1 Summary

1.1 Overview

The nuclear theory town meeting was attended by close to 100 participants representing the broad range of research in nuclear theory in the United States. The large attendance, which was more than twice that of the 1989 town meeting, demonstrates the liveliness and enthusiasm pervading the field of nuclear theory during the past five years. Thirteen speakers were invited to review progress in different areas of nuclear theory, and there were special reports from the other town meetings, from representatives of the funding agencies, and from the Institute of Nuclear Theory. The complete program of the town meeting is listed in the Appendix. This document makes an attempt to collect some of the important advances in nuclear theory during the past five years and identifies challenges and opportunities for future research.

Important progress has been made since the time of the last Long Range Plan in all major areas of theoretical nuclear physics. Advances in computational techniques have greatly enhanced our ability to address nuclear structure problems from the microscopic point of view. The Schrödinger equation has been solved for the ground and excited states of few-nucleon systems, yielding unique information on the nuclear force. The improved microscopic understanding of nuclear structure has important applications to electroweak interactions in nuclei and nuclear astrophysics, as well as to the interpretation of electron scattering data. Lattice calculations and QCD vacuum models have provided crucial insight into the quark structure of the nucleon and other hadrons. Advances in nuclear transport theory has made new tools available for the quest of extracting the nuclear equation of state from intermediate and high energy heavy ion collisions, as well as for quantitative predictions of the initial conditions to be reached in nuclear collisions at RHIC.

The increased complexity of nuclear interactions at the higher energies reached at CEBAF, and in the future at RHIC, poses unprecedented challenges for nuclear theory. A thorough understanding of the implications of the data that will emerge from these two facilities will require massive theoretical efforts. Theorists from many different areas of nuclear physics will have to work together, in collaboration withexperimentalists, to identify meaningful observables for new physics, to reliably calculate background effects, and to solve the underlying nuclear and hadron structure physics. Nuclei far off the island of stability will provide stringent new tests for theories of nuclear structure, and a significant theoretical
effort will be needed to derive the astrophysical implications of their observed properties. A fundamental, quantitative understanding of the structure and interactions of hadrons in terms of quantum chromodynamics remains an essential long-term goal of nuclear theory.

1.2 Recommendations

In order to meet these challenges and progress towards our long-range goals, we make the following recommendations:

1. The strength of nuclear theory groups at both universities and national laboratories must be commensurate with the challenges posed by the ongoing and future experimental initiatives. The creation of new positions for young theorists should be encouraged, e.g., with bridging arrangements, joint appointments, and distinguished fellowship programs.

2. We support the continuation of the Institute for Nuclear Theory, and give high priority to its successful programs and workshops focussed on forefront areas of importance to both theory and experiment.

3. In order to be able to address important scientific problems and to maintain their leading role in computational science, nuclear theorists must have access to state-of-the-art high performance computing platforms. Adequate local computing facilities for research groups must also be assured.

1.3 Highlights

Here we list a small number of recent achievements that highlight the scope of progress in nuclear theory since the 1989 Long Range Plan. These topics are to meant provide salient examples for the breadth of progress in theoretical nuclear physics and are not the only important achievements. More detail on the highlighted topics as well as other progress is provided in subsequent sections.

1.3.1 Nuclear Structure and Dynamics

- Light nuclei—ab initio structure calculations with Faddeev and Green’s function Monte Carlo methods;
- Halo nuclei—prediction of unusual properties due to neutron pairing in a low-density environment;
- Interacting Shell Model—promise for a Monte Carlo technique to overcome the $N!$ problem;
- Heavy Nuclei—nuclear shapes and single-particle structure from Hartree-Fock-Bogoliubov theory.
1.3.2 Towards the Quark Structure of Matter

- Understanding how to measure the complete set of quark and gluon distributions in hadrons;
- Providing evidence for a major role of instantons in the QCD vacuum and in light-quark hadronic structure;
- Calculation of properties of mesons and baryons in lattice gauge theory, including masses, radii, and scattering properties;
- Applications of chiral perturbation theory to low-energy hadron dynamics.

1.3.3 The Phases of Nuclear Matter

- Validation of one-body transport dynamics for heavy ion collisions at intermediate energies;
- Development of phenomenologically successful relativistic hadron cascade models for heavy ion collisions at the AGS and SPS;
- Development of partonic cascades predicting the formation of thermalized high-density matter as required for a quark-gluon plasma at RHIC and LHC;
- Improved theoretical understanding of signatures for the QCD phase transition, including charmonium, jets, lepton pairs, and photons.

1.3.4 Weak Interactions and Nuclear Astrophysics

- A more precise understanding of solar neutrino flux uncertainties and strengthening of the evidence for neutrino mixing;
- A qualitative understanding of the enhancements seen in parity-violating compound nucleus reactions;
- Identification of the likely source of r-process nuclei in the supernova envelope and the role of neutrino spallation in nucleosynthesis;
- Stellar models including convection and neutrino physics which show that collapsing stars can explode in supernovae.

Acknowledgments

We wish to express our sincere gratitude to those colleagues who have helped us in producing this report, especially, A.B. Balantekin, B.A. Brown, P. Danielewicz, D. Feng, J. Ginocchio, W. Haxton, F. Iachello, X. Ji, M. Musolf, W. Nazarewicz, R. Perry, J. Randrup, and B. Serot.
2 Nuclear Structure and Dynamics

The past five years have seen impressive development of quantitative theoretical tools to describe and predict nuclear structure properties. The information sought depends on the kind of nucleus studied, and the theoretical techniques are correspondingly diverse. In particular, few-body methods, the microscopic shell model many-body methods, and the phenomenological application of dynamical symmetries have seen much progress.

2.1 Microscopic Theory

2.1.1 Light Nuclei

For three-particle nuclei, the Faddeev equations are the method of choice, and the theoretical precision has reached a point where the data on reactions in the three-particle system can be used to refine our knowledge of three-body forces and of the neutron-neutron interaction.

For nuclei somewhat larger, \( A \approx 4 - 7 \), significant advances were made with Green’s function Monte Carlo methods, which allow one to obtain accurate wave functions and energies from a trial wave function starting point. Accurate (called “exact” when the Monte Carlo sampling error is reduced to below levels of interest) solutions were obtained for the ground states of \(^4\text{He}, ^6\text{He}, ^6\text{Li}, ^6\text{Be}\), the \( 3^+ \) and \( 0^+ \) excited states of \(^6\text{Li}\) and the \( 3/2^- \) and \( 1/2^- \) scattering states of \(^5\text{He}\) with most realistic models of two- and three-nucleon interactions. In the near future it appears possible to calculate several seven and eight nucleon states with available parallel computer platforms. Calculations of the \(^{16}\text{O}\) ground state may also be possible with somewhat less accuracy. Such exact solutions provide detailed information required to study nuclear forces and nuclear structure.

The quantum Monte Carlo method can also provide information to analyze electron-nucleus scattering experiments, electroweak radiative capture and other reactions. This is obtained through the Laplace transform of the linear response function. Pioneering calculations of the response have been made which resolve the long standing problem of understanding the longitudinal and transverse electromagnetic responses of \(^4\text{He}\) observed at Bates and Saclay laboratories. The nuclear interactions modify both these response functions, and the pair currents due to pion exchange interactions enhance the transverse response function as illustrated in Fig. 1. In the near future it will be possible to calculate the response functions of nuclei to other probes as well.

2.1.2 Halo Nuclei

The recent experimental accessibility of nuclei near the neutron drip line has engendered much theoretical work to describe the properties of these nuclei. In particular, the nucleus \(^{11}\text{Li}\) has emerged as a paradigm for systems marginally bound by the neutron-neutron pairing interaction. Due to the low average density of the neutron halo, ab initio calculations are simpler. The weak binding of \(^{11}\text{Li}\) and the lack of binding in the neighboring nucleus \(^{10}\text{He}\) is explained by realistic modeling of the interaction between valence neutrons. Many of the measurable properties around \(^{11}\text{Li}\) were predicted by theory and confirmed by experiment. In particular, the presence of a very soft quasi-resonance in the excitation spectrum and the influence of the neutron pairing correlations on break-up reactions are quantitatively
Figure 1: The ratio of the Laplace transform of the response function of $^4$He to that of four free nucleons. The agreement of the full calculations with the data provides a sensitive test of the role of nuclear interactions and meson exchange currents, especially in the case of the transverse electromagnetic response function.

described by prior theory. The conclusion one can draw from this interplay of theory and experiment is that our current understanding of the nuclear force is adequate for the theory of neutron pairing in a low-density environment.

2.1.3 Shell Model

Shell model calculations for light nuclei can now be made using all many-particle states within a large oscillator space. This so-called “no-core” model space simplifies the determination of an effective interaction from an underlying realistic force via the Brueckner G-matrix theory. The method is thus ab initio beginning from a realistic interaction with a well-defined approximation scheme.

For many years the systematic application of the shell model basis to open-shell nuclei has been stalled at nuclei lighter than the $A = 40$ magic number, due to the factorial growth of configurations in open-shell systems. A new technique shows promise to overcome this problem. The strategy is to sample the relevant configurations rather than try to include them all explicitly. The method is most appropriate to study properties of thermal ensembles, and it relies on an extrapolation of the nuclear interaction to allow effective Monte Carlo sampling. An application to the Gamow-Teller strength of nuclei in the $Z = 26$ region demonstrates that the method can produce results of interest for nuclear physics input to supernova dynamics and element production.

The possibility to go to much larger shell model bases underlines the problem of determining the effective interaction appropriate to a given basis. For nuclei near closed shells,
progress has been made on finding a consistent global effective interaction with a range extending from mass number \( A = 40 \) to \( A = 208 \). However, much work remains to be done in the search for a realistic global interaction.

### 2.1.4 Mean Field Theory

Mean field theory provides the starting point for a microscopic theory of heavy nuclei. With the advent of fast computers, self-consistent mean field calculations can be performed eliminating all artificially imposed symmetries. These Hartree-Fock-Bogoliubov (HFB) models are remarkably accurate in describing the global and single-particle properties of medium-mass and heavy nuclei. Several versions of the input Hamiltonian have been developed, emphasizing simplicity, exact treatment of the exchange interaction, or relativity.

In one recent example, the quadrupole moment of a high spin isomer, predicted in HFB, was measured for the first time. The nucleus \(^{178}\text{Hf}\) was found to have a quadrupole moment of 7.2 eb comparing very well with the theoretical value of 7.3 eb. Other, more exotic shapes are also predicted by mean field theory. For example, the octupole deformations in barium, radium and thorium isotopes is rather well described by HFB. Mean field theory gives the best guidance on the energies of heavy nuclei at the farthest limits of stability. The recent observation of a nucleus with charge \( Z = 110 \) confirmed predicted binding energies to an accuracy in the range 0.1–0.3 MeV. Finally, the puzzle of identical bands has been addressed within the framework of relativistic mean field theory.

Calculations of ground state properties in stable and exotic nuclei, and at high spin states, indicate the importance of density dependent pairing forces. Significant progress has been made in the description of collective dynamics. Examples are many-dimensional self-consistent calculations based on the generator coordinate method.

### 2.2 Collective Models

#### 2.2.1 Interacting Boson Model

The Interacting Boson Model (IBM) has been further extended to cover odd-odd nuclei and broken pair states. Detailed predictions are now available for all types of nuclei (even-even, even-odd and, to some extent, odd-odd) extending to nuclear species far from stability. These predictions, which include beta-decay strengths and binding energies, can be tested at radioactive beam facilities and can form the input for calculations of astrophysical interest.

Calculations of the spectra of medium mass and heavy nuclei with realistic interactions have been completed by making use of the bosonization method. This method has many similarities with techniques used in condensed matter physics and in its present version includes \( S^- \), \( D^- \) and \( G^- \)-pairing. The results of the calculations agree with experiment within few percent. Recent progress in fermion to boson mapping may lead to progress for very deformed systems as well.

The robust and elegant concept of dynamical symmetry is one of the central threads of physics. One of its original manifestations has been in very deformed nuclei with axial symmetry. For instance, the O(6) symmetry, which occurs in both the interacting boson model and the fermion dynamical symmetry model, is unique to nuclear physics and has
not been observed in other systems with collective motion, such as molecules. Recently many bands of the U(5) dynamical symmetry has been observed. Furthermore, dynamical supersymmetry, first observed in odd-even nuclei, and not observed in any other physical system to date, may help bringing an order to the complex spectroscopy of odd-odd nuclei. Also, dynamical symmetry gives an elegant classification of neutron-proton symmetric and antisymmetric states.

Relatively strong magnetic transitions have been observed at about 3 MeV excitation in heavy nuclei, and the strength is found to be proportional to the B(E2) strength in the nucleus. This systematics has been explained from several points of view. It is implicit in the original collective model of the excitation as a “scissors” mode oscillation between deformed proton and neutron ellipsoids. Recently, sum rules have been derived to explain this proportionality. In a sum rule derived from the Interacting Boson Model, the dipole strength is proportional to the number of quadrupole bosons in the ground state. In a schematic shell model with quadrupole-quadrupole interactions, an energy-weighted sum rule has been derived that also exhibits the proportionality between magnetic and quadrupole transition strength.

By combining the reaction mechanism and the nuclear structure in a unified manner within the IBM, higher order coupling terms beyond the Born approximation are calculated and lead to improved agreement between barrier distributions calculated in the IBM and measured in fusion reactions. In particular it has been shown that the barrier distribution has a marked dependence on the nuclear shape, a prediction which will inspire measurements on transitional nuclei.

2.2.2 Superdeformation

Since the original discovery of the first superdeformed band, identical bands have been seen in the neighboring superdeformed nuclei having an additional nucleon. A partial explanation for this striking fact stems from a discovery made many years ago. In heavy nuclei certain doublets of single particle orbits are almost degenerate. Although these orbits are not spin-orbit doublets, they have single-particle angular momentum \( J \) differing by 1/2, which is called the pseudo-spin. If this pseudo-spin does not participate in the collective rotation, the rotational energy is the same in the neighboring nuclei provided the moment of inertia does not change. The origin of this symmetry is just beginning to be understood. Why the moments of inertia are identical to better than the one percent change expected from the variation in mass and radius still remains to be clarified.

Recent experiments have detected a \( \Delta J = 2 \) staggering in the spectrum of a superdeformed band, and it has been suggested that this may be evidence for a change from an axially symmetric shape to a non-axial shape with \( C_{4v} \) symmetry (invariant under rotation of 90° about the original symmetry axes). Initial calculations with an intrinsic Hamiltonian show that this staggering can be reproduced with a deformed shape which includes a small hexadecapole deformation of the form \( Y_{44} + Y_{4,-4} \), although precise calculations are not possible at this time.
2.2.3 Nuclei Far from Stability

In order to have states with good isospin for nuclei with neutrons and protons filling the same major shell, a collective neutron - proton pair must be included along with the neutron pair and proton pair to complete the isospin triplet. This IBM-3 model, previously applied only to light nuclei, has been applied to the nuclei with \( N \approx Z \approx 40 \); a comparison of the calculated and measured spectrum of \(^{80}\)Sr shows good agreement. Although the nuclei in this region are very deformed, the deformation is not axially symmetric but gamma unstable, and with good O(6) symmetry. This type of collective motion is unique to nuclear physics and needs to be studied more. Present studies suggest that nuclei with \( N \approx Z \) and the valence shell nearly half filled will have O(6) symmetry. Also for \( N \approx Z \) magic numbers may change due to large neutron-proton interaction, as we have seen for \(^{80}\)Zr. An interesting question is whether \(^{100}\)Sn will be doubly magic.

2.3 Challenges and Opportunities

One of the challenges which emerges from these past developments is to exploit the full power of emerging computer technology to solve important nuclear many-body problems which are now accessible for the first time. Unrestricted HFB calculations of nuclei far from stability will play an essential role in understanding the physics to be explored with radioactive ion beams. Green’s function Monte Carlo solutions could be extended beyond \( A = 6 \) nuclei, and offer the potential for a microscopic understanding of both ground state properties and response functions of light nuclei. Given the progress in proving feasibility of Monte Carlo shell model calculations using simple phenomenological interactions, another major challenge will be to develop microscopic effective shell model interactions whose physics content is commensurate with the large numerical effort required for these calculations.
Towards the Quark Structure of Nuclei

Given the major investment which has been made in CEBAF, BATES, and RHIC as well as in nuclear physics experiments at HERA, SLAC, and Fermilab, understanding the role of quark and gluon degrees of freedom in hadrons and nuclei has become a major focus of contemporary theoretical nuclear physics.

3.1 Quark and Gluon Distributions in Hadrons

Deep inelastic lepton scattering has provided extremely important but as yet incomplete information about the quark/gluon structure of the nucleon. For example, the measurement of the spin-independent quark distribution \( f_1(x) \) shows that only half of the energy plus momentum of the nucleon is carried by quarks and the longitudinal spin-dependent distribution \( g_1(x) \) shows that quark helicity carries very little of the nucleon spin and suggests that the strange quark sea may be strongly polarized. Recently, a careful, systematic analysis has provided a complete classification of all the quark and gluon distribution functions which can be defined in the nucleon with precise, quantitative relations of these distributions to the structure functions which can be measured experimentally in high energy scattering.

Based on this understanding, theorists have proposed new experiments to measure previously unknown quark and gluon distributions and several of these proposals are already being carried out or planned. The theoretical idea of using pion production by a polarized electron beam on a transversely polarized proton target to measure the chirally odd transverse spin distribution \( h_1(x) \) is being carried out by the Hermes collaboration at HERA and will be the first measurement of this new spin dependent quark distribution. The Drell-Yan process in polarized \( \vec{p}\vec{p} \) collisions at RHIC has been proposed as another way to measure \( h_1(x) \) and is an important part of the experimental program proposed by the RHIC Spin Collaboration. Direct photon production in proton-proton collisions is a sensitive probe of the gluon distribution, since the scattering of a gluon from a quark to produce a photon plus a quark involves the gluon distribution at tree level. Thus, the theoretical observation that direct photon production from longitudinally polarized protons would measure the helicity polarization of gluons \( \Delta g \) has led the RHIC Spin Collaboration to propose measurement of \( \Delta g \) as well. These are important examples of the intellectual leadership QCD theorists can provide in exploiting the full potential of the emerging facilities in our field.

3.2 Structure of the QCD Vacuum and Hadrons

Significant evidence has been found that instanton-induced forces play a dominant role in light quark physics. At the phenomenological level, an instanton liquid model economically accounts for the gross behavior of light quark systems. It accounts in detail for the behavior of point-to-point correlation functions of hadronic currents in the QCD vacuum, it generates the quark condensate and pions, it reproduces the gross properties of hadrons and accounts for the major features of glueballs.

These phenomenological features have been confirmed by numerical solution of QCD on the lattice. Analysis of the instanton content of lattice calculations confirms the phenomenological average instanton size of \( \frac{1}{3} \) fm and density of about 1 fm\(^{-4} \). Perhaps the strongest
Figure 2: The instanton content for a typical slice of a gluon configuration calculated in lattice QCD at fixed $x$ and $y$ as a function of $z$ and $t$. The left column shows the action density $S(1, 1, z, t)$ including all gluon contributions (a) and after removing all contributions except for instantons (c). The right column shows the topological charge density $Q(1, 1, z, t)$ before (b) and after (d) removal of non-topological excitations, revealing the presence of 3 instantons and 2 anti-instantons.

Evidence for the dominant role of instantons arises from comparison of lattice calculations which correctly include all the excitations of the gluon degrees of freedom with those in which essentially all excitations except for instantons have been removed as shown in Fig. 2. The result is that the gross distribution of quarks in hadron ground states and the behavior of point-to-point hadron vacuum correlation functions are hardly affected by removing all other degrees of freedom. Thus, in considering light hadron physics, the task of understanding nonperturbative QCD is greatly simplified by identifying the instanton configurations which saturate the QCD vacuum, which allows one to ignore summing over all the other gluon degrees of freedom which in the end do not play a major role.

### 3.3 Lattice Gauge Theory

Numerical solution of QCD on a discrete space-time lattice is the only known way to solve, rather than model, QCD. Starting with a Euclidean path integral, the Gaussian integral over quark fields is performed analytically, yielding an integral over gluon fields which is evaluated
numerically using Monte Carlo sampling. The so-called quenched or valence approximation, in which the numerical calculation is greatly simplified by omitting the non-local fermion determinant, corresponds to omitting all quark-antiquark excitations out of the Fermi sea.

One major accomplishment over the past few years has been the successful calculation of a broad range of hadron observables in the quenched approximation. These include masses, form factors, magnetic moments, moments of structure functions, meson decay constants, the quark condensate \( \langle \bar{\psi} \psi \rangle \), vacuum correlation functions of hadron currents, pion-pion and pion-nucleon scattering lengths, and the pion-nucleon sigma-term \( \sigma_{\pi N} \). In the best cases, such as masses, agreement with experiment is at the 5% level, and systematic effects due to lattice spacing, lattice volume, and finite quark mass are well understood and controlled. A second major development has been the demonstration that in cases where one knows that the Fermi sea should contribute significantly, such as decay constants and the sigma-term, inclusion of the fermion determinant yields large corrections which significantly improve agreement with experiment.

Lattice QCD has also provided important insight into the structure of hadrons and the QCD vacuum. In addition to elucidating the role of instantons in quark propagation, numerical calculations also yield direct evidence for the role of monopoles in confinement and provide a quantitative measure of the contribution of gluons to hadron wave functions.

### 3.4 Light-Front QCD and Dyson-Schwinger Equations

Lattice calculations are still limited to ground or low-lying excited states and equilibrium thermodynamic quantities at zero chemical potential, which excludes much of nuclear physics. The development of other analytic techniques and numerical approaches that provide systematic approximations is therefore of great importance.

One interesting approach is light-front QCD, which offers the advantages of a simple vacuum and close correspondence to the quantities measured in deep inelastic scattering. Present computational schemes employ cutoffs that violate explicit rotational invariance and gauge invariance, forcing symmetry-breaking terms to appear in the Hamiltonian. Using renormalization group techniques, progress has been made on these renormalization problems and in seeing how asymptotic freedom and confinement emerge in this theory. Since light-front field theory effectively reduces the number of non-trivial dimensions by one, it has proven to be a powerful numerical tool in 1 + 1-dimensional gauge theories. The light-front framework is also useful phenomenologically, providing a boost invariant tool for generalizing nonrelativistic quark model calculations to intermediate energies. There has been substantial progress in applying light-front constituent quark models to the study of electromagnetic form factors and reactions. Dynamic restoration of rotational and gauge invariance broken in these models remains an outstanding challenge.

Another promising computational approach to QCD is provided by the Dyson-Schwinger equations, which can be truncated without breaking gauge invariance or chiral symmetry. It has been shown that the three-gluon vertex is sufficient to drive confinement, while the known perturbative ultraviolet behavior of QCD is explicitly recovered. It is presently necessary to parameterize the low-momentum behavior of the gluon propagator since it has not been calculated analytically or numerically on the lattice, but reasonable parameterizations reproduce \( \pi-\pi \) scattering and the electromagnetic form factor of the pion.
3.5 Effective Low-Energy Theories of QCD

Effective Chiral Lagrangians are the result of transforming QCD from its underlying quark and gluon degrees of freedom to effective hadron degrees of freedom. The broken chiral symmetry manifested by these building blocks acts to constrain the strong interactions, and the resulting chiral perturbation theory provides a quantitative calculational framework. A wide variety of observables such as the electric and magnetic polarizabilities of the neutron and proton, the \( \gamma p \rightarrow \pi^0 p \) amplitudes near threshold, and many properties of pions have been calculated, yielding agreement with experiment in the pion sector. Recent measurements of the proton polarizabilities at Saskatoon, Illinois, and Mainz, and the neutron electric polarizability at ORNL are in agreement with these calculations. The novel predictions for near-threshold neutral-pion photoproduction from the proton are currently being tested experimentally.

An interesting new development is the application of techniques from the heavy quark effective theory to include baryons in a systematic manner in the chiral perturbation expansion. This approach has been applied to predict electromagnetic properties of the ground state decuplet baryons, such as magnetic moments and electromagnetic decay widths, which will soon be tested at CEBAF.

Recently, chiral perturbation theory has also been applied to nuclear forces and was shown to provide a quantitative scheme for understanding the fact that three-body forces are significantly weaker than two-body forces and that four-body forces are almost negligible. It also accounts for the fact that charge independence breaking in the nuclear force is larger than charge-symmetry breaking and for the suppression of heavy-meson exchange currents in weak and electromagnetic interactions.

Several \( np \) charge symmetry experiments were stimulated in part by the efforts of theorists to delineate possible sources of charge-symmetry-breaking and charge-independence-breaking in the NN interaction. The reexamination of \( \rho - \omega \) mixing, particularly its evolution with the momentum carried by the meson, has been the focus of recent work.

3.6 Relativistic Nuclear Many-Body Theories

Relativistic hadronic field theories can be constrained to fit low-energy phenomena observed in ordinary nuclei and then extrapolated to more extreme situations of density, temperature, flow velocity, and four-momentum transfer, such as those that will be produced in experiments at RHIC and CEBAF. Relativistic approaches provide a natural way to incorporate the symmetries of QCD, such as chiral symmetry and broken scale invariance, at the hadronic level.

The relativistic quasipotential approach to nuclear matter, known as Dirac-Brueckner-Hartree-Fock theory, incorporates large scalar and vector self-energies into the nucleon wave functions. The effective scalar field represents the correlated two-pion exchange between nucleons in a nonlinear realization of the chiral symmetry. The introduction of a quartic self-interaction of the vector field has been found to be important for accurately modeling the self-energies and consequent nuclear properties. This approach introduces a density dependence into the NN interaction that goes beyond what is included in nonrelativistic Brueckner theory and makes it possible to simultaneously fit both the NN phase shifts and...
the nuclear matter equilibrium point at first order in the low-density expansion.

To extend these results to finite nuclei, one parameterizes the density dependence of the self-energies and then introduces this density dependence into the hadronic Lagrangian by allowing the meson-baryon couplings to be functionals of the baryon fields. The resulting Dirac-Hartree equations naturally include rearrangement terms. The results for rms radii, binding energies, and charge distributions of closed-shell nuclei are quite successful.

A recent conceptual insight is that the phenomenologically important term associated with so-called “Z-graphs”, which mix the free positive- and negative-energy Dirac wave functions, is a natural consequence of Lorentz covariance. This term is therefore model independent and should be present whether the nucleon is composite or not. At present, nothing is known about the origin of the important spin-orbit terms, which are also signatures of the Dirac approach, but work is underway to see if these can also be generated in a model-independent fashion.

3.7 Challenges and Opportunities

The most important challenges in this field are to obtain a fundamental description of hadron structure through the quantitative solution of QCD and to improve our understanding of the quark structure of nuclei through both explicit QCD solutions and models that are consistent with low-energy QCD. Recent developments provide unprecedented opportunities for progress.

To date, the primary focus in studying quark and gluon distributions in hadrons experimentally has been the so-called leading twist distributions which dominate structure functions at the highest momentum transfer. With the advent of CEBAF, the opportunity now exists for precision exploration of the sub-dominant higher twist distributions which become measurable at low $Q^2$. These distributions display the effects of coherent parton scattering beyond the Feynman parton model, and directly measure the QCD initial and final state interactions at the quark and gluon level. Theoretical challenges include subtle ambiguities in separating distributions of different twist because of infrared physics and learning to calculate and understand the role of important quark and gluon configurations revealed by higher twist matrix elements.

With the emergence of teraflops-scale computers, improvements in algorithms, and the discovery of more accurate discrete approximations to the continuum action, definitive lattice calculations of many important observables will be possible for the first time. Moments of spin-dependent structure functions and transition form factors can be calculated accurately in the next few years and will be directly relevant to measurements in the same time frame at HERA and CEBAF. Definitive calculation from first principles of the low energy parameters of chiral perturbation theory will elevate what is now a limited phenomenology with a large number of free parameters to a far more fundamental and quantitative theory. The quest for insight into the role of topological structures such as instantons will also advance significantly with the possibility of studying instantons in full unquenched QCD with lattices which provide an accurate approximation to the continuum limit. A major challenge to the field is to devote the computational resources and effort required for the solution of QCD and understanding the data from new experimental facilities.
Light-front QCD poses substantial theoretical challenges associated with lack of rotation invariance, renormalization, and understanding the relation between observables in the lab and infinite momentum frames. A crucial question is whether the advantages outweigh the renormalization difficulties in 3 + 1-dimensional QCD. The method of truncated Dyson-Schwinger equations is now poised for application to a large variety of problems in hadronic structure and dynamics. A major challenge for this approach will be constructing a controlled, systematic framework for using solutions from lattice gauge theory to characterize the low-momentum gluon propagator and effective vertices.

It will be important to determine the extent to which effective chiral Lagrangians can provide a tractable framework for calculating the nuclear force, with all of its richness and complexity. Quantitative progress would further solidify calculations in few-nucleon systems and light nuclei. The development of a reliable, quantitative low-energy effective theory based on hadrons will be important for understanding CEBAF experiments and will depend on the identification of relevant expansion parameters for strongly interacting, relativistic many-body problems. Such a theory would be extremely valuable in understanding the novel forms of dense matter which are of astrophysical interest, such as the possibility of pion or kaon condensation occurring in neutron stars. It would also permit calculations of hadronic properties as functions of density and temperature that can be used to extrapolate to extreme conditions.

Even with expected significant progress in analytical and numerical solution of QCD, there are a number of expected developments in low-energy hadron spectroscopy at CEBAF and other laboratories for which quantitative solutions will be impractical and hadron models will therefore play a crucial role. Enlightened model building must address at least two classes of questions. One is why states predicted by otherwise successful models are not observed experimentally. The other is understanding the precise nature of hadron resonances, for example the structure of the Roper resonance, $N(1440)$, the mixing of the $S_{11}$ resonances, $N(1535)$ and $N(1650)$, and whether states like the scalar mesons $f_0(975)$ and $a_0(980)$ can be understood as quasi-molecular states. Quark models, flux tube models, and algebraic models offer the potential of complementary insights.
4 The Phases of Nuclear Matter

An important goal of nuclear physics is to observe and measure the possible phases that nuclear matter can assume under various conditions of energy and density. Heavy ion collisions are the experimental means to produce such phases, but the measurements can be meaningfully interpreted only if a reliable transport theory is available to relate the observables back to the fundamental dynamics. There has been substantial progress in the last five years in the development of transport theory and applications to heavy ion collisions. The specific theoretical models emphasize different aspects of the dynamics, depending on the energy regime studied. At low energies, one-body transport with mean field and collisional dynamics has proven useful. At higher energies, the transport models necessarily probe the quark and gluon degrees of freedom within the colliding nuclei.

4.1 Low energies: One-body transport and beyond

Transport theory at nonrelativistic energies is based on a one-body approximation in which the nucleon density in phase space is evolved as a classical variable. Quantum physics enters implicitly through the parameters of the interaction and explicitly through Pauli-blocking of nucleon-nucleon collisions. This approach has been successful in describing a number of experimental observables. Angular distributions for nucleon production are reproduced at the level of 10 to 20 percent for beam energies from tens of MeV to several GeV. The production of light composite nuclei, such as deuterons, and of pions is also well described. At energies above a GeV, nucleon resonances are important as intermediaries for the production of $\eta$ mesons, kaons and antiprotons. Proton-proton correlations, which provide information on the space-time evolution of the colliding nuclei, also agree reasonably with observation.

An important goal of heavy ion reaction studies is to measure the nuclear equation of state. The collective sideways flow in an off-center collision is an important observable since it is sensitive to the equation of state at higher densities, as well as to the effective cross section between nucleons in the nuclear medium and to the momentum dependence of the mean field. From flow data on medium-heavy nuclei at a bombarding energy of 400 MeV/n, one can constrain the nuclear incompressibility, with current theory yielding $\kappa < 250$ MeV.

An intriguing prediction of transport theory is that a doughnut-shaped nucleus can be produced in nuclear collisions under certain circumstances. The collision has to be nearly head-on to preserve the symmetry of the shape, and the energy has to be in a rather small window around 60 MeV/n to produce the large-scale deformation without blowing the combined system apart. The result of a transport model calculation is shown in Fig. 3. An outstanding challenge is to confirm this prediction with a clear experimental signature.

Another goal of studies in the medium energy range is to find observable effects of the gas-liquid phase transition. To understand multifragmentation yields, the average Boltzmann collision term is augmented by a fluctuating Langevin term and the resulting theory describes an ensemble of one-body densities. Simplifying analytical approximations have recently reduced the numerical effort to the point that the method is now practical for realistic calculations.

A more quantum mechanical approach to treat the regime of large fluctuations is to constrain the A-body wave function to be a Slater determinant of Gaussian single-particle
Figure 3: A doughnut-shaped nucleus predicted by transport theory. This shape was produced simulating a collision of $^{93}$Nb on $^{93}$Nb at a beam energy of 60 MeV/n. The contour shows the surface at 1/3 nuclear matter density at a time $t = 160$ fm/c from the start of the collision.

wave packets, yielding a set of dynamic equations for the positions of the wave packets and their widths. This approach has given a new understanding of the reactions involving relatively light ions, but remains impractical for heavy systems.

4.2 Hot and Dense Hadronic Matter

Experiments with relativistic heavy ions at the Brookhaven AGS and the CERN-SPS aim to investigate the properties of dense and highly excited hadronic matter, and possibly to study the onset of chiral symmetry restoration in baryon-rich dense matter. Substantial progress has been made since the last Long Range Plan on the theoretical description of nuclear collisions at AGS and SPS energies, and on the problem of medium effects on hadrons in hot and dense hadronic matter.

A number of relativistic transport models has been developed during the past six years which model collisions of nuclei at relativistic energies as cascades of colliding hadrons and take into account rescattering. These are implemented in codes such as VENUS, RQMD, and ARC. At AGS energies, these codes are based on almost identical assumptions, i.e. hadrons interacting pairwise with free-space cross sections determined by experimental data from $pp$ collisions and quark model extrapolations, with the possible addition of a density dependent mean field. At the higher CERN energies, the codes make use of $pp$ collision phenomenology, mostly within the framework of the Lund string model.

Overall, these models have enjoyed impressive success in describing and even predicting a wealth of inclusive particle spectra measured at Brookhaven and CERN with few, if any, adjustable parameters. This has allowed theorists to obtain a detailed picture of the reaction dynamics, especially at AGS energies, in terms of a dense gas of meson and baryon resonances reaching baryon densities up to $9\rho_0$, where $\rho_0$ is the density in the nuclear ground...
state. As an example, Fig. 4 shows the evolution of the baryon density in Au+Au, Si+Au, and Si+Si collisions at AGS energies. The rising part of the curves describes the rapid compression and heating of nuclear matter upon impact, followed by a slower, almost isentropic expansion and ending in a freeze-out of hadrons after about 15 fm/c. A large fraction of the nucleons is temporarily in excited states which form a major source of the pions created in these collisions. The matter appears locally equilibrated in the later stages of the reaction, when densities are still far above normal nuclear density, providing strong arguments for the validity of thermal models for the spectra of emitted particles.

Theoretical expectations are that the properties of hadrons, such as mass and decay width, should be modified in the presence of a dense and highly excited environment, even before the phase transition to a deconfined quark-gluon plasma. At temperatures much less than $T_c$ it is most efficient to think of the matter as a relatively dilute gas of hadrons. This may be described by a virial expansion, using low energy effective Lagrangians, chiral perturbation theory, or QCD sum rules. Although it is generally agreed that there is a tendency toward restoration of chiral symmetry at high temperature or density, that is reflected in an approach to degeneracy between parity doublets such as the $\rho$ and $a_1$ mesons, predictions derived from different methods do not coincide. In particular, lattice results currently indicate little or no change in the screening masses with temperature except in the immediate vicinity of the chiral phase transition.

The modification of hadronic properties in the interior of nuclei is being actively studied.
using a variety of techniques. There is strong evidence that the chiral (quark) condensate inside nuclei is significantly reduced (30–40%) from its vacuum value. Through general scaling arguments, QCD sum-rule methods, and quark-hybrid models, this partial restoration of chiral symmetry has been linked to density-dependent phenomena such as mass shifts of vector mesons and large scalar and vector nucleon self-energies suggested by relativistic phenomenology. Density dependent hadron masses have already been used in transport models for relativistic nuclear collisions. The challenge will be to solidify these predictions and to reconcile different approaches.

4.3 Ultrarelativistic Heavy Ion Collisions

The past five years have seen significant progress in applications of perturbative QCD to the problem of thermalization and quark-gluon plasma formation in relativistic heavy ion collisions at RHIC energies and beyond. The techniques of renormalization group improved perturbative QCD, which were developed in the context of jet formation in $e^+e^-$ and $p\bar{p}$ collisions, have been applied to describe the earliest phase of nuclear collisions at RHIC in terms of a partonic cascade. These calculations have led to a revision of theoretical assumptions about the initial parameters for the thermalized plasma to be formed at RHIC toward higher initial temperatures ($T \geq 500$ MeV) and a high density of gluons ("hot glue..."
scenario”). This, in turn, has significantly influenced the conceptual design of the major RHIC detectors, with a stronger emphasis on the measurement of electromagnetic probes and total charm yield.

Quantitative predictions for the full space-time evolution of dense QCD matter at RHIC and LHC energies up to the final hadron distributions are now available, as shown in Fig. 5. Recently, it has been realized that parton densities in large nuclei at small Feynman-\(x\) may be calculable in the framework of perturbative QCD. An intense effort is underway to combine this approach to parton shadowing with medium corrected parton cascade calculations to provide model-independent QCD prediction for heavy ion collisions at RHIC.

4.4 Quark-Gluon Plasma

Historically, lattice QCD has played a central role in our exploration of the deconfinement phase transition at zero chemical potential, which is relevant to the central rapidity regime of relativistic heavy ion collisions. There is now solid evidence that the transition temperature with two flavors of light quarks is \(T_c \approx 150\) MeV and an important new integral technique has been developed to measure energy and entropy densities. Although the order of the transition is not yet clear for the physical case of up, down and strange quarks, in the domain of second-order phase transitions, scaling analysis of lattice measurements strongly suggests that the critical exponents are consistent with O(4) symmetry.

Important progress has also been made in the perturbative description of the equation of state and the transport properties of the quark-gluon plasma. A resummed perturbation theory for the high-temperature phase of QCD has been developed, which permits systematical inclusion of screening effects into an effective action for thermal QCD at momentum scales of order \(gT\) and \(T\). This has facilitated quantitative predictions for photon and dilepton emission from a quark-gluon plasma, as well as the determination of new transport coefficients such as the quark and gluon damping rates, equilibration times, and color conductivity. The resulting picture of a tightly coupled plasma of quarks and gluons with strongly damped collective excitations, which is also supported by new results about the chaotic behavior of the classical nonabelian gauge fields, confirms the prediction of very rapid thermalization from the parton cascade models.

In preparation for the experimental program at RHIC, the various proposed signatures of a quark-gluon plasma have been under intense theoretical scrutiny. The energy loss of jets in a quark-gluon plasma has been calculated and quantitative predictions for jets propagating through dense matter are available. The dissolution of \(J/\psi\) and other heavy vector mesons in the deconfined phase has been extensively studied, and a comprehensive description of \(J/\psi\) and \(\psi\) suppression by hadronic comovers was developed. A new signature for the chiral phase transition, the formation of disoriented chiral condensates (DCC), was proposed and extensively investigated. DCC’s would produce highly specific experimental signatures, such as unusual pion charge ratios, or charge correlations, which should be detectable by the RHIC detectors. Hadronic mechanisms for strangeness equilibration have been studied in the context of cascade codes, and shown to fail in generating the level of equilibration already observed at SPS energies, confirming strangeness enhancement as a promising signature of quark-gluon plasma formation. Significant progress has also been made in our understanding of suitable signatures for a long-lived mixed phase, such as lepton pairs, vector mesons, and
two-particle correlations.

4.5 Challenges and Opportunities

Fundamental challenges in this field are to develop a quantitative description of the phase transition from hadronic to quark-gluon matter, to determine the structure of nuclear matter on both sides of the transition, and to identify reliable experimental signatures for chiral symmetry restoration and deconfinement. An important step toward that goal is the refinement of quantum transport theory for nonequilibrium processes to a point where it can serve as a reliable tool for the description of the reaction dynamics from the initial stage of a heavy ion collision up to the final disassembly phase.

At relativistic and ultrarelativistic energies the problem of medium effects on effective masses and cross sections is of paramount importance. Hadronic cascade models, which predict compression up to ten-fold baryon density at the AGS, nevertheless appear to predict many measured particle yields correctly with the assumption of constant masses and cross sections. Double and triple differential cross sections, as well as improved global event analysis, will provide new stringent tests for these models. Theorists have already begun to question the internal consistency of these models. More work along these lines will be needed to identify the crucial experimental features which may eventually serve as probes for the properties of hot and dense hadronic matter.

Partonic cascade models are beginning to address the problem of screening effects which may act as self-consistent cut-off mechanisms for the infrared divergences of perturbative QCD. This requires that the resummation techniques, which have been very successful in finite-temperature QCD, be extended to strongly interacting matter far from thermal equilibrium. The importance of many-body effects for thermalization of a quark-gluon plasma also deserves further study. Progress in this area during the last five years has been extremely rapid, lending reasonable hope that a consistent description of very highly energetic nuclear collisions from impact well into the thermalized plasma phase could be achieved within the framework of resummed perturbation theory.

There is also a need for definitive Monte Carlo calculations of lattice gauge theory to determine the precise characteristics of the QCD phase transition in the presence of physical up, down, and strange quarks. Questions to be answered include: What is the order of the phase transition? If it is first order, what is the latent heat? If it is second order, what is the universality class? What is the interface energy at the phase boundary and what is the quantitative dependence of the energy density, entropy, and pressure on temperature? How does the spectrum of dynamical modes change through the phase transitions? How are hadron masses affected below $T_c$? Given the magnitude of the commitment to the RHIC project, a more substantial effort of the nuclear theory community is highly desirable.

The formulation of an effective dynamical theory of hadronization remains another important challenge. There exists a wealth of data from $e^+e^-$ and $p\bar{p}$ interactions that can be used to test hadronization models and to determine the parameters of effective theories. The reliability of several proposed quark-gluon plasma signatures, such as strangeness enhancement and especially disoriented chiral domain formation, would be significantly enhanced if the hadronization process were better understood.
In the energy range of the liquid-gas phase transition in nuclear models, the main challenge is the development of a microscopic, quantal theory of multifragmentation. This requires that present transport models be extended to include the formation and evolution of density fluctuations. A solution of this fundamental theoretical problem would most likely also have applications to relativistic heavy ion collisions, most notably to hadronization.
5 Weak Interactions

5.1 Neutrino Properties and Nuclear Beta Decay

Although neither Dirac nor Majorana neutrino masses are included in the minimal standard model, there are strong theoretical arguments suggesting neutrinos may be massive, and nuclear physics has played a major role in both direct and indirect tests of this.

The best direct determinations of neutrino masses are the precise measurements of the end-point region of the tritium $\beta$-decay spectrum. Nuclear theorists have contributed to this effort by evaluating Coulomb corrections to the passage of the outgoing $\beta$-particle through the molecule and by estimating the effects of atomic and molecular excited states on the shape of the end-point spectrum.

Neutrino mixing is also expected in most extended models. The resulting oscillations can provide information on both masses and mixing angles. Furthermore, the effects of modest mixing can be greatly magnified by matter effects. Theoretical characterizations of the spectra of solar and supernova neutrinos provide important yardsticks against which the effects of oscillations can be measured. Nuclear theory has made important contributions to the understanding of signals and backgrounds in neutrino detectors such as KARMEN and LSND. This includes modeling the first-forbidden and quasielastic nuclear responses, and understanding the spallation products that could complicate certain experiments.

Neutrinoless double beta decay probes the masses and right-handed couplings of Majorana neutrinos. Great efforts by nuclear physics have led to agreement on the size of the matrix elements that govern this process, and thus on the scale of Majorana masses that current experiments can probe (about 1 eV/$c^2$). The standard-model process of two-neutrino decay, only recently observed in the laboratory, provides a very stringent test of nuclear structure theory. Shell model studies for nuclei like $^{76}$Ge and $^{82}$Se have successfully predicted rates, while QRPA calculations in heavier systems have defined the “reasonable ranges” for experiment. Recently both Lanczos moment techniques and Monte Carlo methods have been successfully used to calculate the nuclear Green’s functions that govern this process.

5.2 $\beta$-Decay and Unitarity of the CKM Mixing Matrix

Precision measurements of Fermi $\beta$-decay combined with careful theoretical analyses of both inner and outer radiative corrections play a crucial role in testing the unitarity of the Kobayashi-Maskawa matrix. The error on $V_{ud}$ completely dominates this test, which at the present time fails at the $2\sigma$ level. Reducing theoretical uncertainties is essential to further progress. Improvements in treating isospin violation in the nucleus and providing estimates of dispersive effects are important future challenges for theorists.

New theoretical work has been important to progress in a number of other $\beta$-decay studies, including the demonstration of large exchange current effects in axial-charge $\beta$-decay and the extraction of constraints on scalar and tensor interactions and right-handed currents. The origin of the renormalization of $g_A$ in nuclei and the extraction of $F_P$ from nuclear muon capture and radiative muon capture remain challenging problems.
5.3 Weak Lepton-Nucleon and Lepton-Nucleus Scattering

The measurements of the spin structure function of the proton and neutron led to various theoretical speculations regarding the polarization of sea quarks in the nucleon. Spatial as well as spin polarizations of the sea quarks contribute to the nucleon electroweak currents. Several experiments are presently being mounted or performed for the purpose of measuring the neutral weak currents, using either elastic neutrino scattering or parity-violating elastic electron scattering. Because the photon and the $Z$ boson couple to the quark flavors with different strengths, comparing the electromagnetic and neutral weak currents (and assuming that the proton and neutron are an iso-doublet) allows one to extract the contributions of the individual flavors. In particular the contribution of $s$ quarks is of special interest because they exist only in the quark-antiquark sea.

The interpretation of the expected experimental data has been clarified by theoretical work carried out in the recent years. At the nucleon level, one needs to evaluate perturbative contributions, to model the soft contributions (perhaps through mesonic loops or the Skyrme model), and to find some reasonable prescription for matching the two. It also requires an evaluation of the hadronic contributions to one-loop electroweak radiative corrections to tree-level amplitudes that could mimic strange quark effects. At the nuclear level, one must understand many-body effects such as contributions from non-nucleonic strange quarks, meson exchange currents, and electroweak dispersion corrections.

5.4 Parity Nonconservation

Nucleon-nucleon scattering and reactions in nuclei provide the only practical tests of the flavor-conserving nonleptonic weak interaction. Beautifully precise measurements in the pp and few-nucleon systems and in special light nuclei such as $^{18}$F and $^{19}$F have shown that the isoscalar parity-nonconserving interaction has the expected strength, but the isovector interaction is suppressed relative to expectations. As the isovector interaction is thought to be dominated by the weak neutral current, the dynamic origin of this suppression is of great interest. Theory played a crucial role in this physics by providing precise calculations in few-nucleon systems and by accurately determining transition matrix elements for $^{18}$F and $^{19}$F. These results have stimulated new work on enhanced operators associated with strange quarks and on nonperturbative effects introduced through condensates.

Exploiting the unique beams of epithermal neutrons at the LANSCE facility, measurements of the longitudinal spin asymmetry have recently demonstrated parity violation at the level of several percent in multiple compound-nuclear levels in the same nucleus. The large magnifications apparent in such measurements are understood in terms of the chaotic, quantum behavior of the nucleus. Theorists have made great progress in understanding the observed enhancements in terms of the underlying parity-violating nucleon-nucleon interaction using methods of statistical spectroscopy, where the relevant observables are expressed as averages over collections of states. However, in one case ($^{232}$Th) the observed signs of the mixing were found to be highly nonstatistical, posing an intriguing problem to theorists.

It is now widely appreciated that precise atomic PNC measurements can provide information on new physics complementary to collider data. This has stimulated experimental efforts to measure PNC in isotopic chains, where one can factor out the complicating effects
of atomic physics. Theoretical studies indicate that changes in the neutron distributions, which dominate the weak charge, could complicate the interpretation of these experiments if they achieve their anticipated 0.1% accuracy. Progress is therefore likely to depend on improved calculations and theoretical understanding of neutron distributions and radii.

5.5 T- and CP-Nonconservation

The precision of atomic electric dipole moment measurements has reached that of neutron electric dipole moment experiments and will soon far surpass it, posing new challenges to nuclear theory. For many sources of CP nonconservation (CPNC), such as a CP violating $\theta$-term in the QCD Lagrangian, the atomic electric dipole moment arises predominantly from CPNC interactions within the nucleus, making the quality of future CPNC limits dependent on our ability to calculate the CPNC forces between nucleons that arise from the underlying Lagrangian and to evaluate the resulting nuclear polarizations.

Important constraints on CPNC have also been obtained from correlation studies in $\beta$-decay, helped by theoretical estimates of the final-state effects. Constraints on exotic T-odd, P-even nuclear forces have been obtained from calculations of nuclear electric dipole moments induced by weak radiative corrections, and it has been recently argued that neutron transmission experiments similar to those discussed in the section on parity nonconservation could reach similar sensitivities.

5.6 Challenges and Opportunities

Signatures for new physics beyond the standard model may well be first discovered as a subtle symmetry violation at low energies. It is extraordinary how many of the crucial tests, such as small neutrino masses, electric dipole moments of atomic nuclei, and family-number violating muon decays, are now reaching sensitivity levels characteristic of expected new physics. Nuclear theorists will continue to have an important part in connecting the observed phenomena, or bounds on such phenomena, with the underlying fundamental mechanisms.
6 Nuclear Astrophysics

Together, nuclear physics and astrophysics have greatly enhanced our understanding of the universe. A large variety of phenomena in the universe, such as primordial and galactic nucleosynthesis, stellar evolution, neutrino luminosities, supernovae and neutron stars, require quantitative understanding of nuclear processes. The synergy between these two fields will grow further when the proposed radioactive ion beam facilities provide new information on nuclei far from stability and when the QCD structure of nuclear and hadronic matter is better understood via the CEBAF and RHIC programs.

6.1 The Solar Neutrino Problem

New results from the Kamiokande, SAGE, and GALLEX observatories have revealed a pattern of solar neutrino fluxes which is difficult to reconcile with the possible changes in the standard solar model. At the same time, helioseismology provides new constraints on permissible solar model variations. The result is an emerging consensus that the solar neutrino problem most likely involves physics beyond the standard model. The discovery of the MSW mechanism, a solar enhancement of flavor violation engendered by adiabatic level crossings, provides an elegant explanation for the experimental results.

Nuclear theorists played a prominent role in developing many of the analytical and numerical tools for treating the propagation of neutrinos through stellar medium. They have also been involved with proposing new experiments like Borexino and $^{127}$I, and with the efforts to reduce detector cross section uncertainties for $^{37}$Cl, SNO and SAGE/GALLEX observatories.

The primary remaining nuclear uncertainty in the solar neutrino problem is the S-factor for $^7$Be(p,γ)$^8$B reaction. The two available low-energy data sets disagree by $\approx 25\%$. Noticeable progress has been achieved in the theoretical description of the Coulomb dissociation process which can be used to measure this rate using radioactive $^8$B beams. Ab initio calculations of the pp-chain reactions are now within reach of quantum Monte Carlo methods. Initial studies have focused on the weak radiative capture of protons by $^4$He, the source of the most energetic solar neutrinos.

6.2 Nucleosynthesis

Big-bang nucleosynthesis is one of the three cornerstones of modern cosmology. Motivated by the possibility of violent confinement/deconfinement or electroweak phase transitions, nuclear theorists and experimentalists have explored the consequences of inhomogeneities on big-bang nucleosynthesis. Careful work has shown that nucleosynthesis places stringent constraints on such scenarios.

The observed abundances of the presupernova elements up to zinc can now be well reproduced within models of the galactic chemical evolution. Nevertheless some astrophysically important nuclear cross sections are still insufficiently known. Most important is the $^{12}$C(α,γ)$^{16}$O reaction rate which plays a decisive role in both nucleosynthesis and the evolution of massive stars. The theory-stimulated experimental determination of the electric dipole part of this rate was a major milestone of the field in recent years. However, while
microscopic cluster models predict that the $^{12}$C($\alpha, \gamma$)$^{16}$O electric quadrupole S-factor is comparable to the dipole, experimental confirmation is still missing.

The new radioactive ion beam facilities will allow measurements of important reactions that facilitate the leakage of material from the hot CNO cycle, which subsequently leads to nucleosynthesis of elements up to $^{56}$Ni and beyond by rapid proton capture. The theoretical challenge here is to extrapolate the data to the astrophysically important low energies. The predicted enhancement of the low-energy fusion cross section due to partial screening of the nuclear charges by electrons in the target has been observed. Current theoretical modeling underestimates the screening effects for most of the reactions experimentally studied. It is critically important that this discrepancy be resolved, in order to make use of the remarkable efforts currently being made to push laboratory cross-section measurements to still lower energies.

Core collapse supernovae are the major engines driving galactic chemical evolution, ejecting both the hydrostatic burning products and the many less abundant species made by the explosion itself. Two important advances have recently occurred in this area. Network simulations have demonstrated that r-process nucleosynthesis takes place in the hot bubble outside the neutrinosphere of a core-collapse supernova, where neutron rich material driven by neutrino wind mixes with seed nuclei produced by $\alpha$-burning. For the first time the observed pattern and yield of the synthesized elements can be understood. Second, careful modeling of the inelastic neutral current interactions of neutrinos with nuclei in the mantle of the supernova revealed a new nucleosynthesis mechanism, the neutrino process. New elements are produced by spallation following excitation of giant resonances by inelastic neutrino scattering. The process resolves long-standing puzzles such as the origin of $^{19}$F and the inability of cosmic ray spallation mechanisms to produce the correct $^{11}$B/$^{10}$B ratio.

Simulations of the r-process depend on properties and masses of nuclei near the neutron drip line. Hartree-Fock-Bogoliubov calculations predict a closing of shell gaps for closed neutron shell nuclei near the drip line that, when incorporated into r-process simulations, helps to fill the abundance valley below the mass peak at $A = 130 - 135$, in agreement with observation.

Properties of unstable proton-rich nuclei are important to the understanding of the rapid proton capture process which powers the (Type I) outbursts of x-ray bursters. Their understanding also provides a motivation for continued experimental and theoretical studies of nuclei far from stability.

### 6.3 Supernovae

An important recent advance has been the development of two-dimensional hydrodynamical codes for simulating stellar collapse. These calculations find convective cells forming above the neutrinosphere which sweep colder matter to smaller radii, where it can be more effectively heated by neutrinos. Hot material is carried to the shock by buoyancy without having to pay a large gravitational penalty. Convection appears to increase the deposition of neutrino energy into the shock to the point where the delayed explosion mechanism succeeds. This could be the long-sought solution of the supernova problem. The important challenge is to demonstrate that this success persists when all of the physics is fully modeled, including a state-of-art treatment of neutrino diffusion, and that ejection of synthesized nuclei occurs.
Screening effects for weak interactions in a relativistic plasma, which can substantially increase neutrino mean free paths in matter at densities above $10^{12}$ g/cm$^3$ are being studied along with coupling of plasmon excitations to neutrinos.

An interesting result, independent of the details of the explosion, is that the temperatures of the heavy flavor neutrinos are about 8 MeV while those of electron flavor neutrinos are about 4 MeV. It has been recently emphasized that the cosmologically interesting heavy-flavor neutrinos may undergo an adiabatic MSW crossing outside the neutrinosphere. Matter-enhanced mixing between $\nu_e$ and either $\nu_\mu$ or $\nu_\tau$ occurring anywhere above the neutrinosphere will cause a characteristic temperature inversion, and a distinctive signal in terrestrial detectors sensitive to $\nu_e$'s and $\bar{\nu}_e$'s.

The Gamow-Teller (GT) strength of several fp-shell nuclei, important for the electron capture process in the early collapse stage, has been determined experimentally from (n,p) charge exchange reactions. The shell model Monte-Carlo and Lanczos techniques can successfully reproduce the observed strength. The Monte-Carlo method also allows studies of nuclei at finite temperatures and suggest that the GT strength is roughly constant for $T \leq 2$ MeV. It is found that, in even-even fp-shell nuclei, the pairing between like particles vanishes at temperatures around 1 MeV. The consequences of this phase transition for astrophysical scenarios have still to be explored. Neutral current decay of nuclear excited states, by pair neutrino emission, during the collapse, have also been calculated.

### 6.4 Neutron Stars

Ab initio calculations may be possible for neutron stars due to their quasi-static condition, however, they pose many new challenges. The predictions of conventional nuclear many body theory are in accord with the available data on masses, surface red shifts, rotational periods and temperatures of neutron stars. The maximum density of matter in the core of commonly observed $1.4M_\odot$ stars is estimated to be about four times that in nuclei. Interestingly, nuclear forces seem to give rather small contributions to the energy of matter at such densities, as compared to the Fermi kinetic energy; however they enhance the pressure significantly. In heavier stars, near the maximum mass limit, matter is at much higher density and nuclear forces give large contributions with significant uncertainties.

Substantial progress has been made in the theoretical predictions of the structure of matter in the inner crust, where nuclear matter containing neutrons and protons coexists with pure neutron matter. As the density increases to about half nuclear density the structure of matter changes from that of having drops to rods to sheets of nuclear matter in neutron matter. The pure neutron matter in the crust is predicted to be a superfluid whose angular momentum is carried by vortices spatially pinned by the nuclear matter drops and rods. The dynamics of these vortices, which raise theoretical issues also of interest in condensed matter physics, provide one plausible explanation for the observed glitches in neutron stars.

The possible occurrence of new, exotic phenomena in the core of neutron stars is of great interest. It has been realized recently that drops and rods of quark matter may coexist with hadronic matter over an extended region within neutron stars. The question of pion condensation in neutron star matter is still open. Recent speculations regarding kaon condensation in the core, based on effective chiral Lagrangians, have triggered a great deal of interest in kaon-nucleus interactions.
6.5 Exotic Particles

Weakly interacting massive particles (WIMPS) are a leading dark matter candidate. Experiments exploiting existing and new detectors (e.g., cryogenic Si detectors) have placed important limits on WIMPS. Nuclear theorists have estimated the detector cross sections, including form factors that are important at the expected large momentum transfers.

Modeling of supernovae, and the subsequent understanding of their cooling curves, has provided constraints on the properties of new particles or interactions that could alter that cooling. Some of the important constraints include those on axions, Majorons, neutrino magnetic moments, and neutrino Dirac masses.

6.6 Challenges and Outlook

Solving the solar neutrino problem, successfully modeling the supernova explosion mechanism, and understanding supernova heavy element nucleosynthesis are three immediate problems in stellar physics. They contain new, interesting aspects of neutrino propagation in dense matter. If the resolution of the first involves new neutrino physics, the field is positioned to contribute to the construction of a new standard model. The latter two problems are intimately coupled, since the dynamics of the supernova explosion and the fossil record of that explosion in the synthesized nuclei must be understood within a single model.

Calculations of high density neutron star matter is still an active field with many uncertainties. Better understanding, based on QCD and constrained by available data, of the two- and three-hadron interactions is needed. It is also necessary to determine the density at which the transition from cold hadronic to quark matter occurs. Extracting information on the properties of neutron star matter from the ongoing observations of neutron stars is also a challenging problem.

In the longer term, it is apparent that the nature of astrophysics and astronomy is rapidly changing. The explosion of new instrumentation is providing detailed information on the universe. Increasingly, the interpretation of these new data depends on our understanding of the underlying atomic and nuclear microphysics. Thus our field’s partnership with astrophysics will be increasingly important in explaining the phenomena we discover around us.


7 Connections of Nuclear Theory to Other Areas

7.1 Atomic Clusters

Nuclear physics has been seminal for the development of atomic cluster physics. Since the discovery of spherical magic numbers in the mid 1980’s, theoretical ideas from nuclear physics have made several important contributions. Unlike nuclei, atomic clusters can be made with thousands of particles, and for such large systems a new shell phenomenon, the supershell, was predicted by nuclear theorists. This has seen spectacular confirmation in experiments on sodium clusters, which show shells extending up to the thousands of atoms, and a supershell minimum near \( N = 1000 \).

![Fragmentation data compared with the percolation model. On the left is shown the probability of forming fragments with atomic number \( A \) when silver nuclei are bombarded by high energy protons. The right part of the figure shows the fragmentation of \( C_{60} \) clusters by a Xe beam.](image)

The well-known giant dipole resonance in nuclear physics has a close analog in the Mie resonance of simple metal clusters. Many of the properties of the Mie resonance were anticipated from the nuclear example: deformed splitting, thermal broadening and the existence of a collective mode in \( C_{60} \).

The nuclear physics stimulus has also led to new directions in cluster reaction studies. The fission of charged clusters is one example. Another is the fragmentation of clusters by a high-energy probe. The data show intriguing similarities to nuclear fragmentation, and simple theory with the percolation model gives similar rough descriptions of the fragmentation yields. The comparison is shown in Fig. 6.

Rare gas clusters, especially \( ^3\)He and \( ^4\)He clusters, are even more like nuclei in that they are dominated by short range interactions. Nuclear theorists have pioneered the study of

29
quantum helium liquid droplets by exact quantum Monte Carlo methods and have continued to provide leadership in the current research program on impurity scattering and laser spectroscopy in both physics and chemistry.

7.2 Mesoscopic Physics

Many ideas from nuclear physics have been applied to the study of mesoscopic condensed matter systems. In particular, phenomena that involve the discreteness of electron single-particle levels often have analogies in compound nucleus theory. One example is the conductance fluctuations in small wires and quantum dots. The theory of these fluctuations for diffusion-limited wires was developed by applying theory developed in nuclear physics, namely random matrix models of spectra and precompound reaction theory. Theory also explains the fluctuations in the ballistic electron regime with a similar approach to that used to describe Ericson fluctuations of nuclear reactions. Shell physics and its semiclassical description has been found to be related to the phenomenon of persistent currents in mesoscopic rings. The magnitude of these currents depends on an interplay between the regular spectra of the shell model and chaotic spectra of disordered systems. Finally, the quantum dot provides a close analogy to the compound nucleus. Its spectra with isolated resonances gives a new demonstration of the well-known Porter-Thomas fluctuations. Multiple scattering theory has also been an extremely useful tool in understanding the many-electron states in nanoscale condensed matter structures, such as quantum corals.

7.3 Spin Systems

The close relationship between between lattice field theory and problems in statistical mechanics provides fertile ground for interdisciplinary contributions. One example is the contributions nuclear theorists have made in recent years to the study of spin systems in condensed matter physics. In classical spin systems, the phase structure of the planar x-y model on a two-dimensional triangular lattice was determined and led to the discovery of a new class of multicritical points. A particularly important quantum spin system is the spin $1/2$ two-dimensional Heisenberg model, relevant to high temperature superconductors. For this system, several new approaches were introduced, including a loop cluster algorithm utilizing an improved estimator which has allowed the most accurate Monte Carlo calculation to date of the low energy parameters which are in agreement with the experimental data for precursor insulators of high $T_c$ superconductors.

7.4 Molecular Physics

While algebraic methods were initially developed to make the study of finite, strongly–interacting many–body nuclear systems tractable, the formal techniques are broad in scope and have application to other disciplines. One of the areas in which such nuclear physics techniques have had a particularly large impact is molecular physics, in particular, the use of algebraic theory as a way to describe molecular interactions. By converting the differential Schrödinger equations of quantum mechanics into algebraic equations, it is now possible to attack problems previously deemed intractable, especially for strongly anharmonic molecules.
Some such problems include the study of intramolecular relaxation in large molecules, in particular how energy is shared between the many degrees of freedom of a complex molecule; the study of the polymerization process, in particular how large molecules join to form dimers, trimers, etc., and the role of finite size effects in polymer chains. One can now also compute the complete thermodynamics of complex molecules, including the normalized density of states. Because the computational problem grows only linearly with the number of bonds, it is ideally suited for the study of large molecules and polymers. The understanding of molecular geometries and bond angles as functions of temperatures, as well as the physics of phase transitions, can be treated with nuclear mean field methods.

Nuclear physics techniques have also had an impact on more formal aspects of point groups. One can now incorporate discrete symmetries directly into the Hamiltonian, so that the study of large molecules such as C\textsubscript{60}, with icosahedral symmetry, is possible. Further, since anharmonicities can be introduced from the outset, one can study highly excited states of molecules, which is especially crucial for vibrations of CH and OH chromophores.

The formalism used in nuclear physics which determined the scattering matrix for proton scattering from nuclei to all orders in the eikonal approximation has been applied to electron scattering from molecules with great success.
8 Computational Challenges

A recurring theme in the challenges and opportunities for the future is the exploitation of emerging computer resources to make major advances in the solution of previously intractable many-body and field theory problems. From a qualitative advance in the ability to solve the interacting shell model and the development of exact solutions for the response functions of light nuclei to quantitative lattice calculations of hadronic observables central to understanding the physics on frontier accelerators, advanced computation provides unprecedented opportunities for fundamental developments in nuclear science. In addition, maintaining our traditional leadership role in computational science has important societal benefits, ranging from the education of students and postdocs in computational science, which is essential to the scientific infrastructure, to playing a leadership role in the development of high performance computer technology in this country.

Nuclear science needs to provide adequate access to state-of-the-art computer technology at every level. At the highest end, it should take part in pursuing Teraflops-scale computation in this country, contributing to an effort commensurate with the investment being made for example by Italy and Japan. It should also take the lead in providing the optimal balance of local versus centralized facilities, and in pursuing the exploitation of cost-effective workstation farms and symmetric multiprocessors.

An indication of the scale of resources required to meet the immediate challenges can be seen by looking at Table 1, giving a list of examples for the scale of resources used in current efforts in some of the areas in which we have cited opportunities. For convenience, resources are converted to Gigaflops-years. One Gigaflops-year represents the dedicated use of a computer at a sustained rate of one billion floating point operations per second (“flops”) for the period of one year, or the completion of $3 \times 10^{16}$ floating point operations. For reference, the total resources allocated to nuclear theory at NERSC by the DOE corresponds to about 3 Gflops-years.

To fully exploit emerging opportunities, these resources must grow significantly. For example, in Europe, the dedicated APE QCD machines now provide up to 100 Gflops, and significant new resources would be required in the U. S. to remain competitive. Similarly, substantial increases in the resources devoted to Monte Carlo calculations would be required to accomplish the goals described in this report.

| Research                               | Gflops-years |
|----------------------------------------|--------------|
| Lattice QCD                            | 10           |
| Monte Carlo Shell Model                | 0.5          |
| Conventional Shell Model               | 1            |
| Mean-field Theory                      | 0.5          |
| Variational Monte Carlo                | 0.5          |
| Green’s Function Monte Carlo           | 1            |

Table 1: Currently used resources (in Gflops) in some areas of computationally intensive nuclear physics
9 Appendix: Town Meeting Program

Sunday, January 29:

8:30am – 9:40am Reports from other Town Meetings (Chairman: J. Friar)

  8:30am Welcome (Berndt Müller)
  8:35am Technical remarks (Robert Wiringa)
  8:40am Nuclear structure, low energy reactions, etc. (Witold Nazarewicz)
  8:55am Electromagnetic probes (Xiangdong Ji)
  9:10am High energy heavy ions (Xin-nian Wang)
  9:25am Hadronic probes (Mikkel Johnson)

10:00am – 12:00 Nuclear Structure (Chairman: F. Iachello)

  10:00am Structure of normal and exotic nuclei (Joseph Ginocchio, Los Alamos)
  10:15am Few-body systems and nuclear matter (Rocco Schiavilla, CEBAF/ODU)
  10:30am Exact shell model calculations (David Dean, Caltech)
  10:45am Relativistic many-body theory (Brian Serot, Indiana)
  11:00am Short presentations (Brown, Zelevinsky, Carlson, Wiringa, Dickhoff)
  11:25am Open discussion

1:30pm – 4:00pm Quantum Chromodynamics (Chairman: G. Bertsch)

  1:30pm QCD and hadron structure (David Kaplan, Seattle)
  1:45pm Lattice gauge theory (John Negele, MIT)
  2:00pm QCD vacuum and sum rules (Edward Shuryak, Stony Brook)
  2:15pm QCD light cone approach (Robert Perry, Ohio State U.)
  2:30pm Quark gluon plasma (Joseph Kapusta, Minnesota)
  2:45pm Short presentations (Roberts, Qiu, Strikman, Ji, Banerjee)
  3:10pm Open discussion

4:30pm – 6:30pm Nuclear astrophysics and other topics (Chairman: V. Pandharipande)

  4:30pm Nuclear astrophysics (Karl-Heinz Langanke, Caltech)
  4:45pm Weak Interactions (Michael Musolf, CEBAF/ODU)
  5:00pm Nuclear transport theory, (Jørgen Randrup, LBL)
  5:15pm Applications to other fields (Aurel Bulgac, Seattle)
  5:30pm Short presentations (Olinto, Kim, Bauer, Elster)
  5:50pm Open discussion
  6:30pm Adjourn

Monday, January 30:

8:30am – 10:00am Community and infrastructure issues (Chairman: J. Negele)

  8:30am Outlook at DOE, manpower and jobs (Joseph McGrory, DOE)
  8:45am Outlook at NSF, manpower and jobs (Bradley Keister, NSF)
  9:00am Role of the Nuclear Theory Institute (Wick Haxton, Seattle)
  9:15am Short presentations and open discussion

10:30am – 12:00 General discussion of priorities (Chairman, B. Müller)