluon and quark masses which arise from resummation of hard-thermal-loop (HTL) diagrams.

Hard-thermal-loop perturbation theory (HTLpt) is a reorganization of the perturbation series for thermal QCD. In the last year Andersen, Braaten, and M. Strickland have completed the full one-loop HTLpt of the QCD thermodynamic functions. The shaded band in Figure 5 is the result of the pure-glue calculation. The discrepancy between our result and the lattice result is due the neglect of quasiparticle interactions which come in at two-loop order. These calculations demonstrate that HTLpt provides a tractable and gauge-invariant method for incorporating the necessary physics. The two-loop calculation of the QCD free energy within HTLpt is in progress. When the two-loop calculation of the thermodynamic functions is completed the same formalism can be used to calculate real-time processes such as heavy quark and dilepton production from a QGP.
A. Bulgac, P. Magierski (Warsaw), and Y. Yu

In Ref. [69] it was shown that bubble fermion systems have a remarkable soft collective branch, corresponding to the displacement of the bubble. That study pointed to a large number of new physical effects to be found in systems with bubbles. Bubble nuclei—even if they exist—most likely would be almost impossible to create in laboratory. However, similar effects could easily be observed in other fermion systems, see Ref. [70]. However, one of the most interesting systems to consider are neutron stars. It was predicted a long time ago that at about 0.5 km under the surface of a neutron star nuclear matter is inhomogeneous and a sequence of bubble, rod and plate phases should occur [71]. Almost all previous studies of these phases of neutron matter have been performed within the liquid-drop-model approximation. One exception was the work of Refs. [72,73], which however has a limited and incomplete treatment of the shell-correction energy to ground-state energy of the phase corresponding to nuclei embedded in a neutron gas. As we discuss in Ref. [74] these last authors computed the least important contribution to the ground state of inhomogeneous neutron matter.

Until now nobody noticed a rather subtle contribution to the ground state energy of inhomogeneous neutron matter, for which there is naturally no established term yet in the literature. One can term this contribution either as the Casimir energy, as it is somewhat similar to the Casimir energy in quantum field theory [75], or equally well use the more common term in nuclear physics, shell correction energy. Shell correction energy is typically attributed to the difference in single particle spectra in finite systems from a spectrum with a smooth level density. In infinite matter however the spectrum is obviously continuous and one might naively conclude that there is no shell correction contribution.

In order to better appreciate the nature of the problem we are addressing in this work, let us consider the following simple situation. Let us imagine that two spherical identical bubbles have been formed in an otherwise homogeneous neutron matter. We shall ignore the role of long range forces, namely the Coulomb interaction in the case of neutron stars, as their main contribution is to the smooth, liquid drop or Thomas–Fermi part of the total energy.

Under such circumstances one can ask the following apparently innocuous question: “What determines the most energetically favorable arrangement of the two bubbles?” According to a liquid drop model approach (completely neglecting for the moment the possible stabilizing role of the Coulomb forces) the energy of the system should be insensitive to the relative positioning of the two bubbles. A similar question was raised in condensed matter studies, concerning the interaction between two impurities in an electron gas. In the case of two “weak” and point–like impurities the dependence of the energy of the system as a function of the relative distance, \( a \), between the two impurities is given by the Ruderman–Kittel

\[ 14^{\text{PhD student of Bulgac.}} \]
interaction:

\[ E(a) \propto \frac{\hbar^2}{2mk_F a^3} \cos(2k_F a), \]  

(2)

where \( k_F \) is the Fermi wave vector and \( m \) is the fermion mass. In Ref. [74] we developed a method on how to compute the quantum corrections to the ground state energy of inhomogeneous neutron matter, based on quantum chaos techniques. Using the Gutzwiller trace formula and taking into account only the shortest classical period orbits, we have shown in particular that the interaction energy between two isolated bubbles at large separations \( (a = L - 2R \gg R) \)

\[ E_{\infty} \approx \frac{\hbar^2 k_F^2}{2m} \left( \frac{R}{a} \right)^2 \frac{2 \sin(2k_F a)}{\pi^2}. \]  

(3)

This result is unexpected in several respects, not the least its very long-range interaction, c.f. the Ruderman-Kittel result above. We quote explicitly only this result, as it displays the new qualitative nature of our results. In Ref. [74] we have analyzed a variety of inhomogeneous neutron phases: bubble phase, rod phase, plate phase, local defects, various lattice deformations and temperature effects. To our knowledge this is the first approach which considers specifically the shell effects in the outside neutron gas and we aimed at discussing its basic features. Even though in principle Hartree–Fock calculations include in principle such effects already, the calculations performed so far [73] were too narrow in scope and did not address this issue specifically and they were not able to put in evidence a large number of new qualitative and quantitative issues. We have analyzed the structure of the shell energy as a function of the density, filling factor, lattice distortions and temperature. The main lesson we learned from this work is that the amplitude of the shell energy effects is comparable with the energy differences between various phases determined in simpler liquid drop type models. This fact alone suggests that the inhomogeneous phase has most likely an extremely complicated structure, maybe even completely disordered, with several types of shapes present at the same time. It is clear that we have only managed to “barely scratch the surface” of this problem.

Even though we have specifically addressed the case of neutron matter only, it is clear that a similar picture should emerge when the density increased and quarks become deconfined. In the low density quark matter one would expect quark droplets of various shapes embedded in a neutron gas [71]. It is highly likely that similar phenomena are expected in the case of quark–gluon plasma and in the case of strangelets, see Refs. [76]. The calculation reported so far in the literature are very similar in spirit with the calculations performed in Ref. [72] for neutron matter, i.e. shell energy due to “bound fermion motion” only. As we have shown however, most of the quantum corrections to the ground state energy arises from the unbounded fermion motion, which in a way can also be interpreted as the bubble–bubble interaction energy, often mentioned in various papers but never evaluated, since no methods have ever been developed in this direction. We also expect that progress can be made in computing the Casimir energy as well for new geometries, both in QFT and in critical phenomena. We plan to address these range of questions in the near future. Andreas Wirzba from Darmstadt TU has also expressed his enthusiasm and willingness to join our efforts.
B. Dissipative Collective Motion

A. Bulgac, G. Do Dang (Orsay), and D. Kusnezov (Yale)

We have continued to study the problem of quantum dissipative motion. Two review papers will shortly be published [77]. In addition, a collaboration with Hans A. Weidenmüller has started. We are trying to implement new theoretical techniques in the derivation of the quantum kinetic equations based on the supersymmetric techniques, which are widely used in mesoscopic physics [78] and a new development, based on a generalization of the Keldysh–Schwinger formalism [79]. This new development is needed in order to extend the applicability of our kinetic equations to lower temperatures as well as in order to establish the limits of certain approximations used by us in our initial approach, in particular the role played by the so-called crossed (non–rainbow) diagrams in treating the intrinsic nuclear degrees of freedom. In a separate development with Do Dang and Kusnezov we have been able to extend significantly the calculation of the so-called influence functional, to the non–Markovian regime. The influence functional is the key element in this entire approach and is the object which describes the internal nuclear motion.

C. Nuclear Energy Density Functional

A. Bulgac and V. Shaginyan (St. Petersburg)

In the Fall of 1999 we finished writing an extensive computer program which describes spherical nuclei, using the new density functional due to Fayans [80] and which also calculates the linear response to various external fields. A number of theoretical developments were incorporated, which deal primarily with the renormalization of the zero-range character of the residual interaction. Such modifications are required in order to evaluate correctly the Coulomb energy contributions to the nuclear ground state energies, when we have to evaluate loop integrals over the entire spectrum [81,82]. We plan to perform the actual calculations during the Fall 2000 INT program on Nuclear Structure.

D. New Gaussian Single–Particle Wave Function Basis

A. Bulgac and Y. Yu

We recently finished an initial study of a new gaussian single–particle wave function basis to be used for the description of the single–particle properties of many fermion systems, irrespective of the presence or absence of symmetries [83]. This new basis consists of overlapping gaussians with a judicious choice of the distribution of their centers, widths and number. We did not include the spin degrees of freedom in this initial study, due to some technical difficulties we have encountered in dealing with them in an efficient manner. In the absence of the spin–orbit interaction we can describe spectra with an accuracy of about 0.02 MeV in the bulk and 0.15 MeV near the nucleon threshold. The wave functions are reproduced with an accuracy of not worse than a couple of percent, typically better. The size of the basis set is around 1000 basis functions for heavy nuclei. These results are significantly better than those obtained with other basis sets used in nuclear literature, e.g.
harmonic oscillator wave functions. We hope that with more fine tuning we can improve both on the quality and the number of the basis set and thus be able to propose this new basis as perhaps the basis set of choice for mean field calculations of deformed nuclei.

IX. HADRONIC INTERACTIONS AND STRUCTURE

A. Strangeness Content of the Nucleon

M. Alberg (Seattle U.), W. Hazelton, E. M. Henley, and L. Wilets.

Configurations containing all $q^3$ and $q^4\bar{q}$ states, including $s\bar{s}$ quark pairs, up to a cut off of 1.5 GeV, and at most one gluon (OGE) have been included as basis states in calculations of nucleons and hadrons. 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. In adjusting MIT parameters to fit energies, a reasonable positive value for the Casimir term emerges, rather than the problematic negative value employed in the original MIT model. The results for various observables are compared with experiment and with meson-based models. Strange quarks give a minor contribution. Previous perturbation calculations by two other groups were found to contain errors.

There is a delicate matter in the method: The Hilbert space for diagonalization contains $q^3$ and $q^4\bar{q}$ but no explicit gluon states. Gluons are contained in effective 4-quark vertices. The evaluation of the effective vertex involves the self-consistent energy of the state being evaluated. The matrix diagonalization must be iterated to self-consistency. Initial calculations used the unperturbed initial 3-quark energies. Although the difference is expected to be small, work will continue. The strange quark content of the nucleon was found to be quite small.

B. Influence of Kaon-loops on $\phi$ Photoproduction

C. Hanhart, E. M. Henley, G.A. Miller, and K. Nakayama (U. of Georgia)

Questions about the strangeness content of the nucleon are widely discussed in the literature. For some time $\phi$ photoproduction has been thought to be a useful tool to study this. However, up to now there is no calculation available that studies the impact of $K$ and $K^*$ loops on this production. We developed a formalism that will allow us to study this effect in a largely model independent way. The results will be important in two respects: first of all they will give insight into what one can really learn from $\phi$ photoproduction and should further constrain models for the strangeness form factor of the nucleon.

\footnote{Former PhD student of Wilets and currently a Staff Scientist at the Fred Hutchinson Cancer Research Center.}
C. Production of Heavy Mesons in Nucleon-Nucleon Collisions

C. Hanhart, J. Speth (Julich), K. Nakayama (U. of Georgia), and J. Haidenbauer (Julich)

The project aims at an understanding of the physics from polarization experiments of \(\omega, \phi, \eta\) and \(\eta'\) production in nucleon nucleon collisions. Presently we investigate approximation schemes to treat the nucleon-nucleon interaction in the initial state, for there is, as yet, no model of NN scattering at these high energies. Since protons probes provide complementary information to electro-magnetic probes, we hope meson production in nucleon nucleon collisions, when studied consistently with electro production of heavy mesons, allows for deeper insight into the phenomenology of missing resonances.

D. A Meson-Exchange Model for Pion Production in Nucleon-Nucleon Collisions

C. Hanhart, J. Speth (Julich), C. Elster (Ohio), and J. Haidenbauer (Julich)

We have developed a meson-exchange model for pion production in nucleon-nucleon collisions [84] that has proven very successful in the description of charged pion production in both unpolarized and polarized observables. However, in case of the \(\pi^0\) production we still see discrepancies that are not fully understood. So far the final state was treated as an effective two body problem by means of a distorted wave approximation. We are presently working on an improvement of the three body treatment of the problem in order to resolve the discrepancy between theory and experiment.

E. \(pp \rightarrow p\Lambda K^+\) and \(pp \rightarrow p\Sigma^0 K^+\) Near Threshold

A. Gasparian (Moscow), J. Haidenbauer (Julich), C. Hanhart, L. Kondratyuk (Moscow), and J. Speth (Julich)

Very little is known about the hyperon–nucleon interaction at low energies. One possible way to gain experimental information on this system is through production reactions. At low energies there are two interesting quantities accessible: the energy dependence allows a determination of low energy hyperon–nucleon scattering parameters and the total strength of the cross section, that contains information on both the hyperon nucleon interaction as well as the production operator. Our work shows that the energy dependence of the total cross sections is in agreement with predictions from the existing hyperon-nucleon potentials. In order to explain the total strength of the cross section a destructive interference between pion and kaon exchange is required. The relative sign between these exchanges is the only free parameter of the model. This allowed Hanhart and collaborators to propose the measurement of the reaction \(pp \rightarrow n\Sigma^+ K^+\) to check the model. Their investigation was the first microscopic investigation of the associated strangeness production at close to the threshold energies. Further studies aim at a better treatment of the meson-baryon interactions.
F. The Structure of the Roper Resonance

O. Krehl (Julich), C. Hanhart, S. Krewald (Julich) and J. Spe th (Julich)

The spectrum of baryon excitations is still not fully understood. There are different mechanisms discussed in the literature to understand why the Roper resonance, the lightest positive parity excitation, has a lower mass than the lightest negative parity excitation. If the binding were dominated by the confining potential the inverse order is expected.

Hanhart and collaborators [86] took a different point of view to quark models: since most of the experimental information on the Roper comes from pion induced reactions their goal was to describe elastic and inelastic pion nucleon scattering. By employing a coupled-channel meson-exchange model they were able to describe the $\pi N$ scattering phase shifts as well as inelasticities up to center of mass energies of 1.9 GeV. A good description of the Roper partial wave $P_{11}$ was possible without the inclusion of a bare pole diagram. This investigation demonstrates that there is not necessarily a problem with the baryon spectrum since the Roper resonance might be generated dynamically. In any case: we demonstrated that the meson baryon interaction in the $P_{11}$ partial wave is too strong to be neglected when trying to understand the baryon spectrum.

G. Pion-Baryon Couplings and SU(3)

A. Buchmann (Tubingen) and E. M. Henley

Work has been completed [87] on extending a method devised by Morpugo to obtain static properties of nucleons. This method has been used to calculate and predict meson-baryon couplings to the octet and decuplet baryons. This work has been submitted for publication. A talk on the subject at the 3d Annual Symposium on Symmetries in Subatomic Physics will also be published.

This method has also been used to predict quadrupole moments and quadrupole transition moments for the decuplet baryons and between the octet and decuplet. This work is almost ready to submit for publication.

H. Electron-Deuteron Scattering in a Relativistic Current-Conserving Framework

D. R. Phillips and S. J. Wallace (Maryland)

The inclusion of relativity in theoretical models becomes particularly critical in the description of electron-deuteron scattering experiments. In electron-deuteron scattering the standard non-relativistic quantum mechanical treatment of the problem is expected to fail at energies where interesting physics occurs. The various available relativistic formalisms all produce different predictions for the observables, none of which accurately describes all of the experimental data. Phillips and Wallace have developed an alternative three-dimensional relativistic scheme for calculating these processes [94]. Impulse approximation calculations of the experimentally-measured quantities $A$, $B$, and $T_{20}$ show good agreement for $T_{20}$ out to $Q^2 \sim 1\text{GeV}^2$. This calculation is missing strength in $A$ and $B$ [95], while approaches which
are essentially non-relativistic reproduce the data quite well. From this one might con-
clude that the non-relativistic approach is the correct one. Yet it is clear that relativity
should begin to play a crucial role in the description of data at these $Q^2$'s.

In December Phillips visited the Thomas Jefferson National Accelerator Facility and
spent three weeks working there with Wallace on these issues. The time was productive,
and they have made much progress in improving the framework they have been working
on together for the past four years. In particular, the connection of this work to the usual
non-relativistic approaches to electron-deuteron scattering is now much clearer. Further
calculations will be pursued in the coming year.

X. LARGE-\textit{N} QCD AND NUCLEI

\textit{S. R. Beane}

The large-$N$ approximation —where $N$ is the number of colors— is one of the few
systematic approaches to QCD at low-energies. The large-$N$ approximation yields a
great deal of predictive power, particularly in the baryon sector. Less is known in the meson
sector. For instance, according to canonical large-$N$ wisdom, meson-meson scattering is
governed by exchange of an infinite number of mesons in tree graph approximation. However,
little progress has been made in utilizing this property to make predictions.

A. High Energy Theorems at Large-$N$

In recent work it was shown that spectral function sum rules take a particularly
simple algebraic form in the large-$N$ limit. This allows one to correlate the ordering
pattern of narrow meson states at low energies with the size of local order parameters
of chiral symmetry breaking in QCD. The spectral function sum rules are constraints on
time ordered products of two QCD currents and traditionally their derivation relies on the
technology of the operator product expansion.

Recently Beane showed that in the large-$N$ limit one can derive sum rules for products of
two, three and four QCD currents using chiral symmetry at infinite momentum in the large-
$N$ limit. These exact relations among meson decay constants, axialvector couplings and
masses determine the asymptotic behavior of an infinite number of QCD correlators. The
familiar spectral function sum rules for products of two QCD currents are among the relations
derived. With this precise knowledge of asymptotic behavior, an infinite number of large-
$N$ QCD correlators can be constructed using dispersion relations. Beane gave a detailed
derivation of the exact large-$N$ pion vector form factor and forward pion-pion scattering amplitudes.

B. Low Energy Constants from High Energy Theorems

As a phenomenological application of the high-energy theorems, Beane considered new
constraints implied by the sum rules on resonance saturation in chiral perturbation the-
ory [23]. The sum rules imply that the low-energy constants of chiral perturbation theory are related by a set of mixing angles. Beane showed that the simplest nontrivial saturation scheme predicts low-energy constants that are in remarkable agreement with experiment. Further, it was shown that (1) vector-meson dominance can be understood as a consequence of the fact that nature has chosen the lowest-dimensional nontrivial chiral representation, and (2) chiral symmetry places an upper bound on the mass of the lightest scalar in the hadron spectrum.

XI. OTHER

A. Dimensional Regularization of Integral Equations

D. R. Phillips, I. R. Afnan (Flinders), and A. G. Henry-Edwards (Flinders)

One difficulty for standard treatments of hadronic reactions is that form factors are always used to regulate integrals which would otherwise be divergent. This procedure is well-motivated, since we know that the hadrons have substructure which gives them a finite extent, and hence, a form factor. However, if we understand this description of hadronic dynamics as a field theory then it is non-local, and hence the implementation of basic field theoretic principles, such as gauge invariance, can be quite involved. Methods have been formulated to impose gauge invariance on an amplitude containing hadronic form factors, but they are intrinsically non-unique, since they constrain only the longitudinal part of the electromagnetic amplitude.

Some of these difficulties can be resolved by using dimensional regularization (DR) to render divergent integrals finite. This is the method of choice for dealing with the infinities which arise in perturbative field-theoretic calculations. However, there are very few studies of the application of dimensional regularization to integral equations, as opposed to its many applications to integrals in perturbative calculations. Phillips, Afnan and Henry-Edwards [97] recently implemented the numerical solution of this dimensionally-regulated integral equation, and have extracted physical quantities, such as phase shifts, once the regulation and renormalization have been done.

B. Exact Solutions to the Schroedinger Equation for Coulomb-Plus-Oscillator Potentials

M. Alberg (Seattle U.) and L. Wilets

In our study of the infamous cold fusion problem (which yielded a bound on the process orders of magnitude less than claimed), we calculated wave functions of two nuclei in a plasma. We discovered an infinite set of exact solutions to the Coulomb plus harmonic oscillator potentials. Each solution, corresponds to a particular ratio of the coefficients of the two terms, and hence the set is not orthogonal. There is considerable interest in special soluble potentials. A particular application is in the numerical calculation of wave functions for potentials containing singular terms, such as the Coulomb term. If one writes the radial
function as \( u(r) = u_0(r) f(r) \), where \( u_0 \) is an exact solution for a potential with the same singularity, then \( f(r) \) is very well-behaved, especially if one chooses a solution of similar eigenvalue. A paper is in final preparation.
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