# The DNP Town Meeting

on

# Hadronic Physics

Dec 1-4, 2000

at

Jefferson Laboratory

Newport News, VA 23606

*March 2, 2001*

# Contents


**1 Executive Summary** **1**

1.1 Preface . . . . . . . . . . 1

1.2 Recommendations . . . . . . . . . . 1

1.3 The Scientific Case for the Recommendations . . . . . . . . . . 4

**2 Highlights of Scientific Achievements** **14**

2.1 Overview . . . . . . . . . . 14

2.2 Electromagnetic Structure of the Nucleon . . . . . . . . . . 18

2.3 Weak Structure of the Nucleon . . . . . . . . . . 21

2.4 Light Nuclei . . . . . . . . . . 23

2.5 Precision Models of the NN interaction . . . . . . . . . . 27

2.6 Effective Field Theory in Nuclear Physics . . . . . . . . . . 30

2.7 QCD on the Lattice . . . . . . . . . . 35

2.8 Flavor Structure of Hadrons and Nuclei . . . . . . . . . . 36

2.9 Sum Rules and Spin Structure of Nucleons . . . . . . . . . . 39

2.10 New Aspects Of Hadronic Structure and Fragmentation . . . . . . . . . . 42

2.11 Baryon Resonances . . . . . . . . . . 45

2.12 Strangeness Nuclear Physics . . . . . . . . . . 47

2.13 Comparison of the U.S. and global effort . . . . . . . . . . 50

**3 New Initiatives** **54**

3.1 The JLab Energy Upgrade . . . . . . . . . . 54

3.1.1 The Origin and Nature of Quark Confinement: Discovering and Studying the Exotic Mesons . . . . . . . . . . 55

3.1.2 The Quark-Gluon Wavefunctions of the Nuclear Building Blocks . . . . . . . 57
3.1.3 Other New Research Thrusts . . . . . . . . . . . . . . . . . . . . . . . . . 64
3.1.4 The Upgrade Project Summary . . . . . . . . . . . . . . . . . . . . . . . 69
3.2 The Electron Ion Collider . . . . . . . . . . . . . . . . . . . . . . . . . . . . 71
3.2.1 Polarized $\vec{e} \cdot \vec{p}$ studies with EIC . . . . . . . . . . . . . . . . . . . . . . . 72
3.2.2 $e \cdot A$ with EIC . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 75
3.2.3 Accelerator & Detectors . . . . . . . . . . . . . . . . . . . . . . . . . . . 76
3.2.4 Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 78
3.3 The Lattice Hadron Physics Initiative . . . . . . . . . . . . . . . . . . . . . . 78
3.3.1 Motivation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 78
3.3.2 Lattice QCD Resources available Nationally and Internationally . . . . . . . 81
3.4 The Theory Infrastructure Initiative . . . . . . . . . . . . . . . . . . . . . . . 82
3.4.1 Recent accomplishments . . . . . . . . . . . . . . . . . . . . . . . . . . . 82
3.4.2 Nuclear Theory Plan . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 85

**4 Education, Outreach and Societal Impact 87**

4.1 Education and the Role of Universities . . . . . . . . . . . . . . . . . . . . . . 87
4.2 Impact of Nuclear Science . . . . . . . . . . . . . . . . . . . . . . . . . . . . 88
4.2.1 Medicine . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 89
4.2.2 Environment . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 90
4.2.3 Industrial Applications . . . . . . . . . . . . . . . . . . . . . . . . . . . . 90
4.2.4 Energy . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 91
4.2.5 National Security . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 92
4.2.6 Information Technology . . . . . . . . . . . . . . . . . . . . . . . . . . . 92

4.3 Summary . . . . . 93

**5 Facilities** **94**

5.1 U.S. Facilities . . . . . 94

5.1.1 Electromagnetic beam Facilities . . . . . 94

5.1.2 Hadron Beam Facilities . . . . . 99

5.2 Foreign Facilities . . . . . 103

5.2.1 Electromagnetic beam Facilities . . . . . 103

5.2.2 Hadron Beam Facilities . . . . . 106

5.3 Foreign Facility Initiatives . . . . . 110

5.4 An International Perspective . . . . . 113

# 1 Executive Summary

## 1.1 Preface

The Division of Nuclear Physics Town Meeting on Electromagnetic and Hadronic Physics was held at Jefferson Laboratory, December 1-4, 2000. In preparation for the Long Range Plan meeting scheduled for the end of March, 2001, the Nuclear Science Advisory Committee posed a number of questions to the community, the responses to which should provide a strong basis for eventual recommendations in the Long Range Plan. The charge from NSAC to the DNP can be found in Appendix A. NSAC asked first of all about the scientific questions that our community considers most important and their significance for nuclear physics and science as a whole. What has been achieved recently, and what progress can be expected in the near term and over the next decade? What resources, large scale and small scale, financial, technical, and human, are needed to answer these questions? Where do our efforts fit in the framework of international efforts in this field, and what is the expected impact of our program on other fields and society? These questions were addressed in four days of invited talks, contributed abstracts, and extended discussion (see the agenda in Appendix B). The recommendations listed below were put forward during the course of the meeting and voted upon by the participants after more discussion during the final session on Dec. 4. Invited speakers were asked to prepare short papers based on their presentation and these papers provided the raw material for this report. Members of the Town Meeting Organizing Committee (Appendix C) edited it, and, ultimately, all participants in the town meeting had the opportunity to suggest changes and corrections.

We summarize the recommendations in Section 1.2. Scientific justification for the recommendations is laid out in Sec 1.3, and is preceded by a short overview of hadronic physics and highlights since the last Long Range Plan. Sections 2 and 3 represent detailed elaborations of the brief summaries in Section 1.3, with the former focussing on recent achievements and the latter focussing on the details of the recommended new initiatives. The status and plans for current U.S. and international accelerator facilities are described in Section 4. Resources needed for the efficient operation of the U.S. facilities are also noted. Section 5 includes a brief discussion of the educational and outreach activities specific to this community.

## 1.2 Recommendations

Hadronic physics is in full bloom. Since the last long range plan, two major facilities have been commissioned, the CEBAF accelerator at Jefferson Laboratory, in 1996, and the RHIC collider at Brookhaven, in 2000. CEBAF has been a resounding success; it has matched or exceeded, often by a substantial margin, all of its design specifications. Its polarized electron beam, barely considered in the concept documents for the original accelerator, is now the envy of the world; it is used routinely for all experiments and has permitted the study of issues related to spin to an accuracy never before possible. RHIC has only recently begun operations, but even its first two months of running produced a wealth of data on heavy-ion collisions in an energy regime never before achieved. The program of $\vec{p}p$ and $\vec{p}A$ collisions envisioned in the RHIC-SPIN program, which is of high interest to our community, thus looks very promising. Significant upgrades to the MIT and TUNL university-based facilities are beginning to deliver exciting and unique data on hadron structure at long distance scales. The HERMES experiment at DESY over the last five years has, with a leadership role by U.S. physicists, provided substantial insight into the partonic structure of hadrons. We note that with the recent approval for construction of the Japan Hadron Facility, we can now look forward to its completion and to the beginning of its important scientific program in medium energy hadron-beam physics.

A vibrant community of nuclear physicists is now working at these facilities, new young physicists are entering the field, and new ideas are emerging. Our recommendations are laid out on the basis of the three broad areas that are critical to provide the balanced support necessary for progress in hadronic physics: planning and construction of new facilities, an improvement in theoretical tools and support, and resources to maintain vigorous use of existing facilities, both through ongoing operational support of these facilities and through support of university-based research groups. Effective use of existing facilities in the next few years is particularly critical both to meet our science goals and to plan well for the longer term. Our ultimate mission is to serve the public, through development of new scientific ideas, education, outreach, and the development of new technical tools that will have an impact on other sectors of our economy. Our last recommendation is directed towards this goal.

### 1. The JLab Upgrade

**We recommend as our highest priority an upgrade of the CEBAF accelerator at JLab to 12 GeV.** This upgrade will yield critical data on the nature of quark confinement and the quark/gluon wavefunctions of the nucleon, and will extend JLab's international leadership in the study of the transition region between the hadronic and the quark/gluon description of matter.

## 2. An Electron-Ion Collider

**We recommend a vigorous R&D program on accelerator and detector technologies with the objective of producing a detailed proposal for an electron-ion collider with a center-of-mass energy range from about 30 to 100 GeV with a luminosity of at least $\mathbf{10^{33}/A\ cm^{-2}s^{-1}}$.** There is an emerging concensus that the next-generation facility for electromagnetic and hadronic physics should be an electron-ion collider with these characteristics. R & D is necessary to investigate the accelerator/detector tradeoffs and evaluate competing technical solutions for such a facility. It should be completed in time for the next Long Range Plan , so that the facility will become available in timely fashion to build upon the insights gained from new or continuing programs at COMPASS, HERMES, JLab (now and at 12 GeV), RHIC-SPIN and SLAC.

## 3. Support for Theory

We recommend a significant increase in support for nuclear theory to provide key new computational facilities and upgrade theory infrastructure.

- **New Computational Facilities**
  **We recommend funding of the computational facilities necessary for a dedicated, cost- and performance-optimized lattice QCD initiative, sustaining 0.5 Tflops as soon as possible, increasing to 10 Tflops within the next five years.**
- **Enhanced Theory Infrastructure**
  **We recommend increased funding for new positions for students, postdocs, and faculty at universities, for establishing new topical research centers, and for new staff at national laboratories in order to strengthen nuclear theory.** Theoretical research plays an essential role in formulating the fundamental directions of nuclear physics, and is critical to our ability to fully exploit the opportunities created from the wealth of new data coming from our experimental facilities.

## 4. Facility Operations and University Support

Increased support is needed to permit effective utilization of our major research facilities, to exploit unique opportunities through proposal-based funding of experiments at a variety of facilities world-wide, and to provide enhanced support for the university-based groups that carry out much of our research and are the source of our future leaders in the field.

- **Facility Utilization**
  **It is imperative that funding be provided to make effective use of our major**

**research facilities, which include CEBAF, RHIC-SPIN, MIT-Bates, LEGS and TUNL/DFELL HIGS**, given the excitement in the community over the wealth of new data coming from both our new facilities and our pre-existing ones. **In addition, we recommend support for proposal-driven opportunities at other facilities world-wide.** This would include up to two concurrent experiments at the AGS, as well as targeted opportunities at SLAC and Fermilab, and other facilities world-wide (such as HERMES, COMPASS, the Japanese Hadron Facility, etc.) as they arise.

- **University-based Research Groups**
  **We recommend increased federal investment in both people and equipment at our universities.** University-based research groups and laboratories are the lifeblood of our field. These groups must be strengthened if we are to maintain competitiveness in research, provide the best possible training for future generations of scientists for our field, and serve the needs of society.

#### Education and Outreach

Our highest priority in education and outreach must be to attract students in greater numbers at both the undergraduate and graduate level. A significant fraction of Ph.D.'s trained in nuclear physics enter private industry and play an important role in our high technology economy, and undergraduates who get the opportunity of hands-on research develop technical skills that are relevant to most sectors of our society. While we recommend increased federal investment in research universities to help us attract students into physics, we also recognize our responsibility to recruit and retain students from underrepresented groups, and to be advocates for science in the broader community.

### 1.3 The Scientific Case for the Recommendations

#### The Nature of Hadronic Physics

The physics of hadrons, their structure and their interactions, is of profound importance to our understanding of the structure of nature and the structure of matter of which the entire universe is composed. While a highly detailed phenomenology of hadronic processes exists, its explanation in terms of the underlying theory of the basic constituents, quarks and gluons, remains a challenge. The nature of confinement and the manner in which the strong force arises from quark-gluon interactions is a major focus of contemporary nuclear science. Beyond providing a fundamental explanation of nuclear phenomena, a fundamental understanding of confinement and the origin of the strong force will have a deep impact on particle physics, astrophysics, and cosmology.

Hadronic physics encompasses the study of strongly interacting matter in all its manifestations and the understanding of its properties and interactions in terms of the underlying fundamental theory, Quantum Chromodynamics (QCD). It is a vibrant and growing field, that now includes a large fraction of nuclear physics as well as areas of hadronic structure traditionally considered to be particle physics. The field has a long history, starting with phenomenological descriptions of hadron-hadron interactions and the hadron spectrum, and continuing to present day ideas on the quark-gluon structure of hadrons, heavy quark symmetry, effective field theories, the quark-gluon plasma, and novel color superconducting phases of matter among a host of others. Although many of its deepest questions have challenged us for decades, we now have within our grasp unprecedented opportunities for fundamental progress. Some of these questions are: *What are the origin and dynamics of confinement? What is the physical origin of chiral symmetry breaking? How do we quantitatively construct ground-state hadrons from their fundamental constituents?* and *What is the relationship between the parton degrees of freedom we see at high energies and the low-energy structure of hadrons?* In sum, *what is a hadron?* When we deal with systems of more than a single hadron, we can ask additional questions such as *How are hadrons modified when embedded in nuclei?* and *How is the nuclear force generated from QCD and its symmetries?*

### Major Achievements since the Last Long Range Plan

In the last decade there has been remarkable progress, both at the experimental and theoretical level. The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab is operating well in excess of its original design specifications, with a technology that now offers the possibility of tripling its design energy to 12 GeV. Exciting new results on the structure of the proton indicate unexpected deviations between the charge and magnetization currents. Measurements of tensor polarization in deuteron elastic scattering are described very well by standard nuclear physics to distances as small as one-tenth the size of a single nucleon. As one goes to even smaller scales, either by higher momentum transfer to the deuteron as a whole or by photodisintegration, the underlying quark degrees of freedom may be starting to become evident. Studies of parity violation at MIT-Bates and JLab are beginning to provide quantitative information on the contribution of strange quarks to nucleon structure. It is likely that within the next few years, we will have an experimental picture of the neutron's charge distribution comparable to that of the proton. A large program of experiments investigating the excitation of the $\Delta$ resonance at BNL, MIT-Bates and Mainz has increased the precision with which multipole admixtures can be measured by an order of magnitude, primarily through advances in tools such as polarized beams, targets, polarimeters and out-of-plane detection. Complementary studies at JLab have dramatically increased the $Q^2$ range for what we know about this crucial state. These new data are far from the perturbative QCD limit and reveal fundamental information about the proton's shape and polarizability.

At the higher energies, deep-inelastic scattering experiments at Fermilab have provided a precise measurement of the flavor asymmetry in the quark sea of the proton. The meson degree of freedom in the nucleon appears to provide an effective explanation of the asymmetry. From the HERMES experiment, new tools to study the partonic structure of hadrons are emerging, such as the study of "transversity" and semi-inclusive scattering processes. Advances in hadron spectroscopy have revealed a surprisingly universal pattern of slowly varying hadron mass gaps between orbitally-excited and spin-excited mesons as the quark mass evolves from heavy to light quarks. Nonrelativistic quark models provide very good descriptions of the spectra, in spite of the lack of *a priori* justification in the light quark systems.

Advances in theory have also led our field into new directions. A notable example is the newly developed formalism for generalized parton distributions, accessible through deeply virtual Compton scattering. Major improvements in solving the non-relativistic many-body problem numerically have led to very precise predictions of the structure of nuclei up to A$\leq$10. New tools at low energy, such as the effective field theories that reflect the underlying symmetries of QCD, have emerged. These new directions are not only advancing our own field, but are providing new calculational techniques for other emerging research areas such as Bose-Einstein condensation.

## Recommendations for the Next Decade

### A. New Facilities

### The JLab upgrade

The level structure of the hadronic states may provide the key to an understanding of the origin and dynamics of confinement, the most novel and spectacular prediction of QCD. Recently, advances in computer technology have allowed considerably improved studies of hadrons using lattice QCD techniques. Lattice computations indicate that confinement is due to the formation of flux tubes of gluonic field lines which connect quarks. However, it is not understood why these form and what their ramifications on the hadronic spectrum and interactions are. They are believed to be the origin of binding in conventional hadrons, and may provide the basis for a QCD based model of nuclear forces. If flux tubes are indeed responsible for hadronic binding, their excitation should also occur. States where these gluon degrees of freedom are excited in the presence of quarks are called "hybrids." The presence of hybrid states in hadron spectra may be the "smoking gun" for the existence of flux tubes. The mass scale of these excitations is predicted to be just below 2 GeV, and their quantum numbers and decay rates are given by various model and lattice calculations. High quality data from CERN have provided details of the structure of the scalar mesons in this region. Three states are now known with mass near 1.5 GeV, close to the low-lying scalar glueball mass predicted by lattice gauge theory. The current interpretation is that the scalar glueball and the meson nonet are strongly mixed in these three states. The study of their decay modes may provide clear evidence that their structure is beyond the standard $q\bar{q}$ quark model, and involves gluonic excitations. Because the photon carries a unit of angular momentum, it is a very promising probe for these studies. Indeed, a polarized photon beam may provide unambiguous identification of hybrid states having gluonic excitations.

The upgrade will also extend JLab's international leadership in the study of the transition region between the hadronic and the quark/gluon description of matter by a second program that will explore quark and gluon components of the nucleons through measurements of quark distribution functions in the valence region and of exclusive reactions that build on the framework of the newly discovered Generalized Parton Distributions. Probed primarily in exclusive measurements with hard scales, the GPDs describe hard scattering processes that involve the correlations between partons. This new formalism offers an exciting bridge between elastic and deep-inelastic scattering (DIS), *i.e.* in different kinematic limits of the GPDs, one recovers the familiar elastic form factors and DIS structure functions of the proton. The GPDs also provide a direct connection to the unknown parton orbital angular momentum, the last unmeasured component of the spin of the nucleon. The cleanest access to GPDs comes from the exclusive production of real photons, Deeply-Virtual Compton Scattering (DVCS). Measurements of limited kinematic reach are in progress at JLab and HERMES, and fragmentary results have been reported from the H1 and ZEUS collaborations at DESY. Higher energies and luminosities would greatly enhance this type of study. With 12 GeV at JLab, GPDs can begin to be explored systematically for the first time.

The third element of the JLab upgrade program will build on the research underway with the current 6 GeV capability, and extend into the DIS region the studies of the transition from classic hadronic degrees of freedom to perturbative QCD as observed in inclusive and exclusive reactions. With the outstanding polarized source capabilities and polarized targets, polarized deep inelastic scattering will be extended to the region where valence quarks dominate the proton's wave function. Such measurements, combined with future lattice QCD calculations, will provide the essential components to make the bridge between asymptotic freedom and quark confinement. Other aspects of the existing JLab program, such as the investigation of the very short-distance structure of the pion and of light nuclei, will also benefit from the high energies available with the upgrade by improved count rates and/or access to significantly higher momentum transfer. **The above programs motivate the proposed CEBAF upgrade, which was given the highest priority at this Town Meeting.**

The key feature of the upgrade is the utilization of the greatly improved performance of the CEBAF SRF cavities over their design specifications and of the extra space available in the linac tunnel. The existing cryomodules, based on 5-cell accelerating cavities, will be replaced with 7-cell cavity cryomodules, and ten new modules will be installed in the available space along the linac tunnels. The basic layout of the accelerator is unchanged. By converting the existing recirculating magnets from a "C" to an "H" configuration, and adding an extra arc for an additional "half-pass" of acceleration, 12 GeV can be delivered to a new experimental area (Hall D) for the hadron spectroscopy program, and up to 11 GeV can be delivered to the existing experimental halls.

## An Electron-Ion Collider

Essential to an understanding of confinement is an explanation of the manner in which the quarks struck in high energy reactions evolve into the color-neutral hadrons which alone are experimentally observable. This physics is accessed in deep-inelastic scattering, which has been the source of much of our knowledge of the partonic structure of hadrons. In the last decade, vigorous experimental effort in spin-dependent DIS has supplied information on the spin dependent structure functions of the proton, thus illuminating the manner in which quarks and gluons contribute to the overall spin of the proton. The flavor dependence of DIS can be studied via measurement of fragmentation functions; an example is data from HERMES on semi-inclusive reactions in which hadrons were observed in coincidence with the scattered leptons.

A complete description of the spin structure of the nucleon requires the determination of three structure functions, the momentum distribution, $f_1^q(x)$, the longitudinal helicity distribution, $g_1^x$, and a transverse spin distribution function termed transversity, $h_1^q(x)$. Transversity has several properties that make it in many ways a simpler probe of nucleon spin structure than $g_1$. Recent results from the study of pion fragmentation in the HERMES experiment have demonstrated that the polarized DIS experiments planned in the next few years at HERMES, COMPASS, and RHIC will likely provide the first precise estimates of this essential quantity.

With the experimental frontier moving to higher energy and momentum transfer, it is evident that the next generation facility for electromagnetic and hadronic physics must provide high luminosity well into the DIS region. A high-luminosity electron-ion collider is judged to be the ideal machine to address decisively the central issues in hadronic physics. The collider geometry will provide an almost $4\pi$ acceptance and complete kinematic coverage for DIS reactions. A program at energies in the range of the present HERMES and COMPASS experiments will use the high luminosity and collider geometry to study semi-inclusive and exclusive reactions with high precision and much more detail than previously possible. Measurements at the highest energies will extend the accessible range of $x$ and $Q^2$ by as much as an order of magnitude over fixed target experiments. Precise measurements of spin structure functions will be possible down to $x \approx 10^{-4}$ and high enough $Q^2$ that pQCD can be reliably applied. The role of sea quarks and gluons in the nucleon spin can be addressed decisively. It will be possible to probe the quark-gluon structure of the photon, as well as the structure of the light mesons. Collisions of electrons and heavy ions will permit the exploration of high energy soft and semi-hard processes in QCD through measurements at very small $x$. Understanding these small-$x$ processes within the framework of QCD is an outstanding challenge to both theory and experiment. In this regime entirely new many-body manifestations of QCD may become apparent.

To carry out the above program, the electron-ion collider should have a luminosity $\geq 10^{33} cm^{-2} sec^{-1} A^{-1}$ and a center-of-mass energy in the range of 30 to 100 GeV. Such a machine would provide the large kinematic range, high luminosity, and optimal control of spin and flavor necessary for a decisive study of hadron structure in terms of fundamental constituents, in particular, sea quarks and gluons. The use of beams of heavy nuclei would allow, for the first time, a search for gluonic matter of extremely high density. The collider geometry offers the crucial capability of complete event reconstruction in hard scattering processes.

While the basic, science-driven, properties of the collider are reasonably clear, several technical issues related to the design of such a machine still need to be clarified and will require research and development. The precise range of energy tuning required for the science program needs to be defined, as well as the bunch spacing, which is coupled to the detector geometry. Synchrotron radiation from the high energy, high luminosity electron ring will place constraints on the ring magnet design. The ion ring would likely require electron-cooling, and several issues need to be investigated to demonstrate the feasibility of electron cooling at high energies.

This collider should become available in timely fashion in order to build upon the insights gained from new or continuing programs at COMPASS, HERMES, JLab at 12 GeV, RHIC-SPIN and SLAC. **We therefore recommend a vigorous R&D program on accelerator and detector technologies with the objective of producing a detailed proposal for an electron-ion collider within five years.**

### B. Support for Theory

#### Lattice Computational Facilities

Lattice gauge theory has developed into a powerful and essential tool for the understanding and application of QCD. Important contributions to our present understanding of hadronic structure have already been mentioned. We expect that progress in hadronic spectroscopy will follow from a synthesis of results from lattice QCD calculations, empirical quark models, and high-statistics second and third generation experiments. The Jefferson Lab-MIT-Wuppertal Lattice Hadron Physics Collaboration was organized in 1998 with the objectives of full QCD calculations of moments of structure functions and strange quark contributions to the nucleon. In addition, the group is working on optimizing and advancing the relevant computer technologies. Their work on the moment calculations has demonstrated that a terascale machine is essential to further progress.

Algorithms exist that incorporate chiral symmetry exactly on the lattice. Moreover, chiral quark models can be used to extrapolate results from the masses at which lattice calculations are performed to estimate results for the masses relevant to the physical pion mass. The recently developed tools of lattice gauge theory, together with the availability of Teraflop-scale computers, now make definitive calculations of hadron observables possible. QCD has become a crucial tool for hadronic physics, and will be essential to the full exploitation of the new generation of experiments which will be of unprecedented precision and kinematic range. Therefore, **the U.S. hadronic physics community supports the acquisition of dedicated-use, cost-optimized, QCD computer clusters sustaining 0.5 Teraflop operation as soon as possible, and increasing to 10 Teraflops within the next five years.**

The community strongly supports the Lattice QCD Initiative. It can be considered as a "new facility" whose funding is expected to come largely from sources outside the traditional paths available for theory, such as Information Technology. In this sense, it is like the new construction initiatives for experiments discussed above; these will also require new funds. The community also strongly favors increased support for theory infrastructure, along the lines of the recommendation discussed below. The need for such increased support was clear to all, even if there was not sufficient time available during the Town Meeting to carefully consider the priorities among the various elements of the recommendation. The community also did not vote on the relative priority of these two recommendations.

### Enhanced Theory Infrastructure

Research activity in lattice gauge theory, in QCD-based modeling, and in effective theories will be required to resolve the essential issues of hadronic physics. This research activity will require a substantial increase in the number of theoretical nuclear physicists. At the present time, the US community of nuclear theorists is of outstanding quality but lacks sufficient resources to maintain its leadership position in the world. More young theorists must be trained at the graduate level, given the opportunity to mature with postdoctoral positions, and supported in subsequent faculty and laboratory staff positions in order to increase and then continually replenish the cadre of theorists pushing the forefront of nuclear research. Sustaining leadership on the topics pursued by the experimental community at our world-class facilities requires a substantial increase of U.S. nuclear theorists over the present minimal investment. Hadronic physics in particular, and nuclear physics more generally, are characterized by a theory personnel component very much lower than that of its related disciplines. Figures indicate that in 1999 only 20% of the DOE personnel in nuclear physics were theorists, supported by less than 5% of the budget.

The experimental program in hadron physics addresses the fundamental questions of quark-gluon confinement and the related hadronization of high energy partons. Theorists need to develop QCD-based quark models which supersede the naïve constituent quark model. These inquiries will result in a deeper understanding of the origin of the nuclear forces and will have a profound impact on our knowledge of the nuclear equation of state and on neutron star properties, including the possible strangeness content of the neutron star. An example is the recent development of effective field theories that explore the chiral symmetry of the underlying QCD dynamics. These theories can make precise predictions for processes in astrophysics and cosmology. Other major breakthroughs have been made recently in solving the nuclear many-body problem from modern two-nucleon potentials, where, again, precise calculation of reactions important to astrophysics is now possible. The newly discovered generalized parton distributions and the associated parton correlations open a new avenue of both theoretical and experimental investigations.

The hadron physics community recognizes that **the scientific opportunities created by the significant investment in JLab, RHIC, and other experimental programs demand**

**a new and sustained initiative in nuclear theory. We recommend the funding of new students, postdocs and faculty at universities, establishing new topical research centers at universities, and adding new staff at national labs.** In addition, enhanced research support in computing, travel, and student support is key to enhanced productivity.

## C. Operation of Existing Facilities

### Major Laboratory Programs

The CEBAF accelerator has proved to be an incredibly precise and robust tool for nuclear physics, and many important physics results, as detailed in the longer text that follows, have begun to appear from the JLab program. Plans for the near future include a definitive determination of the contribution of strange quarks to the currents in the nucleon, precise measurements of the distribution of charge and magnetism deep inside the neutron, a start on a long term determination of new generalized distribution functions for quarks in the nucleon, and a detailed probe of DIS spin asymmetries approaching the valence quark region. Precision studies of few-nucleon systems and investigation of nuclear medium effects are also a significant component of the ongoing program. **Funding to utilize this outstanding facility to its full potential must be provided.**

As mentioned above, one of the major accomplishments of the last decade has been a significantly improved understanding of the role of quark spins in the determination of the overall spin of the proton. The only experimental estimates of the spin distribution of the gluons, $\Delta G$, come from perturbative QCD analyses at next to leading order of the $Q^2$ evolution of inclusive spin asymmetries, and a single experimental estimate of $\Delta G$ at $x = 0.16$ from a HERMES measurement of wide angle hadron pairs. Both these data suggest that the gluons in fact dominate the spin of the nucleon. Many processes that occur in DIS of longitudinally polarized protons, such as quark-gluon Compton scattering and dijet production, are sensitive to $\Delta G$. The spin program at RHIC is poised to take advantage of this sensitivity. Measurements planned at the STAR and PHENIX detectors in the next five years may give us our first direct detailed measure of $\Delta G$. The community recognizes that the spin program will have a dramatic impact on our understanding of nucleon structure, and looks forward to the timely completion of the ongoing and planned upgrades of the detectors and accelerators needed for RHIC-SPIN. **It is imperative to provide sufficient polarized proton running each year for the next 5-7 years to fully exploit the potential of the program**.

The use of both leptonic and hadronic probes over a wide range of energies and momentum transfers is key to the development of a complete picture of hadronic structure. Meson spectroscopy is an excellent example. Studies based on pion and photon excitation of meson resonances provide a much more complete picture of the meson spectrum than either probe alone. The AGS provides the most intense kaon beams available, and is our primary source of high quality data on hypernuclear spectroscopy. In anticipation of the recently approved next generation Japan Hadron Facility (JHF), major research facilities have been constructed and funded by Japan, and brought to the BNL-AGS. BNL proposes to operate a medium energy program at the AGS which is complementary to the JLab program, primarily based on the unique high intensity kaon beams. It would not involve beam sharing with the high energy program unless its needs were compatible with high energy operation. **The unique beams from the Brookhaven AGS are essential to provide an incisive and balanced program on the physics of strong QCD. The community recommends that a program of up to two high-quality experiments be continued at the AGS.**

**Members of our community have also traditionally carried out important experiments at Fermilab and SLAC and these efforts should be encouraged.** Several experiments with coherent high energy polarized photon beams have recently been approved at SLAC and are expected to run starting in about three years. Plans at Fermilab are less clear at this time. The HERMES experiment at DESY will continue to take data, with substantial U.S. participation, until 2005. The laser-electron gamma ray source (LEGS) operating at the National Synchrotron Light Source at BNL has recently produced a number of interesting results. With their polarized beam and a new unique polarized target, the next few years are expected to yield equally fruitful results.

### University Facilities and Research Groups

A number of university facilities, such as the MIT-Bates Linear Accelerator Center and the Duke University Free-Electron Laser Laboratory, perform forefront research in hadronic physics and serve as a precious resource for educating and training outstanding young physicists. MIT-Bates has brought into operation the South Hall Ring and routinely delivers both extracted and stored high duty-factor electron beams up to 1 GeV. The Bates Large Acceptance Spectrometer Toroid (BLAST) will begin data taking in 2002 and, utilizing polarized internal gas targets and the high intensity stored polarized beam, will produce precise data on spin-dependent electron scattering from the proton and light nuclei. TUNL continues to produce highly precise data on low energy hadronic interactions. The new high intensity gamma ray source at the free electron laser facilty at TUNL promises an important program of measurements on the GDH sum rule, chiral perturbation theory at the pion threshold, and the p-$\pi^0$ scattering length.

University based research groups and laboratories are the lifeblood of the field as well as a vital source of technical support and equipment. **Federal investment in university programs should be strengthened in order to maintain competitiveness in research, to provide the best possible training for future generations of scientists for the field, and to serve the needs of our technology-based society.** University-based user groups provide the backbone for operating the major laboratories. Without the graduate students, postdocs, faculty and staff members of universities to build equipment, and run, analyze, and interpret experiments, efficient operation of these facilities would be impossible. At the same time, these activities contribute strongly to the educational mission of the laboratories and seed the intellectual future of the field.

Outstanding and unique opportunities exist at university based laboratories such as MIT-Bates, using internal targets, and at the Triangle Universities Laboratory, using high-intensity photon beams, and these programs should be vigorously exploited.

### D. The Education Mission

There was an extensive discussion at the Hadronic Physics Town Meeting regarding the various issues related to our education mission. Our discussion is well summarized by the Oakland Town Meetings White Paper on Future Concepts and Perspectives for University-Based Research and Graduate Education. The Oakland report highlights the need for enhanced support of university-based research groups, as discussed above, to educate and train graduate students, and discusses the success of the undergraduate research programs such as REU, RUI and CEU in giving quality research experiences to physics bachelors degree students. The success of the K-12 educational programs at the major labs, such as the BEAMS program at JLab, is well-documented, and we strongly support the re-establishment of the education-based outreach offices at the national laboratories. We emphatically agree that **science education and literacy are critical to the future of the nation. Therefore it is vital that we increase our efforts to recruit and retain scientists, particularly from underrepresented groups.**

There is a continuing need for the involvement of nuclear scientists in our local communities. The newly organized Laboratory Communications Council, made up of Public Affairs Directors from the national laboratories, as well as the ad-hoc DNP Public Information Committee, are examples of the nuclear science community's response to this increasing need for open dialog with community organizations, the media and congressional representatives. We recognize our responsibility to increase our own individual involvement, particularly in media relations. Many university groups and laboratories are actively engaged in outreach activities, but such programs are not always well-advertised. We support the recommendation from the Oakland meeting to increase efforts to better publicize and organize the many individual projects that are taking place within our community with a web-based repository, such as that being developed by the DNP education committee.

# 2 Highlights of Scientific Achievements

## 2.1 Overview

Since the last long range plan, experiments have yielded important new data in many areas of hadronic physics. Theory, too, has made significant advances over this period. The combination has yielded a deeper understanding of the structure of hadrons and the role of strong QCD, and the outlook for progress over the next decade is equally promising. This section includes brief written summaries of the town meeting presentations highlighting achievements since the 1995 Long Range Plan. They are organized around the following questions, posed to each speaker:

- What is the fundamental scientific question addressed?
- What are the major achievements since the 1995 Long Range Plan?
- What are the theoretical and experimental challenges in the immediate future ($<$3 years) and over the duration of the next long-range plan ($\sim$10 years)?
- How does the U.S. effort compare to the global effort?

In this introduction, we summarize some of the fundamental scientific questions suggested by the speakers. The following subsections detail the major experimental and theoretical achievements and the outlook in key areas. The last section contains an assessment of the U.S. role in each area.

**1. What is the ground state structure of nucleons?**

Understanding the structure of the nucleon in terms of the quark and gluon constituents of QCD is one of the outstanding fundamental problems in physics. A major aim of experiments in the last decade and throughout the next is to take detailed "snapshots" of this structure at various levels of resolution. In determining the ground state structure of nucleons and nuclei, this is primarily achieved through measurement of form factors in elastic electron scattering.

Recent measurements show that the charge form factor of the proton decreases markedly relative to the magnetic moment form factor at high momentum transfers. This relative increase of the proton charge distribution at large radii was not predicted and is unexplained at this time. A high precision measurement of the neutron's charge distribution has long been a goal of nuclear physics. A new generation of experiments is poised to provide precise data on the neutron form factor. Provided theorists can reduce the uncertainties related to the target nucleus in which the neutron is embedded, the neutron form factor should be determined almost as well as the proton's. Such precise data on the distribution of charge in the proton and neutron will be vital to constrain theoretical descriptions of nucleon structure. They are also essential for the determination of the strangeness elastic form factors of the nucleon derived from neutral weak form factors.

Measurements of the weak interaction form factor of the nucleon directly address its quark substructure. They will contribute to answering such questions as: *What is the flavor structure of currents in the nucleon? What is the origin of the nucleon's anomalous magnetic moment?* By combining the electromagnetic and weak interaction form factors of the proton and the neutron, the $u$, $d$ and $s$ currents in the nucleon can be separated. Because the $s$ quark contribution arises exclusively from the $q\bar{q}$ sea in the nucleon, it is particularly interesting. Such data will permit an important test of lattice calculations that include dynamical sea quarks.

**2. Can the description of multi-nucleon systems be connected to QCD?**

A basic issue in few-body nuclear physics continues to be the role of quarks and gluons in the structure of atomic nuclei. Understanding the origins of the effective nucleon-nucleon interaction from the fundamental constituents of QCD has now become a realistic goal. New measurements of electromagnetic form factors in light nuclei and of deuteron photodisintegration push the limits of traditional few-body theory. Recent searches for enhancement of antiquarks or pions in nuclei, and the search for medium modifications of nucleons and mesons, will provide additional information about the nature of nuclear binding. Precise studies of three-nucleon forces that are consistent with chiral symmetry provide a benchmark for both traditional NN interaction models and for NN effective field theories.

A major breakthrough has been made in solving the nonrelativistic many-body problem numerically with Green's Function Monte Carlo methods. The work has proved, without the approximations of earlier work, that nuclei arise in nature primarily because of the strong two-nucleon interaction. The questions that can be addressed are: *Can we accurately measure and understand the strong nuclear interaction? Does this understanding allow us to construct a successful model of nuclei and their reactions from the underlying currents and interactions?* Application of precision NN interaction models to inaccessible reactions such as the very low energy cross sections relevant to astrophysical processes provides an important bridge between nuclear physics and our understanding of stellar energy production neutrino yields from the sun.

A fundamental challenge facing the nuclear physics community is the development of a theory that describes the properties and dynamics of the strongly interacting mesons and baryons that is consistent with QCD. Effective Field Theory (EFT) allows one to calculate perturbatively about the symmetry limit, *e.g.,* the almost perfect chiral symmetry of QCD. This is vital not only for understanding nuclear structure and multi-nucleon processes, including electroweak probes, under normal conditions, but also for making reliable predictions for processes that are not accessible to controlled measurement, such as those that exist in supernovae, or during hadronization following the formation of a quark-gluon plasma.

Recent advances in EFT approaches are addressing this challenge. Traditionally, in the context of chiral perturbation theory, this method has been applied to the physics of pions of energies smaller than the chiral symmetry breaking scale, which is comparable with the nucleon mass. Currently, it is being extended to address many-nucleon interactions. These effective field theories have the potential to provide a systematic and quantitative tool to study the low-energy properties of nuclei, and, when combined with future lattice QCD calculations, may directly connect QCD to nuclei.

### 3. What Is the partonic substructure of hadrons?

Deep-inelastic scattering (DIS) experiments have provided much information on nucleon structure functions over a wide range of Bjorken-$x$ and $Q^2$. The $Q^2$-evolution of these structure functions is well described by perturbative QCD and provides an important confirmation that QCD is the correct theory for the strong interaction. In contrast, many features of the structure functions, such as the $x$-dependence, the flavor and spin structures, and the nuclear dependence, cannot be described by perturbative QCD; their understanding requires non-perturbative QCD at the confinement scale. The interplay between perturbative and non-perturbative QCD makes the study of parton distributions a challenging subject for experimentalists and theorists.

Our relatively poor understanding of the non-perturbative aspects of parton distributions in hadrons was reflected in several major surprises discovered in DIS experiments. The famous "EMC" effect showed that the quark distributions in nuclei are significantly different from those in free nucleons. Polarized DIS experiments revealed the so-called "spin-crisis", suggesting that only a small fraction of the proton's spin is carried by quarks. The observation that the Gottfried sum rule was violated suggested a large asymmetry between the up and down sea quarks in the nucleon.

Many outstanding questions in hadron physics remain that can finally be addressed with advances in both theoretical and experimental tools: *What is the flavor decomposition of parton structures in the nucleon? What are the mechanisms for generating sea quarks in hadrons? What is the quark and gluon content of nuclei? How is it different from that in a free nucleon?*

Detailed study of the spin and flavor structure of the nucleon offers a unique opportunity to examine QCD through the test of sum rules like the Bjorken [Bj66] and Gerasimov-Drell-Hearn (GDH) [Ge66, Dr66] sum rules. Both connect an intrinsic property of the nucleon (the axial coupling constant or the anomalous magnetic moment) to the spin response. However, while the Bjorken sum rule probes the theory at very short distances where incoherent scattering from the constituents dominates the spin response, the other probes the coherent behavior of the constituents in a region where the resonance excitations provide most of the spin response.

Recently a generalized version of the GDH sum rule valid at all momentum transfers has been derived [Ji99, Ji00]. Two well-established techniques, the Operator Product Expansion (OPE) and chiral perturbation theory, have allowed a tentative exploration of the intermediate region of momentum transfer. Progress in both phenomenological models and in lattice QCD will likely offer new opportunities to understand the dynamics in this region. Data are just becoming available that explore the generalized versions of the sum rules at moderate momentum transfer where nucleon resonances dominate the excitation spectrum, and that probe the electric and magnetic susceptibilities of the nucleon.

One of the most important and remarkable aspects of QCD is confinement. This property of the strong interaction prevents the observation of quarks in isolation, and is responsible for both the structure and the formation of all hadronic matter. It is becoming increasingly clear that hadronic structure and formation must be studied *together*: new fragmentation effects provide a *tool* for probing new hadronic structures, and vice versa. The goal of such studies is to enhance our understanding of confined systems by exploring new degrees of freedom. Recently developed partonic structure functions will answer basic questions about transverse spin distributions, orbital motion, partonic correlations, and transversity. New aspects of hadronization will help provide related insight on the length scale, spin transfer mechanism, phase coherence and correlations between spin and angular momentum in the hadronization process. Each of these aspects of the problem represents a *qualitatively new* piece of information that will guide our intuitive and quantitative understanding of the behavior of confined systems.

### 4. What do the spectra of hadronic states tell us about the interactions of quarks and gluons?

The primary goal of hadron spectroscopy is to determine the relevant degrees of freedom and the effective interactions of quarks and gluons. Like atomic spectroscopy, the spectrum yields important information about the underlying force among the constituents. On the other hand, hadron spectroscopy has many additional features, like the partial decay widths, which must be measured before a reasonable picture can be developed.

The most basic elements of baryon spectroscopy are the ground state properties of the proton–spin, parity, charge radius, etc. While the establishment of SU(3) symmetry was a key result in particle physics at the beginning of baryon structure studies, advanced experimental capabilities and the ability to solve models which simulate QCD more closely now allow for a far deeper understanding of the constituents and their effective interactions. The main goals of modern experiments are the full determination of the spectrum of resonance states, identification of possible symmetries in the spectrum, determining the underlying mechanism for the strong decays of the states, and illuminating the microscopic structure of states which are nominally built of three valence quarks.

One of the unique features of QCD is the role that glue plays in the formation of hadron structures, beckoning the question, *Where is the glue in hadron structure?* Major breakthroughs have been realized in the last decade in the search for hadrons lying outside the scope of the constituent quark model such as glueballs ($gg$) and hybrid mesons ($q\bar{q}qg$). Collectively, they represent a new class of "exotic hadrons" with explicit gluonic degrees of freedom. The measurement and understanding of exotic hadrons is critical to forming a complete picture of the confinement predictions of QCD.

Antiproton-proton annhilation at rest has produced the best scalar glueball candidate near 1500 MeV/$c$. Although likely to be a mixed state with other nearby $0^{++}$ mesons, the finding is very much in line with predictions from lattice QCD. Evidence for isovector $1^{-+}$, $J^{PC}$ exotic mesons at a masses of 1370 and 1600 MeV/$c^2$ have also been reported by several groups using both pion and antiproton probes. These tantalizing findings may indicate that we are finally on the verge of the true discovery of the full spectrum of exotic hadrons. The new Hall D program proposed as part of the JLab upgrade is designed to produce and measure exotic hybrid states over their full range of predicted masses and main decay modes.

**5. Can the study of strange particle interactions and hypernuclei provide answers to basic questions in hadronic physics?**

The study of nuclear physics in the strangeness sector provides insights into three topics recognized [Ne98] as priorities in non-perturbative QCD studies: *What is the connection between QCD and the strong force as manifested in nature?* Current efforts in this area include measurements of the spin-dependence of the $\Lambda N$ interaction; precise determination of the $\Lambda N$ interaction can be used to discriminate between models upon which we base our understanding of the $NN$ force. Progress in the $S = -2$ sector also probes our understanding of the strong force as manifested in the interaction between two baryons. *What is the mechanism of confinement?* Models continue to predict exotic mesons and strange dibaryons. Confirmation of these particles, followed by detailed studies of their properties, would represent a significant step towards understanding how matter is built from quarks and gluons. Furthermore, hypernuclei can be used as a laboratory to study the behavior of baryons in nuclear matter since the absence of Pauli blocking allows the bound $\Lambda$ to sample the nuclear interior. *What is the role of strangeness in hadronic matter?* The knowledge gained in the strangeness sector has direct consequences for astrophysical problems, particularly in the study of neutron stars. Some theories suggest that neutron stars have significant hyperon content and their equation-of-state cannot be determined without input from the strangeness sector.

The following sections will highlight specific examples of achievements in the above areas and an outlook over the time scale of the upcoming Long Range Plan.

## 2.2 Electromagnetic Structure of the Nucleon

### Major achievements since the last Long Range Plan

How charges and currents are distributed in the nucleon is central to answering fundamental questions about the quark structure of ordinary matter. The proton electric ($G_E^p$) and magnetic ($G_M^p$) form factors have been studied extensively in the past from unpolarized electron-proton elastic scattering. Polarization measurements are often subject to much less systematic error than has been possible with unpolarized reactions. New data from polarization transfer in elastic $e$-$p$ scattering at Jefferson Lab [Jon00] indicate that the ratio of $\frac{\mu G_E^p}{G_M^p}$ drops to 0.6 at $Q^2$ above 3.0 (GeV/c)$^2$, as shown in figure 1. This depletion of the proton charge form factor relative to its magnetization form factor at short distance scales was not predicted and is unexplained at this time.

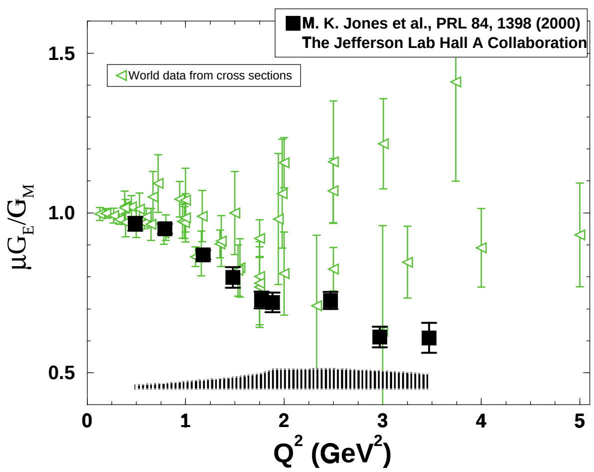


Figure 1: New Jefferson Lab data on the proton form factor ratio, $\frac{\mu G_E^p}{G_M^p}$ as a function of $Q^2$ together with the existing data from unpolarized measurements.

Precise measurement of the neutron's charge distribution has proved difficult over the years. However, at the time of the last Long Range Plan, the first experiments using polarization techniques had been completed at Bates and Mainz, demonstrating the feasibility of such measurements. In the last five years, $G_E^n$ has been measured at low momentum transfer using $d(\vec{e}, e'\vec{n})$ at Mainz [Ost99, Her99], and with $\vec{d}(\vec{e}, e'n)$ at NIKHEF [Pas99]. Experiments have also been carried out with polarized $^3$He targets at Mainz and NIKHEF [Bec99, Roh99, Bul00]. As a result, our knowledge of $G_E^n$ at low $Q^2$ has significantly improved in the last five years.

Although the neutron's magnetic form factor is better known, precise new data have allowed for advances here as well. Recently, $G_M^n$ was extracted from the cross section ratio of neutron and proton knockout from deuterium with uncertainties of <2% in the low $Q^2$ region [Ank94, Bru95, Ank98], but with inconsistent results from the different data sets. New measurements from Hall B at JLab using the same technique over a large $Q^2$ region (from 0.2 to 4.8 (GeV/c)$^2$) [Bro94] are presently being analyzed. The first precision measurement of $G_M^n$ using a polarized $^3$He target was carried out recently at JLab [Xu00]. In all of these examples, correction of the data for target-related effects is an issue.

Whether the proton is deformed or not is a fundamental and longstanding issue, and a large experimental effort has been devoted to further understanding the shape of the proton in the last five years. In QCD the proton is expected to be non-spherical, because of the color hyperfine interaction. The proton's shape can be addressed by studying the $N \rightarrow \Delta(1232)$ transition, and new measurements of the small Electric (EMR) and Coulomb (CMR) quadrupole excitations carried out at Mainz [Pos00, Bec97], Bates [Mer00] and LEGS [Bla97] indicate that the $\Delta$ has an oblate shape, similar in magnitude to the deuteron but of opposite sign. Recent electroproduction data at JLab indicate that the EMR transition remains small up to 4 $(\mathrm{GeV/c})^2$ [Fro99], unlike what one might expect from the simple picture of helicity conservation in pQCD. Additional information can be gained from a detailed multipole analysis, which is presently being carried out with focal plane polarimetry in Hall A at JLab [Sar00] and planned for Bates.

**Short term (<3 years) and long term (<10 years) outlook**

The intriguing $\frac{\mu G_E^p}{G_M^p}$ result at high $Q^2$ from JLab [Jon00] has stimulated an extension of this measurement to momentum transfers up to 5.6 $(\mathrm{GeV/c})^2$ [Per99]. In the limit $Q^2 \rightarrow 0$, a precision measurement of the proton rms charge radius ($r_p$) [Gao00] is planned at Bates using the BLAST apparatus, with the expectation of improving the precision of $r_p$ by a factor of three compared with the single most precise measurement from electron scattering. This level of precision will allow high precision tests of QED from hydrogen Lamb shift measurements and provide reliable tests of Lattice QCD calculations.

Polarization experiments to measure $G_E^n$ continue at JLab and Mainz using deuterium targets. At Bates, $G_E^n(Q^2)$ will be measured with BLAST at $Q^2 = 0.1$ to 0.8 $(\mathrm{GeV/c})^2$ on deuterium and $^3$He. With overall uncertainties $\leq 5\%$ it should be possible to carry out a detailed comparison of $G_E^n$ in the deuteron and $^3$He, allowing a high precision search for the predicted modification of the neutron pion cloud in the nuclear medium. With new data to be published in the next few years, we can expect that our knowledge of the neutron charge distribution will be improved to a level becoming comparable to that of the proton.

Measurements of the proton's shape will continue at Bates with the OOPS apparatus. With the possibility of installation of focal plane polarimetry in the OOPS modules, a unique set of complete polarization measurements would be possible. The study of the $N \rightarrow \Delta$ transition is also an important component of the JLab experimental program. With an energy upgrade of CEBAF to 12 GeV, nucleon electromagnetic form factor and transition form factor measurements can be extended to much higher momentum transfer where pQCD may become applicable.

Electric and magnetic polarizabilities describe the response of a system to applied electric and magnetic fields. Virtual Compton scattering has the great advantage over the use of real photons in that the momentum of the virtual photon may be varied independently of its energy, thus allowing one to study the dynamics of the polarizabilities. At low energy, these fundamental quantities may be calculated in the framework of chiral perturbation theory, while at high energy, there is great interest in the VCS process as a means to study the partonic structure of the nucleon. Recently, a significant experimental program has developed at several laboratories, following initial experiments at Mainz [Roc00] and JLab [Ber93]. In a recent Bates [Sha97] experiment, the large Bethe-Heitler coherent background was suppressed by going out of the scattering plane using the OOPS apparatus. Such studies are expected to multiply over the next few years.

## 2.3 Weak Structure of the Nucleon

### Major achievements since the last Long Range Plan

An ongoing effort has been underway to determine the weak interaction analogs of the nucleon's electromagnetic form factors over a broad range of momentum transfers. Five years ago, this program was just beginning to take shape. The goal of the experiments is to measure $s$-quark contributions to both the charge and magnetization distributions by performing the analog of a Rosenbluth separation of the weak form factors. These weak form factors are determined experimentally by measuring the parity-violating asymmetry in electron scattering. For a spin-$\frac{1}{2}$ target, the asymmetry contains three terms, the charge and magnetization pieces described above, as well as the nucleon axial current. This axial current involves the nucleon anapole moment – the effective parity-violating coupling of a photon to a nucleon. The anapole moment is a measure of the effect of the weak interaction between quarks on the structure of the nucleon. It can be independently determined in these experiments by measuring quasi-elastic scattering from the deuteron at backward angles. The anapole moment is likely to be another important and interesting testing ground of detailed models of the nucleon.

The first generation of parity-violation experiments is now nearing completion, with first results coming from the SAMPLE experiment at MIT-Bates and from HAPPEX at Jefferson Lab. In the SAMPLE experiment, elastic scattering from the proton [Mu97, Sp00] and quasi-elastic scattering from the deuteron [Ha00] are measured at backward angles and low momentum transfer. The hydrogen asymmetry is sensitive to both the weak magnetic form factor and the nucleon's axial current. The deuterium measurement is sensitive primarily to the axial current, and the combined data allow determination of the two quantities independently. The results are shown in figure 2 plotted as a function of the strange quark contribution, $G_M^s$, and the effective axial current, $G_A^e(T = 1)$. It can be seen that the result is rather far from the expectation of $G_M^s \sim -0.3$ predicted by many calculations, and $G_A^e(T = 1) = -0.71 \pm 0.20$. [Zh00] The interpretation of these results is ongoing. For example, there is only marginal agreement with the lattice calculation of $G_M^s$ (ref. [Do98]). The rather large anapole effect predicted by [Zh00] is supported by these results and may be larger in magnitude than expected.

At higher momentum transfer, the HAPPEX experiment [Ani99, Ani00] utilized the two spectrometers in Hall A at JLab to measure parity-violation in elastic electron scattering at very forward angles, resulting in the first measurement of the strange form factors away from the static limit. A unique achievement of the HAPPEX program was the use of strained GaAs to achieve high beam polarization. As is the case for the SAMPLE experiment, the systematic uncertainties due

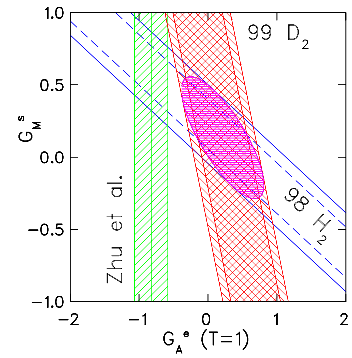


Figure 2: Results from the SAMPLE experiment on hydrogen [Sp00] and deuterium [Ha00]. The contribution of strange quarks to the proton magnetic moment at $Q^2 = 0.1$ (GeV/c)$^2$, $G_M^s$,is plotted vs. the effective isovector axial current seen by the electron, $G_A^e(T=1)$. The vertical band is the theory of ref. [Zh00].

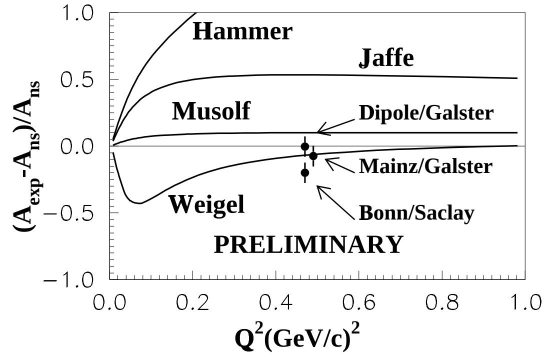


Figure 3: Results from the HAPPEX measurements of parity-violating electron scattering on hydrogen. The three points on the plot correspond to the different values for the "no strangeness" asymmetry ($A_{ns}$) determined with different combinations of neutron electromagnetic form factors.

to false asymmetries are very small, less than 1% of the measured asymmetry, demonstrating the high quality with which the parity-violating asymmetries can be determined.

The deviation of the measured asymmetry from that assuming no strange quark effects is shown in figure 3, along with several predictions. The three data points represent the uncertainty in the HAPPEX result arising from uncertainty in the neutron electromagnetic form factors. As noted above, this error should reduced by upcoming measurements.

**Short term (<3 years) and long term (<10 years) outlook**

Several experiments are planned to follow the initial successful SAMPLE and HAPPEX experiments. A new SAMPLE deuterium measurement is planned at lower momentum transfer to improve the determination of the axial current. The HAPPEX group will also make new measurements on the proton [Lh99] and on $^4$He [Ar00] at low momentum transfer utilizing new septum magnets placed in front of the existing spectrometers (allowing measurements at smaller angles). A measurement on $^4$He at higher momentum transfer [Be91] is also planned. In the case of $^4$He, the measurements are directly sensitive to the $s$-quark contribution to the charge form factor of the nucleus.

The G0 apparatus, presently under construction, will be installed in Hall C at JLab in 2002. The goal of G0 [Bec91] is to measure forward proton asymmetries and backward asymmetries for both the proton and deuteron in order to provide a complete set of observables from which the charge, magnetic and axial neutral weak currents of the nucleon can be determined. G0 will not only provide detailed information about strange quark contributions over a range of momentum transfer, but will also for the first time investigate the axial current over a broad range of momentum transfer.

These measurements will have strong physics impact particularly because they pose cleanly defined questions. The physics impact of the axial current measurements will also be significant, both intrinsically and because many of the same types of contributions arise in precision electroweak tests (both Moller scattering and atomic parity violation) and in neutron beta decay.

## 2.4 Light Nuclei

### Major achievements since the last Long Range Plan

Form factors in elastic electron scattering have been essential in the investigation not only of nucleon structure but also of nuclei. One of the benchmarks for detailed study of the transition from the region where the traditional meson-nucleon picture works well to that where perturbative QCD is applicable is the form factors of the deuteron. New experiments in the last five years have pushed both the development of precision NN models and the exploration of this transition regime. Recently, the alignment known as $t_{20}$ was measured at Jefferson Laboratory [Abo00]. These results, shown in figure 4, are consistent with the traditional meson-nucleon picture of nuclear reactions, and have provided a precise determination of the zero-crossing of the deuteron's charge distribution. However, at very high momentum transfer, new unpolarized data (figure 5) from JLab [Ale99] indicate that the deuteron structure function $A(Q^2)$ is consistent with the quark counting rule picture as well as the nucleon-meson picture. In order to resolve these two pictures, it is essential to extend the form factor measurements of other light nuclei to the highest possible values of momentum transfer, where sensitivity to the quarks alone would be enhanced.

Another avenue for investigating the role of quarks in nuclei is photodisintegration of the deuteron. In general, the momentum transfer given to the constituents in photodisintegration can be substantially larger than that in elastic electron scattering because of the large momentum mismatch between the incoming photon and the constituents of the nucleus. Thus, one might expect to see the effects of QCD in photodisintegration in the GeV region. Indeed, it appears that high energy two-nucleon break up of the deuteron is consistent with the constituent counting rules as shown in the top panel of figure 6. Meson exchange models have failed to explain these data. Recent polarization data in deuteron photodisintegration also show a very interesting and seemingly simple behavior. The induced proton polarization in deuteron photodisintegration vanishes at the high energies as shown in the lower panel of figure 6. This would be completely unexpected from a meson-nucleon picture of deuteron photodisintegration, because of the presence of known excited states of the nucleon.

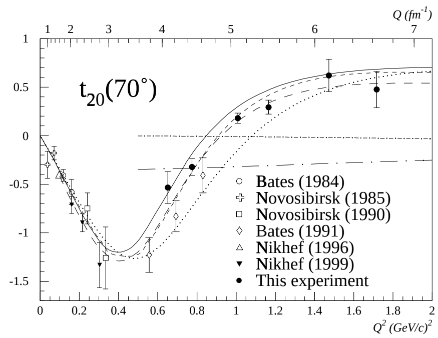


Figure 4: New $t_{20}$ data from JLab (dark circles). The traditional meson exchange calculations of $t_{20}$ agree best with the data.

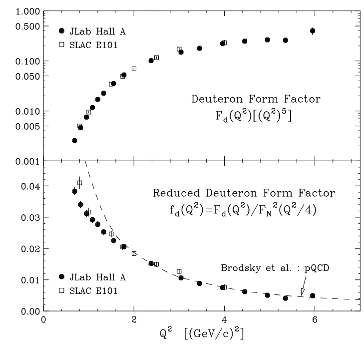


Figure 5: High momentum transfer data on $A(Q^2)$, showing the possible onset of scaling indicative of quark counting rules.

Another important issue is whether there is a pion or light antiquark excess related to the binding of nucleons into a nucleus. Traditional theory [Fri83, Pan94] of nuclear interactions predicts a net increase in the distribution of virtual pions in nuclei relative to that of free nucleons. Nevertheless, this pion excess has yet to be observed. Drell-Yan experiments [Ald90] have failed to observe an excess of antiquarks in nuclei. New preliminary results [Jac00] from Jefferson Lab indicate that there is no observable pion excess in electropion production, A(e,e$'\pi$). Recent theoretical analyses [Kol98] have suggested that the pion excess in nuclei is more difficult to observe than previously believed. It is suggested that the pion strength occurs in the tail of the response function where the experiments performed to date have little or no sensitivity. This is an open question and the resolution of this issue is important.

A celebrated example of medium modification is the EMC effect, in which deep inelastic scattering from nuclei and free nucleons exhibit different parton distributions. This effect is well-documented in heavy nuclei, and while many models exist to explain the effect, none are well accepted. Light nuclei offer a more rigorous study of the EMC effect since exact few body calculations can be performed. A noted example is a recent calculation by Benhar *et al.* [Ben98], in which many of the features of the EMC effect above $x$=0.2 for nuclear matter are explained, and predictions are made for light nuclei. Nuclear pions improve the agreement with the data in the intermediate $x$ range. These calculations can be tested in $^3$He, but little data exist. The EMC effect in these light nuclei will be studied [Arr00] at JLab. In addition to the EMC effect, there now exists what has become known as a "HERMES effect" [Ack00] at low $x$ in nuclei. The ratio of the longitudinal to transverse cross section unexpectedly appears to be enhanced in $^3$He and $^{14}N$ relative to that in the deuteron at low values of $x$ as shown in figure 7. This effect is not yet understood, although first attempts to explain it [Mil00] in terms of a $\sigma$-$\omega$ model have been quite successful. The recently completed experiment E99–118 at JLab as well as data for $^{41}$Kr from HERMES should provide further information about this novel effect.

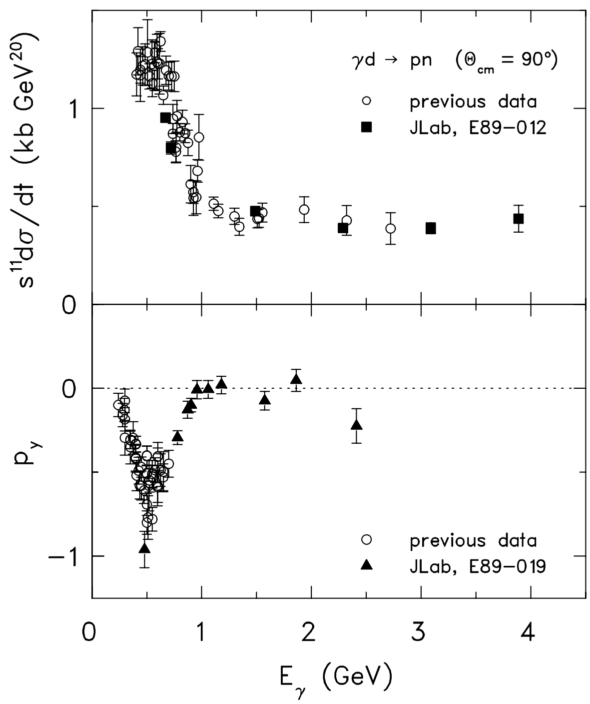


Figure 6: Data for deuteron photodisintegration at $\theta_{cm} = 90°$ as a function of the photon energy. Upper: cross section data from JLab (triangles, refs. [Boc98] and [Sch00], respectively), and other earlier experiments prior to 1996 (crosses). The solid line is a traditional meson-exchange calculation [Lee00], and the shaded area is the quark rescattering model [Fra00]. Lower: Induced proton polarization data from JLab (triangles, [Wij00]) compared with all other existing data.

**Short term (<3 years) and long term (<10 years) outlook**

The prospect for exploring the role of quarks in nuclei through electromagnetic studies of the light nuclei will be continued over the next few years at JLab and with the BLAST facility at MIT-Bates. However, to understand the role of quarks in nuclei, it is essential to extend form factor measurements of light nuclei to the highest possible momentum transfer, where sensitivity to the quarks alone would be enhanced. For this, an energy upgrade at JLab and large acceptance magnetic spectrometers would be necessary.

If we are to understand the traditional model of nuclei, it is essential to observe the pions responsible for the binding. This can be studied at JLab with the $A(e, e'\pi)$ reaction or by using the Drell-Yan process to search for excess antiquarks in nuclei. Presently, the best facility for this search is the 120 GeV injector at FNAL, as discussed further below.

The search for medium modifications in nuclei will continue at HERMES and JLab over the next few years. Such measurements are necessary to fully understand the EMC and HERMES effect. It is likely that light nuclei will prove crucial for these studies since the nuclear part of the calculations can be performed exactly. The JLab upgrade would enable studies over a larger range

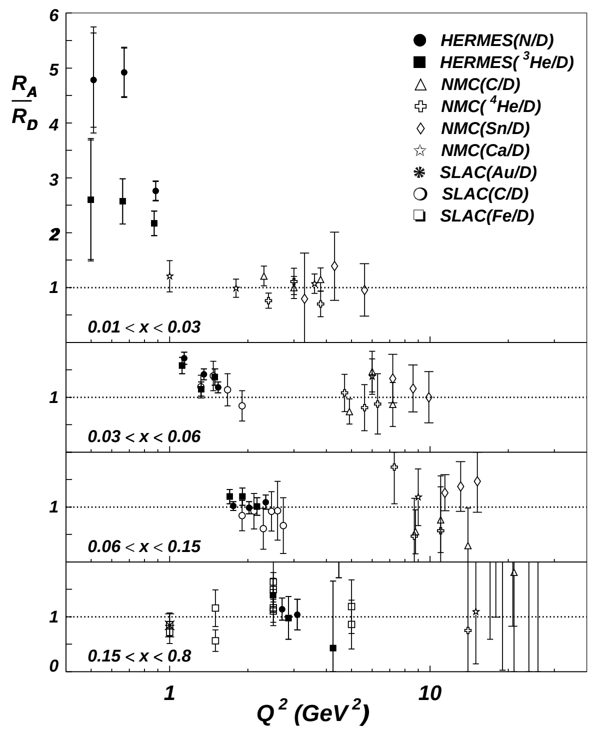


Figure 7: The ratio of the longitudinal to transverse deep inelastic scattering cross section in $^3$He and $^{14}$N compared to that in the deuteron.

of $x$ and momentum transfer than presently achievable.

## 2.5 Precision Models of the NN interaction

### Major achievements since the last Long Range Plan

There has been a tremendous growth in experimental data and theoretical capabilities addressing the NN interaction over the past five years, driven in large part by advances in technology. In the 1993 Nijmegen nucleon-nucleon phase-shift analysis, 1784 *pp* and 2514 *np* 'reliable' data were included up to 350 MeV. In the 2000 analysis, the data set has almost doubled and the analysis has been extended up to 500 MeV. IUCF spin data [Pr98] were vital new input. These precise data have formed the basis for a very accurate phase shift analysis and realistic potential models [Ma96]. These modern potential models reproduce the experimental data essentially within statistical errors.

Important progress has also been made in understanding this rich experimental data set. The model differences in the deuteron, for example, have been explicitly calculated and understood in terms of unitary transformations between different representations of the pion-exchange interaction [Fo99]. In addition, the chiral two-pion exchange interaction has been successfully included in the experimental *pp* analysis [Re99]; the extraction of the correct pion mass in this analysis increases confidence in our understanding of the NN interaction at short distance scales. As discussed above, electromagnetic probes have been decisive in elucidating the structure of the deuteron [Abo00] and the trinucleons [Ma98]. Experimental and theoretical studies of few-nucleon scattering have also rapidly advanced. We can now confront reliable three-nucleon scattering calculations with precision data, providing stringent tests of our understanding. These experiments, combined with data on larger systems, are crucial in exploring the three-nucleon interaction.

In traditional models of nuclear structure, an effective two-body theory in the form of potentials is used, such as the CD-Bonn or Argonne V18, in which isobar (or QCD) degrees of freedom are absent. Such a procedure induces more complicated forces in the effective theory, such as three-body forces, which generally contain a long-range two-pion component, the Fujita-Miyazawa mechanism. Without these three-nucleon forces, the binding energies of light nuclei are too small and the binding energy of nuclear matter is too large at high densities. The most recent three-body force includes a three-pion exchange part and mostly affects the isospin-3/2 part of the force. This part of the force is especially interesting since it is the part that is important in neutron star calculations. Presently it is best constrained by the binding energies and charge radii of neutron rich light nuclei.

An important question, for which polarization measurements in hadron scattering have been essential, is the understanding of the spin-dependent part of the three-nucleon force. Recently, Witala *et al.*, [Wit98] demonstrated the importance of the three-body force at large reaction angles for nucleon-deuteron elastic scattering. To address this, new polarization experiments in proton-

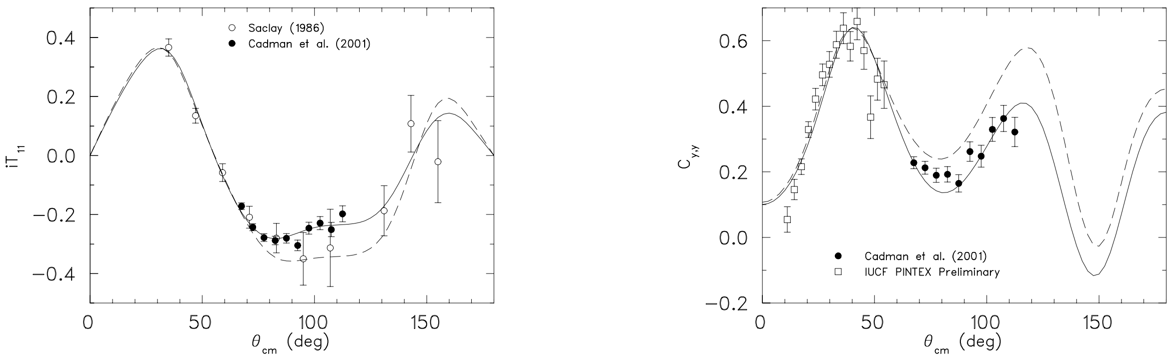


Figure 8: Polarization data for proton-deuteron elastic scattering at IUCF. The dashed curve represents only the two-nucleon force, CD-Bonn, while the solid curve also includes the three-body force, Tucson-Melbourne. There is substantial sensitivity to the three-body force at large scattering angles.

deuteron scattering were carried out at IUCF [Cad00], RIKEN [Sak00], and KVI [Bie00], and some results are shown in figure 8. The calculations of polarization observables are significantly modified by the three-body force. Generally, the corrections are in the right direction, but the magnitudes are not correct, especially for the obervable $A_y$ where the proton beam is polarized and the deuteron target is unpolarized. Problems in describing $A_y$ persist even at low energies and may be an indication of a tensor part to the three-body force. High-quality data are essential in determining the spin-dependence of the three-body force, and future experiments are planned at both IUCF and RIKEN.

Dramatic progress has also been made in calculations of more complex nuclei starting from realistic two- and three-nucleon interactions. At the time of the 1995 Long Range Plan, it was clear that realistic two-nucleon interactions could be used to provide a comprehensive picture of 3- and 4-nucleon systems, including their electromagnetic properties. However, only the very first calculations of nuclei beyond A=4 had been attempted. By now it has been clearly demonstrated that the spectra of light nuclei up to A=10 can be reproduced with realistic models of the NN interaction augmented by small three-nucleon interactions [Wir00] (figure 9). In addition, the first calculations of other observables, including electromagnetic form factors [Wir98] and beta decays [Wipc], have been very successful. These successes give confidence that the models can be made more accurate and used to provide a microscopic understanding of nuclear processes.

Confidence in this microscopic model of nuclei is crucial for calculations of low-energy capture reactions important for astrophysics and fundamental symmetries issues. In studies of the *pp* capture reaction [Sc98], it has been demonstrated that the model dependence is reduced to much less than 1% if the two-nucleon weak currents are constrained by tritium beta decay. Studies in larger systems have shown how important microscopic calculations can be. The recent calculation of weak capture in A=4 [Ma00] demonstrates that the cross section for the production of the *hep* neutrinos is roughly a factor of five larger than previous predictions. Investigations of the $\alpha - d$

capture process [No00] demonstrate that one can simultaneously include the short-distance physics of realistic NN interactions and the clustering properties so important in low-energy reactions.

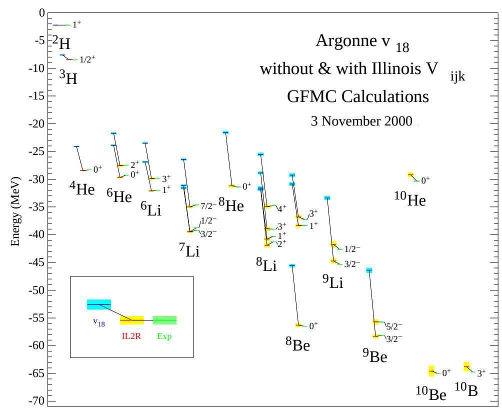


Figure 9: Light Nuclear Spectra from Realistic Interactions

**Short term (<3 years) and long term (<10 years) outlook**

Exciting immediate opportunities exist in theoretical studies of light nuclei and their reactions utilizing realistic interactions and currents. Precise measurements of electromagnetic observables will allow us to test and refine our models of the nuclear current; these models can then be used to more reliably predict observables ranging from low-energy cross sections of importance to astrophysics through high-momentum transfer studies of the nuclear form factors and reactions.

Increased capabilities in the study of dynamics in 3- and 4-nucleon systems and low-energy reactions in all light nuclei are essential. Properties at higher momentum transfer require, at a minimum, relativistic approaches to nuclear structure and dynamics. Exact calculations for low-energy reactions and responses up to A=10 now appear within immediate reach. The basic response of nuclei to electroweak probes remains a very difficult problem, but experimental and theoretical efforts now are converging to make a much broader and more direct investigation possible. Low-energy reactions in light nuclei are important in a variety of fields ranging from astrophysics to fundamental symmetries. Exact calculations of these processes will enhance both our microscopic understanding and our ability to calculate processes that cannot be directly measured.

The best known means for dynamical studies of the three-body force is polarization in proton-deuteron elastic scattering and break-up reactions. At present, IUCF is the only facility that can pursue this with polarization of both target and beam. For example, asymmetries in the break-up channel, planned in the next few years at IUCF, are the most sensitive observables to detect the three body force. However, with the sharp cut-off date at IUCF, it is not clear that these studies can be completed. At present, there is no other facility either existing or proposed that can perform the necessary studies. Complementary studies are continuing at RIKEN where elastic proton-deuteron scattering can be studied with polarized beam and a polarimeter. Together these data will provide valuable constraints on our understanding of the spin dependence of the three-body force.

It appears possible to study much larger systems using combinations of auxiliary-field and diffusion Monte Carlo. The great advantage of these new methods is that computational time grows with roughly the fourth power of system size rather than the exponential scaling obtained with present-day methods. Initial studies in nuclei like oxygen and calcium are expected within the next few years, as well as calculations of dense matter. Such calculations will test present-day methods like coupled-cluster and integral equation techniques, and also extend them to regimes that are not presently accessible. Over the longer term, accurate microscopic models and dramatically increased computational capabilities will greatly expand the scope of such approaches. More accurate studies of dynamics, in particular exclusive processes, should become possible in the light nuclei. Simultaneously, new algorithms will be developed to let us probe a variety of processes in medium and heavy nuclei, exploring astrophysical reactions, fundamental symmetries, and the electroweak properties of nuclei and dense matter, all from the same microscopic basis.

### 2.6 Effective Field Theory in Nuclear Physics

Effective field theory (EFT) is an approach that organizes quantum field theories according to hierarchies of physical scales [Man96]. It is the most general description consistent with all underlying symmetries and physical principles, and the uncertainty associated with an EFT calculation of any observable can be estimated and controlled. The Standard Model of electroweak interactions, which describes observables at energies below the scale of supersymmetry breaking, is a beautiful example of an EFT. Its reliability and rigor are undisputed.

It is sometimes the case that, in a particular limit of the parameter space of the underlying theory, additional symmetries become manifest, e.g., chiral and heavy-quark symmetries in QCD. The EFT then allows one to calculate perturbatively about the symmetry limit. To describe hadronic interactions, a dual expansion in the up and down quark masses, $m_u$ and $m_d$, and in the momentum of external probes is required. This approach was pioneered by Weinberg [We67] and has been successfully applied to mesons, including both two and three flavors [Ga82], and to single nucleons (for a recent review see [Me00]). This body of work, collectively known as chiral perturbation theory ($\chi$PT), provides a cornerstone in our understanding of QCD and is the only rigorous way in which to encode the entire body of QCD predictions at low energy. Nevertheless, challenges remain in its development.

Influential work by Weinberg [We90] in the early 1990's and by many others (see [Bea00] for example) in the late 1990's has led to remarkable progress in describing multi-nucleon systems at low energies. There are, however, many unresolved issues about how best to organize and optimize the EFT expansion, in particular as regards the treatment of the pion. Resolution of these issues is essential in order to develop a systematic expansion about the chiral limit and to push the range of validity of the EFT beyond the Fermi momentum of nuclear matter.

## Major achievements since the last Long Range Plan

*Chiral Perturbation Theory*

Chiral perturbation theory was first introduced [We67] over 30 years ago, and subsequently developed by Gasser and Leutwyler [Ga82], who wrote down the most general counterterm Lagrangian for mesons at one-loop order that included ten *a priori* unknown parameters, commonly known as the $L_i$'s. Empirical values for the $L_i$ are obtained by comparing the predictions with experiment. Examples are shown in Table 1, where predictions are compared with experimental determinations for quantities that receive contributions from just two of the constants, $L_9$ and $L_{10}$. The agreement is excellent, except perhaps for the for the electric polarizability of the $\pi^+$, where there is some disagreement between the experimental results that requires further study.

| Reaction | Quantity | Theory | Experiment |
|---|---|---|---|
| $\pi^+ \to e^+\nu_e\gamma$ | $h_V\,(m_\pi^{-1})$ | 0.027 | $0.029 \pm 0.017$ [Pd96] |
| $\pi^+ \to e^+\nu_e e^+ e^-$ | $r_V/h_V$ | 2.6 | $2.3 \pm 0.6$ [Pd96] |
| $\gamma\pi^+ \to \gamma\pi^+$ | $(\alpha_E + \beta_M)\,(10^{-4}\,\mathrm{fm}^3)$ | 0 | $1.4 \pm 3.1$ [An85] |
| | $\alpha_E\,(10^{-4}\,\mathrm{fm}^3)$ | 2.8 | $6.8 \pm 1.4$ [An83] |
| | | | $12 \pm 20$ [Ai86] |
| | | | $2.1 \pm 1.1$ [Ba92] |

Table 1: Predictions of $\chi$PT and data for radiative pion processes.

In the extension of $\chi$PT to include baryons, it has been found that in order to have consistent power-counting it is necessary to perform a simultaneous expansion in energy-momentum and in inverse powers of the nucleon mass. This procedure is called heavy baryon chiral perturbation theory (HB$\chi$PT) [JM91] and has been used to address most of the problems in low energy baryonic interactions [Me00]. Unlike the case of the mesons, however, there are issues which are still not completely understood. The convergence of the perturbative expansion is slower than in the meson sector, and in some cases chiral SU(3) loops produce large effects which must be partially canceled by corresponding counterterms. However, there are a large number of successful predictions with which to challenge experiment, especially for Compton scattering, both real and virtual. Calculations and empirical results are available for the polarizabilities and generalized polarizabilities [He00], which characterize the response of a system to an applied electromagnetic field. Within the last few years precision experimental results for near-threshold pion photoproduction and electroproduction have also become available. Theoretical calculations at $\mathcal{O}(p^4)$ generally compare well with data but convergence may be problematic for the S-wave multipoles.

In general, a reliable calculational framework in both the meson and single nucleon sectors exists with which to confront precise experimental data. However, important theoretical challenges remain, such as the convergence issues mentioned above, extensions to higher momentum transfer, extensions to processes involving $\eta$ and $\eta'$ mesons, and calculation of the empirical constants from first principles. Work on these issues is ongoing, as well as efforts to extend specific calculations to two-loop order [Ga99], and attempts to marry $\chi$PT to other theoretical efforts such as dispersive methods [Don93] and $1/N_c$ expansions [Fl00].

*Multi-Nucleon EFT*

For very low-energy processes involving energy and momentum much less than the pion mass, an EFT has been developed, EFT($\not\pi$), that allows for a perturbative calculation of processes involving two nucleons. Consider radiative capture, $np \to d\gamma$, and $\nu d$ break-up. The radiative capture cross section, $\sigma_{np}$, plays a central role in predicting the abundance of elements from Big-Bang nucleosynthesis (BBN). For many years an error of 5% was assigned to $\sigma_{np}$. Recently, $\sigma_{np}$ was computed in EFT($\not\pi$), and is now described at the $\sim$ 1% level by a compact analytic expression. The cross sections for $\nu d$ break-up are required input to determine the flux of neutrinos from the sun with the Sudbury Neutrino Observatory (SNO). The differences among existing potential model calculations are at the $\sim$ 5% level, arising primarily from differing treatment of meson exchange currents (MEC's). Using EFT($\not\pi$), it has been shown that in order to perform a $\sim$ 1% calculation of this cross section, only one *a priori* unknown coefficient, $L_{1,A}$ needs to be determined. Comparisons between the analytic EFT calculation and the numerical potential model calculations are shown in figure 10. As it is likely to be many years before lattice QCD can produce a value for $L_{1,A}$, an experiment to measure the cross section of $\nu_e d \to ppe^-$ at the $\sim$ 1%-level is timely and important. EFT($\not\pi$) predictions also exist for other two-nucleon observables, such as $\gamma d \to \gamma d$, that may, with precise experimental data, yield reliable determinations of the polarizabilities of the neutron.

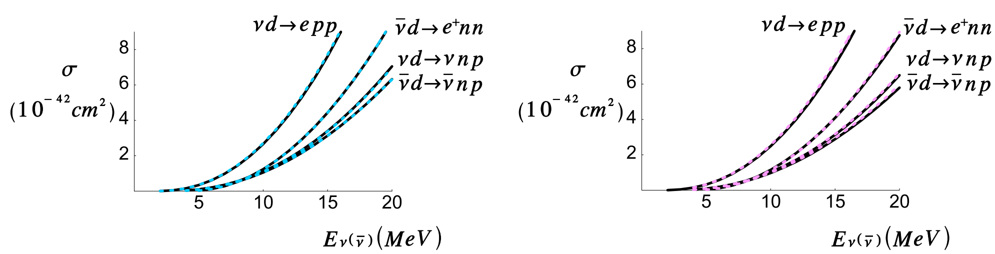


Figure 10: Inelastic $\nu(\overline{\nu})d$ cross sections as a function of incident $\nu(\overline{\nu})$ energy. In the left panel the solid curve is the result of the potential model calculation of Ref. [Na00] while the dashed curve is the EFT($\not\pi$) result with $L_{1,A} = 5.6$ fm$^3$ [Bu00]. In the right panel the solid curve is the result the potential model calculation of of Ref. [Yi89] while the dashed curve is the EFT($\not\pi$) result with $L_{1,A} = 0.94$ fm$^3$ [Bu00].

Significant progress has also been made in the computation of three-body scattering cross sections and in our understanding of how multi-nucleon operators such as the three-body force contribute to low-energy processes. Spectacular results have been obtained for the $nd$ scattering length, computed at next-to-next-to-leading order in perturbation theory to be $a_{3/2}^{\rm EFT} = 6.33 \pm$

0.05 fm. This is to be compared with the experimental determination of $a_{3/2}^{\mathrm{expt}} = 6.35 \pm 0.02$ fm. The calculation of the energy dependence is similarly impressive. The Phillips line, relating the triton binding energy and the three-body scattering length, is recovered, and has been shown to result from the freedom associated with choice of three-body force. In addition, $Nd$ scattering has been studied in the p-wave and higher partial waves, producing very nice predictions that are yet to be confirmed experimentally. These three-nucleon techniques have also been successfully applied to some observables in the area of Bose-Einstein condensation (BEC).

The EFT description including pions has also advanced significantly. Weinberg's original proposal to compute $NN$ potentials using the organizational principles of $\chi$PT has been widely developed. Nucleon-nucleon scattering phase shifts, $\gamma d$ Compton scattering, and other inelastic processes have been computed with great success using Weinberg power counting. Three-body calculations at third order in Weinberg power counting are underway, and preliminary results appear to provide insight into the well-known $A_y$ puzzle. Weinberg's method is intrinsically numerical and is similar in spirit to traditional nuclear physics potential theory. Unfortunately, the renormalization group scaling of operators in this EFT is complicated. Moreover, there appear to be inconsistencies in the handling of divergences proportional to the quark masses, which can potentially lead to uncontrolled errors. In contrast, KSW power counting, where pions contribute at subleading orders in the expansion, and which allows for analytic results, is found not to converge at higher orders in the spin-triplet channels. In exploring these two different types of power counting a large amount of expertise has been acquired, and efforts are ongoing to formulate a consistent and converging power counting, that is sure to involve ingredients from both Weinberg and KSW power-counting schemes.

Work is underway to incorporate the rigor introduced by the EFT framework into the nuclear many-body problem. While this effort is still in its infancy, very encouraging results have been obtained which suggest that these new techniques will lead to a dramatic simplification in this arena.

**Short term (<3 years) and long term (<10 years) outlook**

There are several lines of investigation that need to be pursued in order to make substantial progress in low-energy nuclear physics where one must deal rigorously with the consequences of strong QCD.

In the case of meson and single nucleon observables, methods based on the chiral symmetry of QCD offer perhaps the best way to addresss this challenge in the near term. Chiral perturbation theory is a reliable low energy procedure that is very successful in this regard. For pseudoscalar meson interactions, a successful calculational scheme has been developed, but it remains a challenge to experimentally resolve the apparent discrepancy with the pion polarizability, and to extend the predictive power to higher energy. Combining chiral effective theory with other techniques such as dispersion relations has been able to substantially increase the energy range over which solid predictions can be made. In the baryonic regime, the convergence problems which plague some observables must still be solved. Comparison of theoretical and empirical values of the low energy constants using Dyson-Schwinger as well as other techniques, such as quenched lattice QCD, will also continue.

In the case of two- and three-nucleon EFT, a consistent and convergent power counting must be established for systems of nucleons and pions below the chiral symmetry breaking scale. This will allow for the calculation of processes that are both experimentally accessible and inaccessible and for rigorous comparison with data. A good example would be the extraction of the nucleon anapole moment from low-energy electron scattering. Precise predictions of a multi-nucleon EFT will provide a bench mark for lattice QCD calculations in much the same way as chiral perturbation theory presently does in the meson sector. Including electroweak gauge fields into systems with three or more nucleons is a short term priority. High precision calculations continue to be carried out with EFT($\not\pi$). These calculations of low-energy processes can be continued to even higher orders, allowing for calculations with uncertainties at the fraction of 1% level. There are large theoretical uncertainties in potential model calculations of some electromagnetic processes of great importance in astrophysical environments. It is essential that these uncertainties be significantly reduced.

Early efforts to implement an EFT description of multi-nucleon systems must continue and be extended to nuclei of moderate atomic number. The traditional potential model calculations describe above provide a benchmark. As numerical studies of lattice QCD will be unable to directly compute observables in multi-nucleon systems in the foreseeable future, in order for such efforts to have implications that are not purely academic, a partially-quenched multi-nucleon EFT is required. Ultimately it must be shown that many-body nuclear physics methods emerge as a leading order effect in EFT. This will open the way for systematic improvement of these methods.

A good indication of the recent effort in chiral perturbation theory can be found in the proceedings of the recent Chiral Dynamics meetings which have taken place at MIT (1994)[Be95], at Mainz (1997)[Be98], and at JLab (2000)[Be00B]. In each case about 100 physicists, both theorists and experimentalists, met to discuss developments in the field. Discussions were lively and a program setting out future work was developed. There was a good mix of ($\sim 70$) senior and ($\sim 30$) younger colleagues. In the area of two-nucleon EFT, a conference was held in February 1999 [EF98], with attendance equally split between active physicists in tenured or tenure track positions and younger researchers in non-tenure track positions. There is thus considerable evidence that this is a vibrant area of research attractive to young scientists.

## 2.7 QCD on the Lattice

The only known way to solve nonperturbative QCD with controlled errors is by the numerical solution of lattice field theory. Although the idea of lattice regularization was introduced shortly after the discovery of QCD [Wi74], it is only recently that the algorithmic, analytical and computational tools have been developed to the point of having decisive impact.

### Major achievements since the last Long Range Plan

*Tools of Lattice Field Theory*

Essential tools for using lattice field theory in nuclear physics have been developed in recent years. Two practical methods have now been found for incorporating an exact form of chiral symmetry [Gi82] on a lattice, the domain wall formalism [Ka92] and the overlap formalism [Na95], and both have now been implemented efficiently [Ch99a] [Ed99]. The invention of the meron cluster algorithm [Ch99b], which solves the fermion sign problem in lattice Monte Carlo calculations for a large class of problems, is a breakthrough that opens the door for the first time to the possibility of calculating the properties of dense hadronic matter arising in neutron stars and relativistic heavy ion collisions. In addition, improved actions help control errors associated with finite lattice spacing [Bi96]; the methods of lattice chiral perturbation theory control errors associated with extrapolation to physical quark masses; and random matrix theory has provided quantitative confirmation of aspects of the lattice Dirac spectrum [Ve00]. With these developments, all the tools are at hand to undertake a large class of definitive lattice calculations of nuclear observables.

*Hadron Observables*

Progress in using these tools to calculate hadron observables is currently limited by the availability of computer resources. Thus, results are divided into selected definitive calculations using Teraflop-years at the world's biggest computers, and exploratory calculations demonstrating the feasibility of important physical calculations using tens of Gigaflop-years at modest facilities.

Hadron spectroscopy is a striking success of lattice QCD. *Ab initio* calculation of the hadron spectrum in Japan, where the dedicated lattice QCD resources now sustain 980 Gflops, have shown excellent agreement with the lowest hadron masses of each spin and parity for both non-strange and strange mesons and baryons in full QCD[Ka00]. These calculations instill confidence that, with sufficient resources, lattice QCD will produce comparable agreement for other observables. A number of smaller calculations of interest to nuclear physicists have been also been carried out, including calculation of the lowest negative parity $N^*$ state [Ri00], a comprehensive calculation of the glueball spectrum [Mo99], calculation of hybrid mesons [Ju99], and a study of the existence of the H particle [Ne99].

Calculations of key aspects of hadron structure, including evaluation of the renormalization factors and mixing coefficients for the relevant lattice operators, have been carried out on modest lattices, obtaining qualitative agreement with experiment and providing algorithms and programs that can be used for realistic calculations when world-class computers become available. In particular, recent results include calculation of the nucleon form factor [Ca98], moments of the quark density, helicity, and transversity distributions in both quenched [Go96] and full [Do00] QCD, calculation of the axial charge [Gu99], and calculation of the contributions of strange quarks in the nucleon [Do98].

In addition to calculating numbers to compare with experiment, the lattice has also provided valuable physical insight. The calculation of the color electric and magnetic fields in the presence of quark - antiquark sources has provided vivid evidence for the existence of flux tubes in QCD [Sch98], as well as for their breaking. Gauge fixing to maximal abelian gauge [Kr87] and maximal center gauge [De97] provides insight into the role of color magnetic monopoles and center vortices in confinement. The study of instantons on the lattice [Neg98] has shown the role of instantons and their associated zero modes [Iv98] in the propagation of light quarks in the QCD vacuum, in chiral symmetry breaking, and in light hadron observables.

#### Short term(<3 years) and long term (<10 years) outlook

As is clear from the preceding discussion and the description of the lattice QCD initiative in this white paper, the primary current limitation in using lattice field theory to explore hadron structure and spectroscopy is the availability of computer resources. During the next three years, theorists in the countries that have access to computers sustaining the order of 1 Teraflops will carry out precise calculations with chiral fermions in quenched QCD of the spectroscopic and hadron structure observables described above. On a ten year time scale, theorists with access to computers sustaining tens of Teraflops will be able to perform definitive calculations of these observables in full QCD.

### 2.8 Flavor Structure of Hadrons and Nuclei

#### Major achievements since the last Long Range Plan

Since the last Long Range Plan, significant progress has been made in our understanding of the non-perturbative aspects of parton distributions. Extensive efforts at SLAC, CERN, and HERA have produced new and precise data on spin structure functions in the proton and the neutron. Important advances have also been made in determining the flavor structure of the nucleon sea. Many outstanding issues in hadron physics can be addressed, including the flavor decomposition of parton structures in the nucleon, mechanisms for generating sea quarks, and the quark and gluon content of nuclei as compared with free nucleons.

From a measurement of Drell-Yan cross section ratios of $(p+d)/(p+p)$, Fermilab experiment

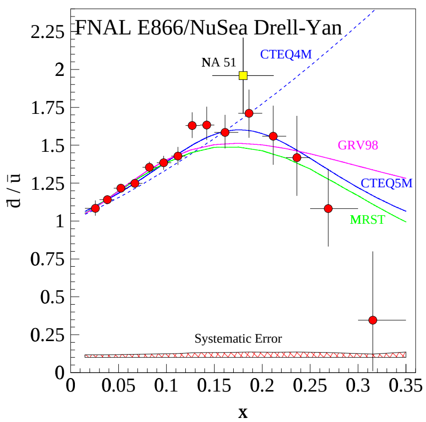


Figure 11: E866 data on $\bar{d}(x)/\bar{u}(x)$ versus $x$ are compared with parametrizations of various parton distribution functions. The data point from NA51 is also shown.

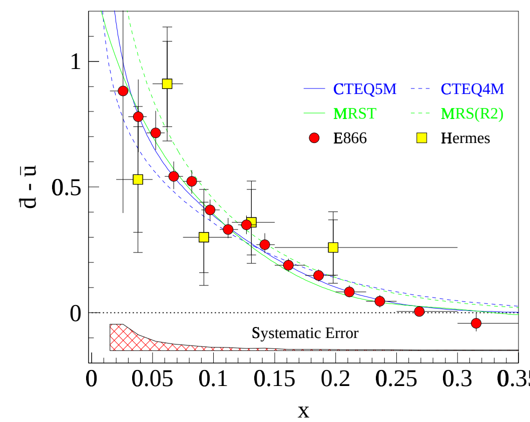


Figure 12: $\bar{d}(x) - \bar{u}(x)$ from HERMES and E866 are shown versus $x$. Parametrizations from various parton distribution functions are also shown.

E866 clearly established the flavor asymmetry of the up and down quarks of the nucleon sea [Ha98]. Figure 11 shows $\bar{d}(x)/\bar{u}(x)$ obtained from E866. The measurement covers the range $0.015 < x < 0.35$ with $\langle Q^2 \rangle = 54$ (GeV/c)$^2$.

By detecting charged pions emitted in semi-inclusive DIS on hydrogen and deuterium targets, the HERMES collaboration [He98] determined $\bar{d}(x) - \bar{u}(x)$ over the range $0.02 < x < 0.3$ with $\langle Q^2 \rangle = 2.3$ (GeV/c)$^2$. As shown in figure 12, the values $\bar{d} - \bar{u}$ from HERMES are consistent with those deduced from E866, even though the two experiments have very different $Q^2$ values.

Results from E866 and HERMES, together with earlier measurements from NMC and NA51, clearly show that the light-quark sea in the nucleon is flavor asymmetric. Many theoretical models have been proposed to account for the origin of this asymmetry. A common feature of most is that the meson degree of freedom in the nucleon can effectively explain the observed flavor asymmetry. As a result, they have distinct implications for the spin and flavor structure of hadrons that can be tested in future experiments.

Pronounced nuclear effects of charmonium ($J/\Psi$ and $\Psi'$) production as a function of longitudinal momentum ($x_F$) and transverse momentum ($p_T$) were observed in 800 GeV p-A interactions [Le00]. The polarization of $J/\Psi$ and $\Upsilon$ resonances in p-A interactions has also been measured [Br00]. The $\Upsilon(2S+3S)$ states were observed to possess large transverse polarization, in striking contrast with the $\Upsilon(1S)$ state. While the heavy quarkonium production data are in principle sensitive to the gluon distributions in nuclei, other nuclear medium effects might make it difficult to extract such information. The nuclear dependence of Drell-Yan cross sections has been measured [Ma99] down to $x = 0.015$, showing good agreement with earlier Drell-Yan data that there is no nuclear enhancement for antiquarks.

**Short term (<3 years) and long term (<10 years) outlook**

The interplay between the perturbative and non-perturbative components of the nucleon sea remains to be understood. Since the perturbative process gives a symmetric $\bar{d}/\bar{u}$ while a non-perturbative process is needed to generate an asymmetric $\bar{d}/\bar{u}$ sea, the relative importance of these two components is directly reflected in the $\bar{d}/\bar{u}$ ratios. Thus, it would be important to extend the $\bar{d}/\bar{u}$ measurements to a wider kinematic region. The new 120 GeV Fermilab Main Injector (FMI) and the approved 50 GeV Japanese Hadron Facility (JHF) present opportunities for extending the $\bar{d}/\bar{u}$ measurement to larger $x$ ($x > 0.25$). Additional $(e, e'\pi^{\pm})$ data from HERMES are expected to further improve the accuracy of $\bar{d}(x) - \bar{u}(x)$. There are also plans for $(e, e'\pi^{\pm})$ measurements using lower energy beams at JLab [Jia00], extending the kinematic coverage towards larger $x$. At the other end of the energy spectrum, RHIC offers a unique opportunity to extend the Drell-Yan $\bar{d}/\bar{u}$ measurement to very small $x$ ($x \sim 0.001$). The asymmetry of $W^{+}$ versus $W^{-}$ production in $p$-$p$ collisions is also very sensitive to $\bar{d}/\bar{u}$. An important advantage of this method is that it is completely free from the assumption of charge symmetry.

The antiquark distributions in nuclei can be further studied in the future at RHIC and at the FMI. For 100 GeV protons colliding with 100 GeV×A nuclear beams at RHIC, one could reach $x$ down to $10^{-3}$. This will extend the current reach in low $x$ by roughly a factor of 20. Qualitatively new information on the sea-quark content in nuclei, such as shadowing and non-linear saturation effects, could be revealed.

The gluon distribution in nuclei is presently poorly known. The gluon content of the nucleus could be measured at RHIC using a variety of tools including direct-photon production, photon-jet production, di-jet production, and heavy-quark production. Such new information is closely connected to one of the physics goals of a possible future e-A collider.

Many important features of nucleon parton distributions, such as the flavor structure and the nature of the non-perturbative sea, find their counterparts in mesons. Almost all information on the quark distributions in mesons came from Drell-Yan experiments using pion and kaon beams. The existing pion Drell-Yan data are mostly for $\pi^{-}$, and the corresponding data for $\pi^{+}$ are surprisingly meager. The situation is even worse for kaons – only a few hundred Drell-Yan events exist for $K^{-}$. With the termination of the 800 GeV fixed-target program at Fermilab, secondary pion and kaon beams will be available only at the Fermilab Main Injector. The relatively low beam momenta are suitable for studying parton distributions at large $x$. One interesting study is to compare the valence quark distribution in kaons versus pions. Early data suggested that the $\bar{u}$ distribution in the $K^{-}$ might be significantly softer than in the $\pi^{-}$. The gluon content of the mesons is very poorly known and any new data would be highly desirable.

The success of the meson-cloud model in explaining the $\bar{d}/\bar{u}$ asymmetry suggests a novel technique to study meson substructures without using a meson beam. The idea is that the meson cloud in the nucleon could be considered as a virtual target to be probed by various hard processes.

Recently at the HERA e-p collider, meson structure functions were measured in a hard diffractive process, in which forward-going neutrons or protons were tagged in coincidence with the DIS events [Ad99]. Analogous measurements could be made at RHIC for $p+p$ collisions. In particular, a Drell-Yan pair in coincidence with a forward-going neutron or proton could provide information on the antiquark distributions in pions at small $x$. Similarly, by tagging on forward-going $\Lambda$, it might be possible to probe the antiquark distributions in kaons. The large-acceptance detectors and the collider environment at RHIC are ideal for such measurements.

Many of the proposed measurements could benefit from a modest increase in beam luminosity at RHIC. To reach the lowest possible $x$ region, the detectors need to cover the smallest possible angles around the beam direction, and modest upgrades of the RHIC detectors can be envisioned. To effectively measure hard diffractive processes, it is necessary to have tagging detectors at very forward angles. Possible upgrades of the existing Zero Degree Calorimeters [Adl00] as well as installation of a "Roman-Pot" [Gu00] detector near the beam axis will greatly facilitate the tagging of forward going neutrons and protons.

## 2.9 Sum Rules and Spin Structure of Nucleons

### Major achievments since the last Long Range Plan

Much of the effort in the study of parton distributions in nucleons since the last Long Range Plan has been focussed on spin structure, and a vigorous experimental program of inclusive polarized deep-inelastic scattering has been carried out at SLAC, CERN and DESY. These spin-structure measurements have tested the Bjorken sum rule and provided quantitative information about the contribution of quark spins to that of the nucleon [An00]. In figure 13 are shown the world's data on the proton and the neutron $g_1$ spin structure function along with a Next-to-Leading Order (NLO) pQCD analysis fit. The experimental test of the Bjorken sum rule at $Q^2 = 5$ (GeV/c)$^2$ using these data shows that it is verified within 5 to 10%. Using the same NLO fit at the same momentum transfer, the net contribution of quark spins to the nucleon's spin is found to be $\Delta\Sigma = 0.23 \pm 0.04$ (stat) $\pm$ 0.06(syst). While an attempt was made to extract the gluon contribution ($\Delta G$) from these data, the error on its determination is too large to draw quantitative conclusions.

A few years ago, a program of experiments to test the Drell-Hearn-Gerasimov (GDH) sum rule using real photons began. The first experiment was performed at MAMI (Mainz) and offers high precision polarized total photo absorption data in the resonance region (photon energies between 200 and 800 MeV). The GDH integral over this range was found to be $223 \pm 6 \pm 13$ $\mu$b. Because of the limited access to a large excitation energy range, a test of the sum rule using only these experimental results is premature. Nevertheless, if the unmeasured region is evaluated using theoretical models, the sum becomes 207 $\mu$b, in good agreement with the predicted value of 205 $\mu$b but with an unknown theoretical uncertainty due to extrapolation into the unmeasured region. Since the experimental test of the sum rule requires measurements over a very large excitation energy range, experiments

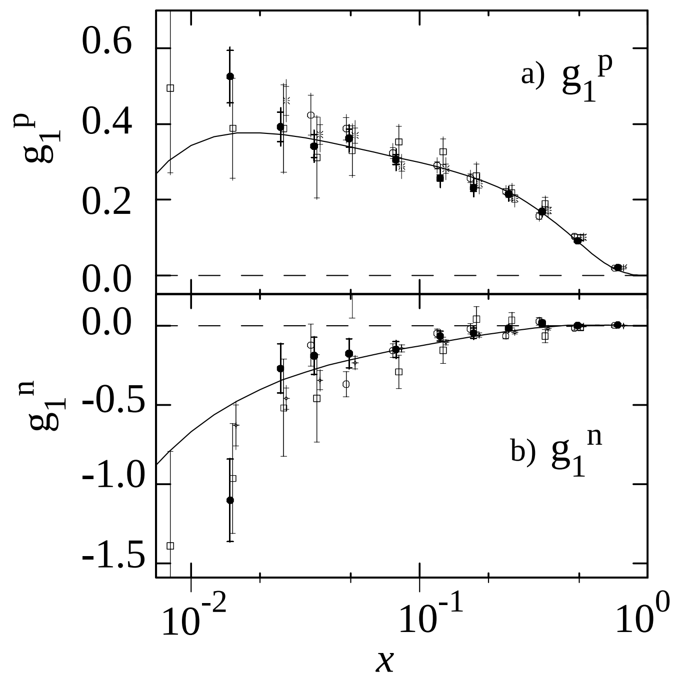


Figure 13: Data for $g_1^p$ (a) and $g_1^n$ (b) evaluated at $Q^2 = 5$ $(GeV/c)^2$. The data are from experiment SLAC E155 (solid circles, E143 (open circles), CERN SMC (squares), DESY HERMES (stars) and E154 (crosses). The solid curves correspond to a Next-to-Leading Order QCD fit.

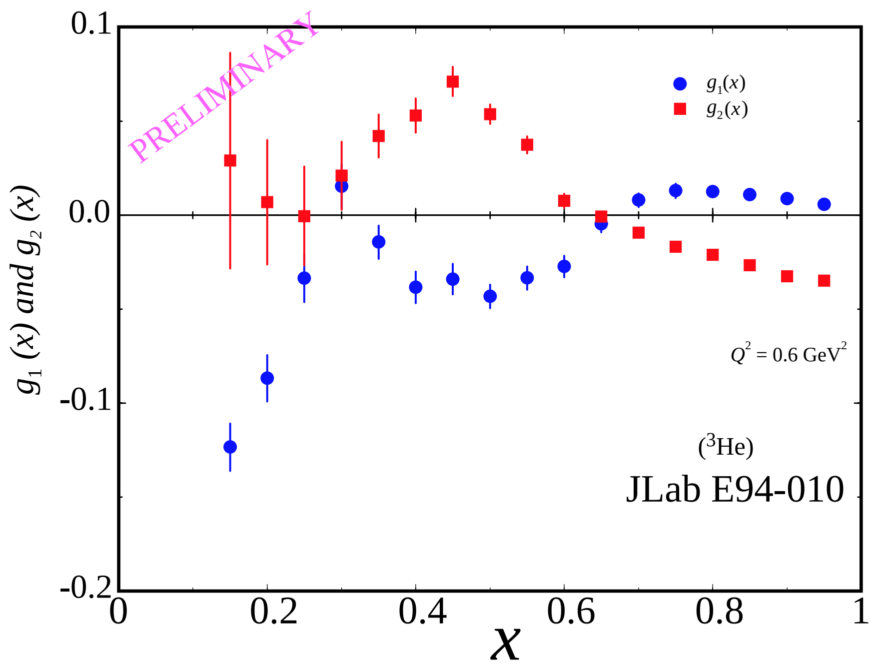


Figure 14: Neutron spin structure functions $g_1$ and $g_2$, as measured with polarized $^3$He, in the resonance region. The peak around $x = 0.4$ corresponds to $\Delta$ excitation.

at nearly all available electromagnetic facilities are now planned in order to extend the polarized photo-absorption cross section data to photon energies from pion threshold up to 40 GeV.

A new program of experiments aimed at investigating the generalized version of the GDH sum rule has recently begun in Halls A and B at Jefferson Lab [Jl91]. This generalized version, valid at all momentum transfers, provides a connection between very low $Q^2$, studied using chiral perturbation theory, and moderately large $Q^2$, where the operator product expansion with higher twist contributions is used. In the region of strong QCD, the GDH integral can be evaluated using Lattice QCD, and it is important to provide data in the intermediate region in order to test the lattice calculations. First experimental results of the spin asymmetries at moderate $Q^2$ in the proton, deuteron and $^3$He are just becoming available from Jefferson Lab. Preliminary results for a neutron embedded in $^3$He from experiment E94–010 in Hall A at Jefferson Lab are shown in figure 14. The precision of the data allows a detailed investigation of the evolution of the GDH sum and its connection to the Bjorken sum. A striking feature is the contribution of the $\Delta$ resonance and the expected relation between $g_1$ and $g_2$, that for the leading twist contributions $g_2 = -g_1$.

**Short term (<3 years) and long term (<10 years outlook)**

It is likely that several of the experiments planned to test the GDH sum rule using real photon beams will be completed within the next five years, at which time we will have a much clearer picture of the evolution of the GDH integral from low to high energy. New experiments in Halls A and B at Jefferson Lab [To97] will provide high precision data for several other key questions. For example, is there a duality in the behavior of the spin structure function $g_1$ in the resonance and deep inelastic region? Recent analysis of inclusive electron scattering data show [Ni00] that *on average* the experimental yields in the resonance region have the same scaling behavior as in the deep-inelastic region where presumably one is scattering from nearly free quarks. Extending this comparison both to polarization observables and to exclusive reactions is of great interest.

Understanding the behavior of the nucleon asymmetry in the valence quark region, comparison of the quark-gluon and quark-quark interactions at low-momentum transfer and developing a more detailed understanding of nucleon polarizabilities are also key questions. The ability to address them will be strongly improved by the larger momentum transfer that would be available with the CEBAF 12 GeV upgrade at JLab. Two examples of experiments that can be carried out are the precison measurement of the neutron asymmetry in the valence quark region and the determination of the $d_2$ matrix element (defined as a linear combination of the color electric and magnetic susceptibility in a polarized nucleon) in Hall A using the combined performance of the Medium Acceptance Spectrometer (MAD) and the 11 GeV continuous high intensity beam.

The quark angular momentum contribution to the total spin of the nucleon will begin to be investigated at JLab using the 6 GeV beam using Deeply Virtual Compton Scattering. If 12 GeV becomes available at JLab, DVCS will be extended and semi-inclusive measurements in the valence quark region will be carried out to perform a spin-flavor decomposition in the nucleon as well as a measurement of the transversity function $h_1$.

## 2.10 New Aspects Of Hadronic Structure and Fragmentation

### Major achievements since the last Long Range Plan

For three decades, deep inelastic scattering (DIS) experiments have provided an increasingly precise map of the momentum distributions $f_1^q(x)$ (or $q(x)$) of the quarks and gluons in the proton. While vigorous experimental efforts in spin-dependent DIS have supplied information on the helicity distributions $g_1^q(x)$ (or $\Delta q(x, Q^2)$), describing the degree to which the spins of the quarks and gluons contribute to the overall spin of the proton, in the last five years it has recently come to light that at leading twist, *three* distribution functions are required for a complete description of the nucleon.

Transversity [Ja92], denoted by the symbol $h_1^q(x)$ (or $\delta q(x, Q^2)$) is the transverse analog of the helicity distribution function $g_1$. Here, 'transverse' denotes a direction perpendicular to that of the incoming probe. Transversity has several properties that make it in many ways a simpler probe of nucleon spin structure than $g_1$. One of the fundamental matrix elements of the proton, known

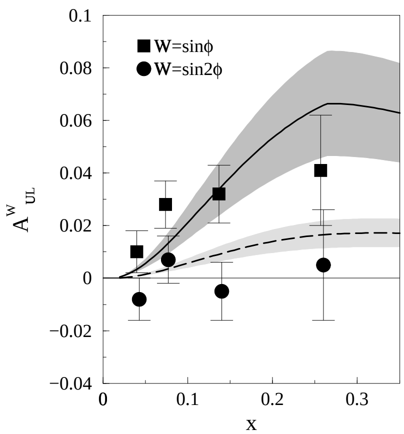


Figure 15: First glimpse of $h_1$: $\chi$QSM calculation compared with HERMES data.

as the tensor charge, is related to the difference of $\delta q(x)$ and $\delta\overline{q}(x)$. It is thus a purely valence object, a feature which offers a promising point of comparison with both phenomenological and lattice QCD calculations. Furthermore, transversity is unique in that the gluon does not contribute. This removes one of the features which significantly complicates the analysis of longitudinal spin measurements, and gives $h_1$ very different properties under QCD evolution compared to $g_1$.

The HERMES collaboration has recently made the first measurement [Ai00] of tranversity by observing a pronounced single-spin azimuthal asymmetry in the production of positive pions from a longitudinally polarized target. This asymmetry is related to $h_1$ and the Collins fragmentation function $H_1^{\perp}$ , discussed below. Figure 15 shows a successful comparison between the extracted $\langle \sin\phi \rangle_{UL}$ azimuthal moment and a parameter-free calculation of $h_1$ in the Chiral Quark Soliton Model ($\chi$QSM ) [Ef00].

Another recent highlight is the identification of a new class of parton distributions, known as *Generalized Parton Distributions* (GPD). Probed primarily in exclusive measurements with hard scales, the GPDs describe hard scattering processes which involve the correlations between partons. GPDs provide a bridge between elastic and deep-inelastic scattering: in different kinematic limits of the GPDs, one recovers the familiar elastic form factors and DIS structure functions of the proton. GPDs have a direct connection to the unknown parton *orbital angular momentum*, which is an essential contribution to the total spin of the nucleon.

Clean access to GPDs comes from deeply-virtual Compton scattering (DVCS) experiments. First data have appeared from HERA: cross sections have been measured by the H1 and ZEUS collaborations, while HERMES has measured the single-spin asymmetry with respect to the polarization of the lepton beam. Single-spin asymmetries for charged and neutral pion production have also been measured by HERMES, but their interpretation is likely to be more complicated than that of DVCS.

The hadronization process (often termed *fragmentation* in DIS reactions) also appears in an astrophysical context, as part of the transition from a deconfined state of free quarks and gluons in the Big Bang into stable protons, the seeds for nuclear synthesis. Hadronization is a complex, non-perturbative process which is related to both the structure of hadronic matter and to the long-range dynamics of confinement, and understanding it from first principles has proven very difficult.

New results in fragmentation studies are beginning to shed light on some of the important identified mysteries of hadron formation. Precise new data from HERMES [Mu00] on hadron attenuation in nuclei have revealed the importance of parton energy loss in describing the formation process [Ko96], and have provided a direct indication that the time scale for baryon formation is much larger than that for mesons.

The E704 experiment at Fermilab found a surprising result: when one scatters transversely polarized protons from an unpolarized proton target, positive pions produced in the reaction show a pronounced tendency to go to 'beam-left', while negative pions prefer the opposite direction [Ad91]. Explanation of this single-spin asymmetry (SSA) requires the presence of a soft (non-perturbative) function in the cross section with distinctive properties: it must be odd under time reversal, and it disappears on integration over transverse momentum $k_T$. Intrinsic $k_T$ is a feature which is neglected in the familiar picture of the nucleon as a collection of collinear non-interacting partons. One candidate for explaining the data is the Sivers distribution function $f_{1T}^{\perp}$ (x,$\mathbf{k}_T$ ) [Si90] which describes the dependence of the quark $\mathbf{k}_T$ distribution on the spin of the nucleon, and is likely related to quark orbital motion. Another equally satisfactory explanation of the E704 data is the Collins fragmentation function $H_1^{\perp}$ [Co93] which relates the momentum distribution of final state hadrons to the transverse polarization of the initial state quark. The results from HERMES [Ai00] and DELHPI [Ef99] suggest that the Collins effect is sizable. The Collins fragmentation function appears to represent a rather astonishing *phase coherence* between the large number of amplitudes required to describe the production of the many particles in the final states of such reactions.

Single spin asymmetries have also been observed in inclusive hyperon production where unpolarized hadron beams incident on unpolarized targets produce hyperons with strong transverse polarization. The pattern of measured polarizations is distinctive [He96] but it is not understood. New results on transverse $\Lambda$ polarization are available from HERMES using quasi-real photons [Be99]. Myriad possible explanations exist and much work needs to be done to understand these intriguing results.

### Short term (<3 years) and long term (<10 years) outlook

New data on several of the subjects presented above are expected in the coming few years. The HERMES result on transversity was obtained using a longitudinally polarized target. The most direct access to $h_1$, however, is obtained with transverse target polarization. This measurement is planned for the next HERMES running period (2001-2006). The RHIC-spin experimental program will explore transversity using a different technique, involving an interference fragmentation function.

Experimentally, exclusive scattering measurements at large $Q^2$ and small $t$ are just beginning. The important question of where scaling sets in can be answered only with data. Considerable statistical improvements in the existing measurements are anticipated as HERMES, H1 and ZEUS continue to take data. Also, spin rotators are presently being installed at HERA that will enable H1 and ZEUS to perform SSA measurements. A dedicated DVCS experiment is also planned at JLab, which will help establish our first basic knowledge about the new field of GPDs.

Improvements in the HERMES spectrometer will permit the collection of a data sample of unprecedented precision on DIS fragmentation to $\pi$, $K$ and other identified particles, from a variety of nuclear targets. Such data will be of great value in understanding the fragmentation process. The results from heavy targets will be useful to the heavy ion community because nuclear effects in both the parton distribution functions and in fragmentation must be understood in establishing the observation of the Quark-Gluon Plasma.

## 2.11 Baryon Resonances

### Major achievements since the last Long Range Plan

Many fundamental issues in baryon spectroscopy are still not well understood, largely due to the lack of data beyond the early high-energy physics experiments of a few decades ago. There is good evidence for about 60 baryons – about 28 $N^*$ and $\Delta$ states (u and d quarks), about 24 $\Lambda$ and $\Sigma$ (one s quark), a few $\Xi$ (2 s quarks), and about a dozen charmed baryons. The very limited knowledge of states beyond the lowest S and P wave supermultiplets provides very weak constraints on models. The possibility of new, as yet unappreciated, symmetries could be addressed with better data. Several $q^3$ states, the so-called "missing resonances" predicted by constituent quark models (CQM) have not been observed experimentally. This has led to the controversial suggestion that perhaps all baryon resonances are quark-diquark states. It is also expected that hybrid $q^3G$ states should exist; these are baryons dominated by the state of three quarks oscillating against explicitly excited glue field configurations.

The goals summarized above need a very large experimental and theoretical effort to come to fruition. The year 1998 heralded a new era in the study of baryon spectroscopy by the first production running of the CEBAF Large Acceptance Spectrometer (CLAS) and by the first production running of the Crystal Ball (CB) spectrometer at the Brookhaven National Laboratory AGS. Both CLAS and the CB are effectively "electronic bubble chambers". By combining moderate resolution for particles over a very broad range of momentum and angles, they can obtain high statistics for a wide range of interactions simultaneously. CLAS runs with electron and photon beams with energies up to 5.6 GeV, large enough to span the entire resonance region across a broad range of momentum transfer ($Q^2$). The CB is a multi-photon detector featuring 94% solid-angle acceptance and good energy resolution. Data were obtained in 1998 with both $\pi^-$ and $K^-$ beams with momenta up to 750 MeV/$c$; further pion and kaon running is expected in 2002. Data on the hadronic couplings of $N^*$ resonances as provided by the CB Collaboration are complementary to the electro- and photo-production data provided by the CLAS Collaboration.

CLAS has now accumulated about 7 billion events with initial states of $ep$, $\gamma p$, and $\vec{e}\vec{p}$. The main reaction mechanism at center-of-mass energy $W$ is the intermediate excitation of an $N^*$ state. One of the major goals of the program is to determine the photocoupling amplitudes, which are matrix elements between the $N^*$ wave function and the $\gamma N$ vertex. For meson photoproduction, such a determination also requires a knowledge of the corresponding hadronic vertex. An intermediate step is to do a partial-wave analysis to ascertain the spin-parity structure of the data; the results of such an analysis are called multipole amplitudes. Up to 15 reactions have been identified in a single data set.

The $\Delta$ is the lowest excitation of the nucleon, but is still poorly understood. The two big issues have been to understand why CQMs are unsuccessful in describing the main excitation, the $M1$ (magnetic dipole) multipole, and the measurement and interpretation of the small $E2$ and $C2$ (quadrupole) multipoles. In particular, photon experiments at Mainz and LEGS have established that the ratio of $E2$ to $M1$ strength is small; yet, the perturbative QCD limit is known to be $E2/M1$=1. The preliminary results from CLAS of the first $ep \rightarrow e'p\pi^0$ data are shown in figure 16. The value of $E2/M1$ is small at the photon point and is roughly constant up to the maximum $Q^2$ of these data. The results are clearly far from the perturbative QCD limit and are poorly described by existing models.

The $N(1535)S_{11}$ mass is about 60 MeV above the $\eta N$ threshold. Nevertheless, its coupling to $\eta N$ is very large, about 50% when the branching ratio for all other known states is a few percent or less. In addition, the photocoupling amplitude shows an unusally flat $Q^2$ dependence, implying a quite different spatial distribution than that of the $\Delta$. The CLAS $\eta$ electroproduction data at $Q^2 <2$ GeV$^2$ [Th01] finds qualitative agreement with the previous data, but the quantiative dependence is now much more clear. In addition, a smooth extrapolation of the new CLAS data is compatible with a self-consistent analysis of previous photoproduction data [Kr95] and the previous JLab Hall C data at higher $Q^2$ [Ar99].

Some of the reactions measured with the Crystal Ball include $\pi^-p \rightarrow \gamma n$, $\eta n$, $\pi^0 n$, $2\pi^0 n$, $3\pi^0 n$, and $K^-p \rightarrow \gamma\Lambda$, $\gamma\Sigma^0$, $\eta\Lambda$, $\pi^0\Lambda$, $\pi^0\Sigma^0$, $\overline{K^0}n$, $\pi^0\overline{K^0}n$, $2\pi^0\Lambda$, and $2\pi^0\Sigma^0$. The data on neutral-particle final states provide an important addition to prior data, which were mainly on charged-particle final states. Also, many of the reactions measured with the CB have a unique total isospin, which simplifies the physics interpretation. An example of the quality of the new CB data is shown in figure 17. The left panel shows the total cross section for $K^-p \rightarrow \eta\Lambda$ near threshold and the right panel shows the measured $\Lambda$ polarization at 750 MeV/$c$. These data are consistent with this reaction's being dominated by formation of the $\Lambda(1670)S_{01}$, which along with the $N(1535)S_{11}$ and perhaps one or two other baryons, is unique in having large couplings to channels involving the $\eta$

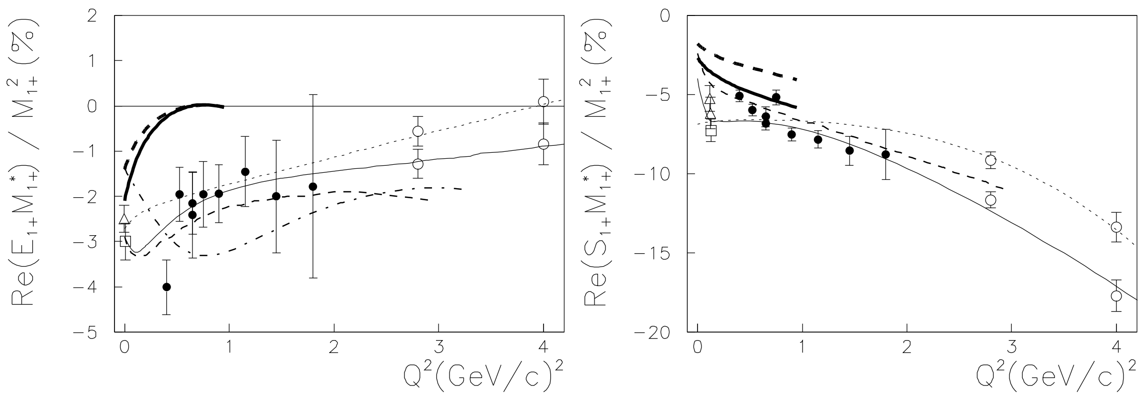


Figure 16: CLAS measurements (solid circles) of $Q^2$ dependence of multipole ratios $R_{EM}$ and $R_{SM}$ averaged over the $W$ range 1.20-1.24. Curves show recent model calculations: chiral quark-soliton (bold solid and dashed [Si99]), dynamical pion cloud (solid [Ka99] and dashed [Sa00]), isobar (dotted, [Ha00]), relativistic quark (dot-dashed [Wa90]). JLab/Hall C points ($\circ$) obtained from fits to cross sections using models [Ka99, Ha00]. Other $R_{EM}$ points are from LEGS (boxes, [Bla97]) and MAMI (triangles [Bec97]). Other $R_{SM}$ points are preliminary data from BATES (boxes, [Me99]) and MAMI (triangles [Sc99]).

meson. These two states are also very similar in their quark structure in the CQM and are therefore an excellent way to study flavor symmetries in detail.

**Short term (<3 years) and long term (<10 years) outlook**

The job of disentangling the baryon spectrum and its microscopic properties is major. No one measurement is sufficient to address more than a component of the issues. A coherent effort of experiments, phenomenologists, and model builders will be required to answer the important questions addressed above. Examples of this coherence are plentiful–the CLAS and Crystal Ball Collaborations, the Baryon Resonance Analysis Group, and the JLab/MIT lattice collaboration are each successfully attacking important pieces of the problem.

For the next few years, maintaining the present effort will allow major advancements in the quality of data and the ability to interpret it.

## 2.12 Strangeness Nuclear Physics

**Major achievements since the last Long Range Plan**


Figure 17: The total cross section (left) and $\Lambda$ polarization (right) at 750 MeV/$c$ for $K^-p \to \eta\Lambda$ measured with the Crystal Ball.

Although some hyperon-nucleon scattering data exist, our knowledge of the $\Lambda N$ potential comes principally from studies of $\Lambda$–hypernuclei, nuclei which contain a $\Lambda$– hyperon. At the time of the last long range plan, the spectroscopy of $\Lambda$-hypernuclei used the $(K^-, \pi^-)$ and $(\pi^+, K^+)$ reactions. The experiments achieved modest resolution of around 2 MeV FWHM in excitation energy which was sufficient to measure the dominant peak structure in low and medium A hypernuclei. The $\Lambda$ binding energies and the s-shell to p-shell energy separation determine the central potential of the $\Lambda N$ interaction. The possibility of probing the effects of the nuclear environment on the $\Lambda$ motivate the spectroscopy of hypernuclei with the largest possible baryon number, but here again the experiments were limited by their modest resolution. Studies of the weak decay of hypernuclei had also been initiated. These experiments were primarily focused on the weak non-mesonic reaction, $\Lambda + N \to N + N$. This reaction is particularly interesting due to predictions that the empirical $\Delta I = 1/2$ rule is severely broken here, despite the fact that it is observed in all previously measured reactions involving the weak-decay of the strange-quark in the presence of strongly interacting quarks and gluons.[Ma94]

Over the past two years, new instrumentation and techniques have improved the field's capabilities dramatically. At Jefferson Lab the first experiment to use the electroproduction of lambdas measured coincident electron-kaon pairs to tag hypernuclei produced through the reaction $^{12}\mathrm{C}(e, e'K^+)^{12}_{\Lambda}\mathrm{B}$. The JLab technique transforms a proton into a lambda; this results in the production of hypernuclei which are isobaric analogs of the hypernuclei created via the $n(K^-, \pi^-)\Lambda$ and $n(\pi^+, K^+)\Lambda$ reactions. Electroproduction is predominantly a spin-flip transition, in contrast to reactions used on meson-beams, and thus tends to populate different hypernuclear states. This pioneering experiment achieved a breakthrough resolution of 600 keV. A new spectrometer specifically designed for JLab hypernuclear work is now under construction in Japan. It is expected to yield a factor of two improvement in resolution and more than a factor of 100 increase in counting rates. The design and construction of this spectrometer is funded by the Japanese science agency and is one of several examples of close cooperation between the U.S. and Japanese hypernuclear physics communities.

Detailed knowledge of the baryon-baryon interaction requires extraction of the spin-dependence of the $\Lambda N$ potential. The potential has the general form:

$$V_{\Lambda N} = V_0(r) + V_\sigma \mathbf{s}_N \cdot \mathbf{s}_\Lambda + V_\Lambda \mathbf{l}_{N\Lambda} \cdot \mathbf{s}_\Lambda + V_N \mathbf{l}_{N\Lambda} \cdot \mathbf{s}_N + V_T[\, 3(\boldsymbol{\sigma}_N \cdot \mathbf{r})(\boldsymbol{\sigma}_\Lambda \cdot \mathbf{r}) - \boldsymbol{\sigma}_N \cdot \boldsymbol{\sigma}_\Lambda]$$

The strength of these spin-dependent terms can now be determined by measuring the level splittings in carefully selected hypernuclei using the newly constructed Japanese *Hyperball*. The Hyperball is a 14-element Ge detector array which was optimized to detect hypernuclear $\gamma$-rays. The Hyperball was commisioned at KEK and then moved to the AGS to take advantage of the enormous increase in kaon flux. The results [Tapc] of the first run successfully determined the energy splitting due to the spin-orbit interaction to be $31 \pm 2$ keV, an unprecedented precision (see figure 18).

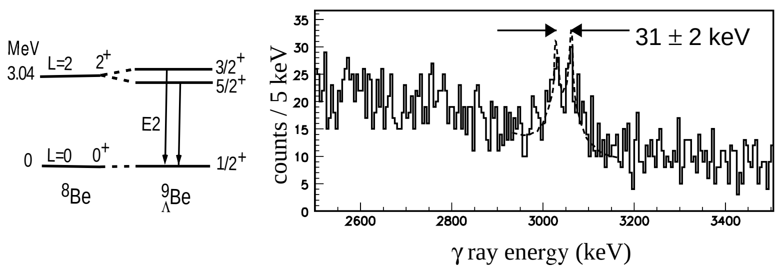


Figure 18: AGS E930 Hyperball results. A kaon beam was used to create ${}^{9}_{\Lambda}$Be. Hypernuclei produced with the ${}^{8}$Be core in the $2^+$ state (energy diagram on left) were tagged using magnetic spectrometers and the energy spectrum of the coincident $\gamma$-rays detected in the Hyperball, shown on right, represents the first direct measurement of the energy splitting due to the spin-orbit term of the $\Lambda N$ potential.

In the strangeness $-2$ sector, a number of experiments have reported upper limits for production of the H-Dibaryon. This six-quark (uuddss) object was first shown to be bound with respect to twice the lambda mass in the MIT bag model by Jaffe [Ja77]. Since the original prediction, dozens of calculations of the H-Dibaryon mass have been performed using a variety of confinement models. Most models have predicted a bound H-Dibaryon, although recent work on the lattice does not show binding. The experiments have produced upper limits which are a factor of 50 or more below predicted production rates over a large mass region although there are large theoretical uncertainties in the rate calculations. There are few experimental data in the mass region very close to $2m_\Lambda$ and in the unbound region.

**Short term (<3 years) and long term (<10 years) outlook**

Three AGS strangeness-sector nuclear physics experiments are expected to take place over the next few years. The Hyperball will be used for additional measurements in p-shell hypernuclei.

The targets were selected to extract the spin-dependence of $\Lambda N$ interaction. Experiment E931 will measurement the lifetime and branching fractions of ${}^4_\Lambda$H. These data, when combined with earlier measurements of the isobaric analog, ${}^4_\Lambda$He, will test predictions that the $\Delta$I=1/2 rule is violated in non-mesonic weak decays. The third experiment plans to use the Cylindrical Detector System (CDS) to study the ground states of $S = -2$ hypernuclei. This device was built in Japan and installed on the AGS D-line. Its initial running in 1998 showed a strong signal in the two decay-pion coincident momentum spectrum which may be associated with the production of double-lambda hypernuclei. An upgrade of the CDS is in progress and future running should show this technique to be an effective method of studying $S = -2$ systems.

In the longer term, the field will greatly benefit from the new hypernuclear spectrometer which should come on-line at JLab around 2004. The improved resolution and two orders of magnitude increase in acceptance will revolutionize the study of $\Lambda$-hypernuclei, complementing the work in progress at the AGS using the Hyperball. Although work at both electron and hadron machines will contribute to our knowledge of the $S = -1$ sector, it appears that the lack of data on $S = -2$ systems can only be rectified at a hadron beam facility. The program would benefit from a new hadron spectrometer which would improve the Hyperball $(K^-, \pi^-\gamma)$ data and could be used to determine the $\Xi$-N interaction through the study of $\Xi$-hypernuclei. It could also be used to determine the $\Lambda - \Lambda$ interaction through the direct production of double-lambda hypernuclei.

## 2.13 Comparison of the U.S. and global effort

### The ground state structure of nucleons and light nuclei

Since the 1995 Long Range Plan, significant progress has been made in understanding the electromagnetic structure of the nucleon, benefiting greatly from new facilities, new experimental techniques using polarization, and new theoretical efforts. Experimental achievements have come from all the U.S. and European electron laboratories. With the recent closing of NIKHEF, the present productivity of JLab, and the startup of BLAST at Bates, it is likely that in the next 5 to 10 years major efforts will be concentrated in the U.S. New precision data over a large kinematic region are anticipated, allowing the understanding of the nucleon's electromagnetic structure from the underlying, fundamental theory of QCD.

The U.S. is presently leading the effort in parity violation and weak nucleon structure with G0, SAMPLE and HAPPEX. However, both the G0 and HAPPEX programs have very strong participation from European groups, with France providing half of the detection apparatus for G0. In the next five years, the U.S. program will be complemented by measurements at Mainz by the PVA4 collaboration. PVA4 will initially measure parity-violating elastic scattering at moderately forward angles, but the same apparatus can be reversed relative to the beam to provide corresponding asymmetries over a range of momentum transfers at backward angles as well and thus a significant program at Mainz is also envisioned. Theoretical support for this program comes primarily from the U.S. and European communities.

At present, there is no other facility in the world that can study either high energy photodisintegration or the form factors of the light nuclei with the accuracy achievable at Jefferson Laboratory because of the unique combination of energy, large acceptance detectors, high beam polarization and high duty factor. Exploring the role of QCD in nuclei, and, in particular, the transition region from meson exchange to perturbative QCD, will be the primary domain of JLab until a facility such as the proposed European machine ELFE is realized.

On the theoretical side, while there is a strong international effort in studies of the NN interaction and microscopic approaches to nuclei, the U.S. plays a leading role in many areas. Development of theoretical models of the nuclear interaction and currents has been extremely strong in the United States. European groups have led recently in exact calculations of three- and four-nucleon systems, while the U.S. is the leader in path-integral approaches to microscopic studies of nuclei, which has been an extremely productive effort.

The development of effective field theories for particle and nuclear physics is a global effort. Important groups that focus on chiral perturbative studies, both in particle and nuclear physics, exist all over Western Europe, in Canada, and in the United States. Groups which focus on multinucleon systems exist in Europe, Korea, and the United States. In the latter case, the simultaneous need for knowledge of nuclear phenomenology and of quantum field theory techniques significantly restricts the number of physicists who have contributed in any meaningful way to the development of this area. It is only during the last few years or so that there has been substantial effort and progress in this field.

Given that EFT has long been the *lingua franca* of the many branches of particle physics, the flow of information and understanding has largely been into nuclear physics. However, recently, the expertise that we have developed in systems with large scattering lengths (*i.e.*, nuclear physics) has been applied to the physics of Bose-Einstein Condensates (BEC) with great success. It is clear that with BEC becoming only recently accessible to experimental investigation, the overlap between the EFT program in nuclear physics and condensed matter physics will continue to grow. During the recent EFT program at the *Institute for Nuclear Theory* in Seattle, Washington, it became clear that the EFT tools being developed for high precision atomic calculations will be influenced by and will influence those being developed for nuclear systems.

**Lattice QCD**

US nuclear theorists have played a significant role in the development of innovative algorithms and exploratory calculations of observables important for nuclear physics, including development of perfect actions, chiral fermions, cluster algorithms for finite density, and calculations of form factors, moments of structure functions, hadron spectroscopy, and the study of instantons. However, the fact that European and Japanese researchers have 20 to 50 times more computer resources than US theorists makes it impossible to compete in world-class calculations. (A detailed comparison for FY00 is given in the section on the lattice QCD initiative). Even the calculation of moments of structure functions [Do00] was only possible by use of full QCD configurations calculated in Germany that could not have been calculated with US computer resources.

Given the current investment in Europe and Japan in facilities of order ten sustained Teraflops, it is clear that definitive calculations of hadronic observables will be completed in the next few years. If the U.S. is to participate in these fundamental developments, and to attract and retain first-rate theorists in the field, it must act aggressively to provide competitive resources.

**Partonic substructure of hadrons**

The most promising means of searching for the antiquark excess related to nuclear binding is Drell-Yan experiments. The two best facilities for this search in the required kinematical regime are the 120 GeV FNAL injector or the recently approved 50 GeV JHF. The time scale for realizing the JHF is unclear, but it is likely to become available for physics only at the end of the decade. The FNAL injector is in operation and a small fraction of the beam is used for the collider experiments, while the remainder of the beam is presently unused. It remains a challenge to establish a viable nuclear physics program at the Fermilab Main Injector. A modest investment in beam lines as well as detectors from the nuclear physics community would be necessary to initiate vigorous new programs at Fermilab in the near future. Many of the other proposed measurements could be pursued at both RHIC and the Fermilab Main Injector.

Measurements of the gluon contribution to the nucleon's spin will be performed at three laboratories, RHIC-SPIN, COMPASS and SLAC. With the RHIC measurements and the recent approval of two experiments at SLAC (one to measure $\Delta G$, the other to measure the high energy portion of the GDH integral), the U.S. will likely lead the world in spin physics in the next decade, although Mainz and Bonn will make significant contributions in the next five years. Exploration of the sum rules in the transition region between strong and perturbative QCD is the unique domain of Jefferson Lab, particularly with the proposed 12 GeV upgrade.

In the last five years, experiments such as HERMES have provided first glimpses of new, fundamental aspects of hadron structure and formation, such as the first data on the transversity structure function and new results on spin-dependent effects in fragmentation. HERMES is a 200-member collaboration with strong U.S. and European contingents.

HERMES and the international H1 and ZEUS experiments (all located at the DESY laboratory in Hamburg) have provided the first data on Deeply Virtual Compton Scattering (DVCS), the process most cleanly sensitive to the unknown Generalized Parton Distributions. Future measurements of novel structure and fragmentation functions are expected from a variety of laboratories: both HERMES and the RHIC-SPIN experiment at Brookhaven plan dedicated measurements of transversity, while DVCS will be further explored by all three DESY collaborations and by experiments at JLAB. The data to be collected by all of these spin-dependent experiments, as well as by the European COMPASS collaboration at CERN, will no doubt also shed light on the mysteries of final-state hadron formation.

### Excited Baryons and Strangeness Physics

CEBAF has the unique advantages of high energy beams and an existing broad range spectrometer. With it, most issues in baryon spectroscopy that can be measured with an electromagnetic beam can be addressed. Although the United States is the major place for experiments in this field, European collaborators have had key roles both in construction and scientific leadership of CLAS. Mainz and Bonn are also making important contributions at lower energies and smaller momentum transfers. Mainz has an outstanding spin program and Bonn has a well-understood neutral particle spectrometer that was moved from CERN. LEGS and Bates (smaller U.S. facilities) are making significant progress into understanding the $\Delta$; although it is the lowest excited $N^*$ state, it has the unresolved issues discussed above. LEGS, Mainz, and Bonn are also measuring important parts of the GDH sum rule for photons.

The AGS has the unique advantage of high energy pion beams; furthermore, it is the only facility with kaon beams of sufficient energy and intensity capable of supporting a coherent, first-rate program for hyperon ($\Lambda$,$\Sigma$) spectroscopy. Without the pion and kaon beams at the AGS, this opportunity will likely disappear.

Strangeness-sector nuclear physics is characterized by close international cooperation, particularly between the U.S. and Japan. This includes three major devices (the JLab hypernuclear spectrometer, the Hyperball, and the CDS spectrometer) which were designed and built in Japan to augment the US facilities. International cooperation has already resulted in major advances in this field. On the ten year time scale, the Japanese Hadron Facility is likely to be on-line and is well suited to continued work in strangeness nuclear physics.

# 3 New Initiatives

## 3.1 The JLab Energy Upgrade

In this section we summarize the scientific case for upgrading the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab to 12 GeV and provide a brief description of the upgraded accelerator and its experimental equipment. An in-depth description of the scientific program and details of the accelerator and end station upgrades can be found in the Jefferson Lab White Paper, *The Science Driving the 12 GeV Upgrade of CEBAF* [JL01].

The CEBAF Upgrade will make profound contributions to the study of nuclear matter, allowing breakthrough programs to be launched in two key areas:

- *The experimental observation of the QCD flux tubes which cause confinement.* Theoretical conjectures, now confirmed by lattice QCD simulations, indicate that the most spectacular new prediction of QCD – quark confinement – occurs through the formation of a string-like "flux tube" between quarks. This conclusion (and proposed mechanisms of flux tube formation) can be tested by determining the spectrum of the gluonic excitations of mesons. Tantalizing evidence for these excitations has appeared in recent years; the combination of a high energy, polarized photon beam and an optimized detector provided by the Upgrade will permit a definitive search.
- *The measurement of the quark and gluon wavefunctions of the nuclear building blocks.* A vast improvement in our knowledge of fundamental structure of the proton and neutron can be achieved through the combination of higher-energy beams and detectors included in the Upgrade. Not only can existing "deep inelastic scattering" cross sections be extended for the first time to cover the critical region where their basic three-quark structure dominates, but also measurements of new "deep exclusive scattering" cross sections will open the door to a new, more complete characterization of these wavefunctions by providing direct access to experimental information on the correlations among the quarks.

In addition to opening up these qualitatively new areas of research, the Upgrade will allow important new thrusts in CEBAF's present research program, generally involving the extension of measurements to substantially higher momentum transfers (probing correspondingly smaller distance scales). Examples include:

- Determining the dynamics underlying the quark-gluon wavefunctions through measurements of the high-momentum-transfer behavior of form factors.
- Mapping out and understanding the transition from the hadronic to the quark-gluonic description of strongly interacting matter through the study of low-energy duality.

- Searching for the onset of color transparency effects in the region where they are supposed to exist.
- Determining the role of color polarization effects in the $NN$ force by measuring the threshold $\psi N$ cross section.
- Executing a unique and global study of short-range correlations in nuclei.
- Examining the role of quark masses in determining hadron spectra by mapping out the currently obscure $s\bar{s}$ spectrum that straddles the boundary between the rigorously understood heavy-quark systems and the poorly understood light-quark world.

The continued availability of 2.2, 4.4 and 6.6 GeV beams simultaneously with the higher energy beams (a natural advantage of CEBAF's recirculated linac design) will support the continuation of CEBAF's present programs as well. Since these experiments do not *require* the higher energies, they are not discussed in this document, which focuses on new capabilities. However, we note that most experiments that want to run at a presently accessible momentum transfer can do so more efficiently (*e.g.*, consuming less total beam time) at higher electron beam energy.

In the sections below we review these three major research thrusts in turn, and then summarize the required detector and accelerator upgrades to provide an overview of the complete plan for the 12 GeV project.

**The 12 GeV Research Program**

### 3.1.1 The Origin and Nature of Quark Confinement: Discovering and Studying the Exotic Mesons

The first breakthrough program made possible by the 12 GeV Upgrade will provide key experimental insights into the origin and nature of quark confinement. In the early 1970s, evidence that the masses of strongly interacting particles increased without limit as their internal angular momentum increased led the theorist Yoichiro Nambu [Na70] to propose that the quarks inside these particles are "tied together" by strings. Numerical simulations of QCD ("lattice QCD") have demonstrated [Ba00] that Nambu's conjecture was essentially correct: in chromodynamics, a stringlike chromoelectric flux tube forms between distant static quarks, leading to their confinement with an energy proportional to the distance between them (see figure 19). The phenomenon of confinement is the most novel and spectacular prediction of QCD – unlike anything seen before. It is also the basic feature of QCD that drives all of nuclear physics, from the mass of the proton and other nuclear building blocks to the $NN$ interaction.

The ideal experimental test of this new feature of QCD would be to study the flux tube directly by anchoring a quark and antiquark several fermis apart and examining the flux tube that forms between them. In such ideal circumstances one of the fingerprints of the gluonic flux tube would be

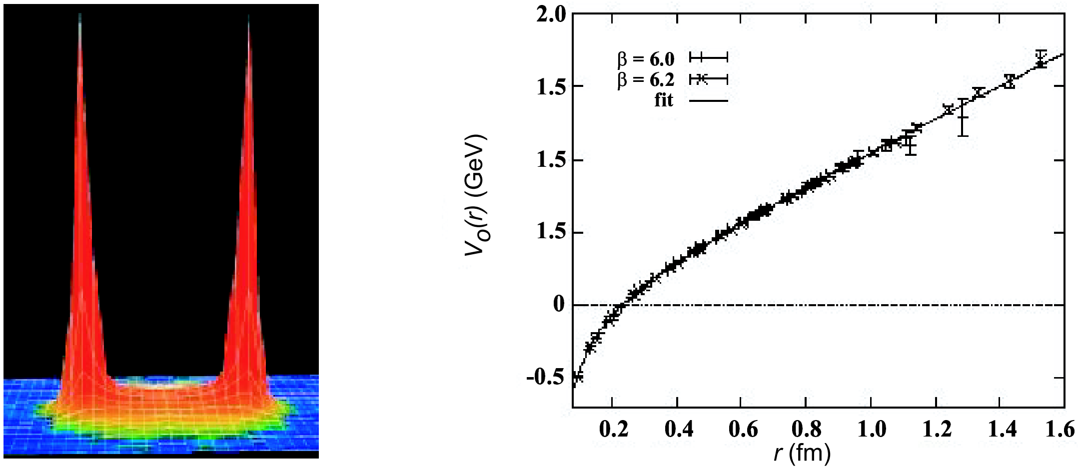


Figure 19: Lattice QCD has confirmed the existence of flux tubes between distant static charges for heavy quarks. In addition to the intense color fields in the immediate vicinity of each quark, one can see the formation [Ba00] along the line connecting the two quarks of a flux tube of constant thickness, leading to the linearly rising potential seen on the right [Ba97].

its model-independent spectrum [Lu81]: its required two degenerate first excited states are the two longest-wavelength vibrational modes of this system, while their excitation energy is required to be $\pi/r$ since both the mass and the tension of this "relativistic string" arise from the energy stored in its color force fields. Such a direct examination of the flux tube is of course not possible. In real life we have to be content with systems in which the quarks move. Fortunately, we know both from general principles [Is85] and from lattice QCD calculations [Mo97] that an approximation to the dynamics of the full system that ignores the impact of these two forms of motion on each other works quite well – at least down to quark masses of the order of 1 GeV.

To extend this firm understanding to yet lighter quarks, models are required [Is85], but the most important properties of this system are determined by the model-independent features described above. In particular, in a region around 2 GeV, a new form of hadronic matter must exist in which the gluonic degree of freedom of a quark-antiquark system is excited. The smoking gun characteristic of these new states is that the vibrational quantum numbers of the gluonic "string", when added to those of the quarks, can under certain circumstances produce a total angular momentum $J$, a total parity $P$, and a total charge conjugation symmetry $C$ not allowed for ordinary $q\bar{q}$ states. These unusual $J^{PC}$ combinations (such as $0^{+-}$, $1^{-+}$, and $2^{+-}$) are called exotic, and the states are referred to as exotic hybrid mesons [Ba77]. Not only general considerations and flux tube models, but also first-principles lattice QCD calculations, require that these states have masses around 2 GeV; furthermore, they demonstrate that the levels and their orderings will provide experimental information on the mechanism that produces the flux tube.

On the experimental front, tantalizing evidence has appeared in recent years for both exotic hybrids and gluonic excitations with no quarks (glueballs); it is discussed in the "highlights" section of this white paper. For the last two years a group of 90 physicists from 26 institutions in seven countries has been working on the design of the definitive experiment to map out the spectrum of these new states required by the confinement mechanism of QCD. Photon beams are expected to be particularly favorable for the production of the exotic hybrids [Is85]. The reason is that the photon sometimes behaves as a "virtual vector meson" with total quark spin $S = 1$. When the flux tube in this $S = 1$ system is excited, both ordinary and exotic $J^{PC}$ are possible. In contrast, when the spins are antiparallel ($S = 0$), as in pion or kaon probes, the exotic combinations are not generated. (In the approximation that flux tube and quark dynamics separate, hybrid production would occur by pure flux tube excitation, and these selection rules would be strictly true. In practice, these two degrees of freedom interact with one another to produce corrections to the rules.) To date, most meson spectroscopy has been done with incident pion, kaon, or proton probes, so it is not surprising that the experimental evidence to date for flux tube excitation is tentative.

In contrast to hadron beams, high-flux photon beams of sufficient quality and energy to perform meson spectroscopy studies have not been available, so there are virtually no data on the photoproduction of mesons with masses in the 1.5 to 3 GeV region. Thus, experimenters have not been able to search for exotic hybrids precisely where they are expected to be found. The planned experiment will have a dramatic impact on this situation. Even if initial running is at only 10% of the planned photon fluxes of $10^8$/s, the experiment will accumulate statistics during the first year of operation that will exceed the world's supply of published meson data obtained by pion production by at least a factor of 10, and the existing photon production data set by at least a factor of 1000. With the planned detector, high statistics, and linearly polarized photons, it will be possible to map out the full spectrum and the decay modes of these gluonic excitations. In doing so, we will have made a giant step forward in understanding one of the most important phenomena discovered in the twentieth century: quark confinement.

### 3.1.2 The Quark-Gluon Wavefunctions of the Nuclear Building Blocks

The 12 GeV Upgrade will also allow two broad advances in the experimental investigation of the basic nuclear building blocks. First, our knowledge of the "deep inelastic scattering" (DIS) cross sections can be extended for the first time to cover the critical region where the basic three-quark structure of the nucleons dominates. Second, it will facilitate the first serious program of measurements of "deep exclusive scattering" (DES) cross sections, opening the door to a new, more complete characterization of the nucleons' quark wavefunctions by providing direct access to experimental information on the correlations among the quarks.

The classic program of DIS experiments began with the Nobel Prize–winning work of Friedman, Kendall, and Taylor [Bl69] in the 1970s at SLAC. These measurements led to the experimental confirmation of the existence of quarks and to precision tests of the fledgling theory of QCD, eventually confirming it as the fundamental theory governing all strongly interacting (*i.e.*, nuclear) matter.

Even though such experiments have been pursued vigorously for nearly 30 years, it is remarkable that there has never been an experimental facility that could measure the DIS cross sections throughout the kinematic regime where the three basic ("valence") quarks of the proton and neutron dominate the wavefunction. At modest values of the momentum transfer $Q^2$, the valence quarks play a big role in determining these cross sections over a large range of the kinematic variable $x$ (which runs from 0 to 1 and is roughly interpretable as the fraction of the momentum of the initial nucleon state along the direction of the incident virtual photon that was carried by the struck quark). The contribution of the valence quarks peaks at $x \simeq 0.2$. However, if one is in the conventionally defined deep inelastic regime, the probability of finding a quark in the high-$x$ "valence quark region" is small, and becomes smaller and smaller as $x \to 1$; moreover, with "pollution" from gluons and quark-antiquark pairs, it is only for $x > 0.5$ that the valence quarks dominate the $x \to 1$ wavefunction. The 12 GeV Upgrade will allow us to map out the quark distribution functions in this "clean" valence quark region with high precision. Such measurements will have a profound impact on our understanding of the structure of the proton and neutron.

Figure 20 shows two examples of measurements that can be done with the proposed upgrade. The neutron polarization asymmetry $A_1^n$ is determined by the spin wavefunction of the quarks, and most dynamical models predict that in the limit where a single quark carries all of the nucleon's momentum ($x \to 1$), it will also carry all of the spin polarization (so, *e.g.* for the neutron, $A_1^n \to 1$ as $x \to 1$). Existing data on $A_1^n$ end before reaching the region of valence quark dominance, and show no sign of making the predicted dramatic transition $A_1^n \to 1$. Figure 20a shows the quality of $A_1^n$ data obtainable in this region with the Upgrade. There are similar (if less dramatic) paucities of data on all other DIS observables in this region. Even in unpolarized DIS, where the available data are best, there are unresolved issues. To extract the ratio of such a simple and basic a property as the relative probability of finding a $d$ quark vs. a $u$ quark at high $x$ requires measurements on both the proton and neutron. However, high-$x$ neutron information is difficult to disentangle from nuclear binding corrections. Figure 20b shows the precision with which this fundamental ratio (which is intimately related to the fact that the proton and neutron, and not the $\Delta$, are the stable building blocks of nuclei) can be measured with the proposed upgrade. The planned experiment will exploit the mirror symmetry of A=3 nuclei through simultaneous measurements of the inclusive structure functions for $^3$H and $^3$He. Regardless of the absolute value of the nuclear effects in the two measurements, their differences should be small, permitting the neutron-to-proton ratio (and thus the $d/u$ ratio) to be extracted with precision.

While the historic DIS program will thus continue to be fruitful, it is intrinsically limited in what it can tell us about quark and gluon wavefunctions: structure functions are *probabilities*. Until recently, attempts to determine the quark and gluon *wavefunctions* of the nucleons have been hopelessly handicapped by the lack of a rigorous framework for making a connection between any experimental measurement and these wavefunctions. (For example, while intuitively related to the momentum wavefunction of the quarks, even the valence quark distribution functions are sensitive

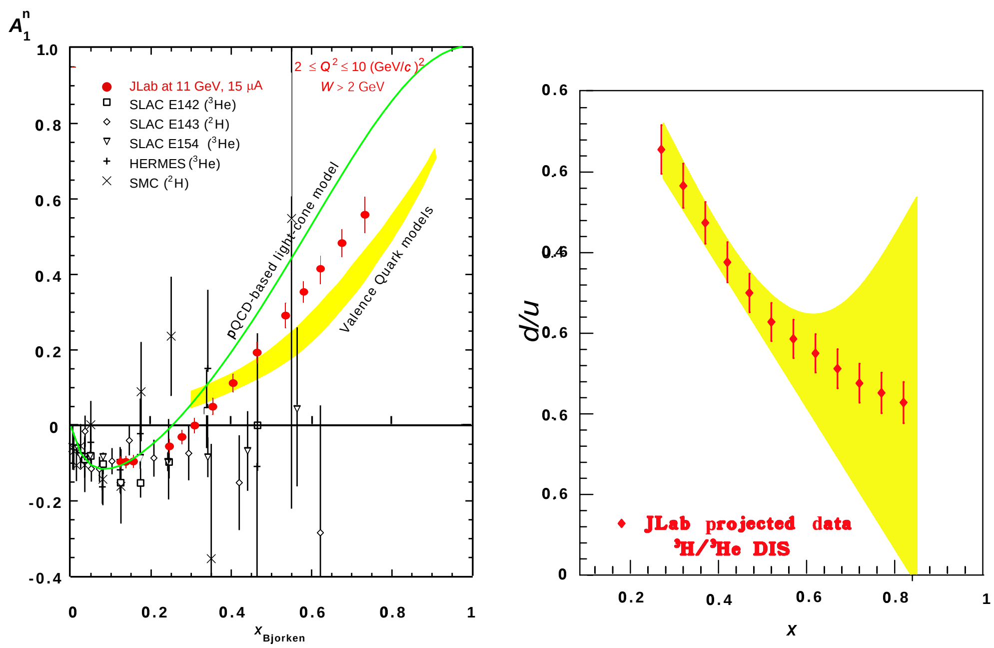


Figure 20: Examples of high-$x$ data obtainable with the CEBAF upgrade. a) A projected measurement of the neutron polarization asymmetry $A_1^n$, determined by the spin structure of the valence quarks, made possible by the proposed 12 GeV upgrade (left). The shaded band represents the range of predictions of valence quark models; the solid line is the prediction of a pQCD light-cone quark model. b) A projected measurement of the ratio of momentum distributions of valence $d$ quarks to $u$ quarks made possible by the proposed 12 GeV upgrade (right). The shaded band represents the uncertainty in existing experiments due to nuclear Fermi motion.

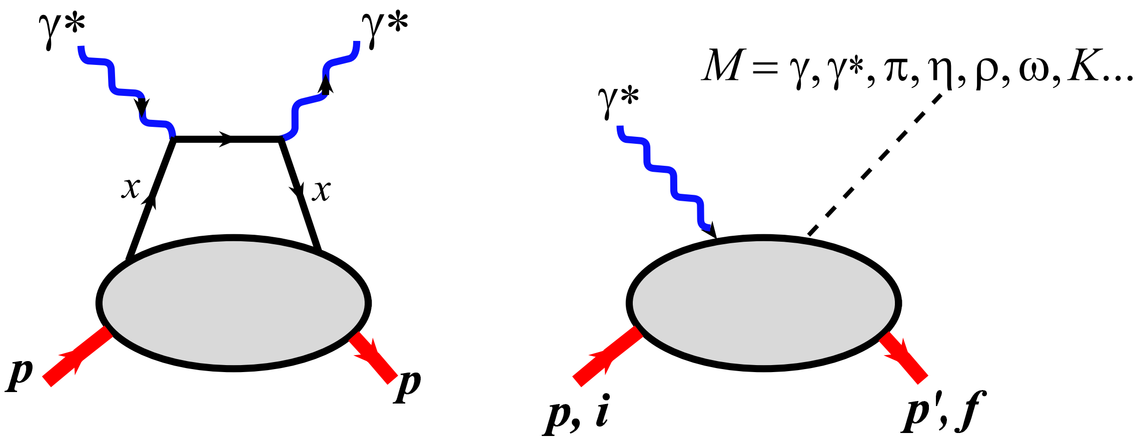


Figure 21: a) The asymptotically dominant contribution to deep inelastic scattering (left); and b) the special deep exclusive scattering (DES) cross sections that have been identified as providing a new window on the quark-gluon wavefunctions of the nuclear building blocks (right).

only to the square of the momentum wavefunction suitably averaged over momenta transverse to the virtual photon direction!) The discovery of Generalized Parton Distributions (GPD's) and their connection to certain totally exclusive cross sections has made it possible in principle to rigorously map out the complete nucleon wavefunctions themselves [Ji97, Ra96]. The GPD's are sensitive to the wavefunction at the *amplitude* level, instead of merely the probability level, and, in particular, explore quark-quark correlations. The 12 GeV upgrade will provide the accelerator and detectors required to perform the difficult measurements that will allow the first comprehensive exploration of this new "Deep Exclusive Scattering" (DES) domain that is rigorously connected to the quark and gluon wavefunctions.

Standard techniques relate the total cross section for deep inelastic scattering to the imaginary part of the forward elastic scattering process $\gamma^* p \to \gamma^* p$, where $p$ is a target particle (such as a proton). Of key importance is that in the deep inelastic scattering regime the elastic process is dominated by the diagram shown in Figure 21a, where pure electron-quark scattering *factorizes* from the probability for the quark to carry a fraction $x$ of the target's momentum, depicted as the blob at the bottom of the diagram.

The new DES processes that lead to GPD's, and thence to quark and gluon wavefunctions, can be extracted *under appropriate kinematic conditions* from the generic cross sections shown in figure 21b. Whereas the DIS process involved a $\gamma^*$ in both the initial and the final state, for these new deep exclusive processes the final particle can be a $\gamma, \gamma^*, \pi, \eta, \rho, \omega, K$, etc. instead of just a $\gamma^*$. Furthermore, the initial and final targets can have different momenta ($p$ can scatter to $p\,'$) and can even be of different types ($i$ can scatter to $f$). If the final particle is a $\gamma^*$, forward scattering is possible, and in that case, assuming one is in the scaling region for these cross sections, the GPD's being studied would reduce to standard quark distribution functions. In every other case (once again assuming one is in the appropriate scaling region), these processes access a rich new body of information about the full wavefunction, including nonforward overlaps of their longitudinal parts and their transverse momentum structure.

While theoretical guidance is available, the kinematic range over which measurements must be done for the above-mentioned DES scaling to apply must normally (as was the case historically for DIS) be determined experimentally. Moreover, as in DIS, there are two related but conceptually distinct requirements for being in the DES scaling regime so that figure 21b can be interpreted in terms of the GPD's and hence the quark-gluon wavefunctions. Wavefunctions are frame-dependent, and those probed in standard DIS and in the new DES processes are *not* those of the rest frame, but rather may be identified with those of a particle whose velocity is approaching the speed of light. Thus one condition for scaling is that the kinematic range of the measurements must bring one close enough to $\beta = 1$ that the wavefunction is close to its asymptotic form. The other condition is that the relevant underlying dynamical processes can be factorized into a "hard" pQCD scattering amplitude and a "soft" amplitude which arises from the wavefunctions.

In the DIS process of figure 21a on nucleons, we know that the conditions for scaling are achieved when $Q^2 > 1$ (GeV/$c$)$^2$ and the produced inelastic mass $W > 2$ GeV. We can understand these conditions intuitively. In this case we can expect that the "hot" quark between the two pointlike $\gamma^*$ vertices (the upper line in the figure) will be effectively free from the remaining quarks (within the lower portion of figure 21a) since these kinematic conditions localize the "hot" quark in space-time to the short-distance regime where asymptotic freedom applies. Moreover, our knowledge of the structure of the excited nucleon resonances strongly suggests that there is no scale greater than 1 GeV to interfere with the rapid evolution of the rest frame wavefunction to its $\beta \to 1$ form.

Similar factorization issues apply to DES. Consider first the $\gamma^* p \to Mp$ reaction with $M = \gamma$, *i.e.*, Deeply Virtual Compton Scattering (DVCS), which can actually proceed *via* a modified version of the Feynman diagram of figure 21a with the second $\gamma^*$ replaced by a $\gamma$ and with the imaginary part of the graph not taken. Since the two Feynman diagrams are the same, one may expect the two processes to have similar factorization and scaling properties. However, the cases of $\gamma^* p \to Mp$, where $M$ is a meson, represent *terra incognita*. Figure 22 illustrates the essential features. For factorization, the kinematics of the experiment must force the struck quark to be effectively free, as before, but now, in addition, the kinematics must create the $q\bar{q}\,'$ meson by the pQCD process depicted. Note that by judicious choice of the meson and its production characteristics, the data probe complementary aspects of the hadron wavefunction, such as correlations among flavors and momenta of quarks, the transverse momentum distributions, and the role of the quarks' angular momentum and spin in building up the hadron's spin. (Note in addition that since figure 22 includes many time-orderings, it includes processes where a quark-antiquark pair is created by the hot photon *and* processes where a $q\bar{q}\,'$ pair in the target is knocked out. There are correspondingly two new types of wavefunctions being probed by these reactions.)

Figure 23 shows two models for the GPD denoted $H(x, \xi, t)$ from which one can gain some

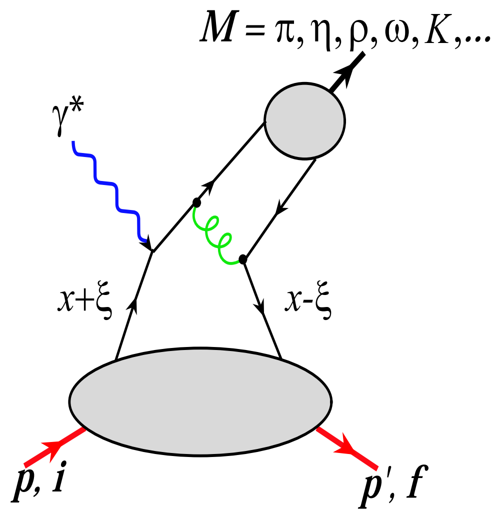


Figure 22: The asymptotically dominant diagram for DES with meson production in which a $q\bar{q}\,'$ pair is "forced" by the $\gamma^*$ and a hard gluon exchange into the meson $M = \pi, \eta, \rho, \omega, K$, etc. These reactions are governed in their scaling regions by the new Generalized Parton Distributions (GPD's) which depend on three kinematic variables: $t = (p - p')^2$, $\xi = \frac{x_{Bj}}{2 - x_{Bj}}$, and $x$ (defined in the figure).

insight into the richness of information available through the study of these new distributions. The figure is a three-dimensional representation at $t = 0$. $H(x, \xi, t)$ is modeled using the so-called double distribution of Radyushkin [Ra99], which parameterizes the usual parton distributions measured in inclusive scattering and parton correlations modeled via quark-antiquark (*i.e.* pion) distributions. In the right-hand surface the "$D$" term by Polyakov and Weiss [Po99] that represents two-pion contributions is included.

DIS experiments can measure the parton distribution only along the line at $\xi = 0$; $H(x, 0, t = 0)$ is the usual quark distribution for $x > 0$, and the antiquark distribution for $x < 0$. The ability of DES experiments to vary the "skewedness" parameter, $\xi$, provides access to the full surface and the ability to *measure* the correlations between the partons in the nucleon. $\xi$ is given by the electron kinematics, and defines the fractional momentum difference between the initial- and final-state partons. For $\xi = 0$ the initial- and final-state partons have identical momenta, and for large $\xi$ they carry very different fractions of the nucleon's momentum. At $\xi \to 1$, $H(x, \xi, t)$ takes on the characteristics of quark-antiquark (*i.e.*, meson) distribution amplitudes that are clearly visible in the figure. Additional information on quark-quark correlations can be obtained from mapping out the $t$-dependence of these surfaces.

The 12 GeV upgrade will allow these critical DES cross sections to be systematically measured in the relevant kinematic regions for the first time. In most cases a wide range of kinematic conditions can be achieved covering nearly an order of magnitude in the relevant variables beyond values at which DIS has exhibited scaling. One may therefore expect that the scaling properties of

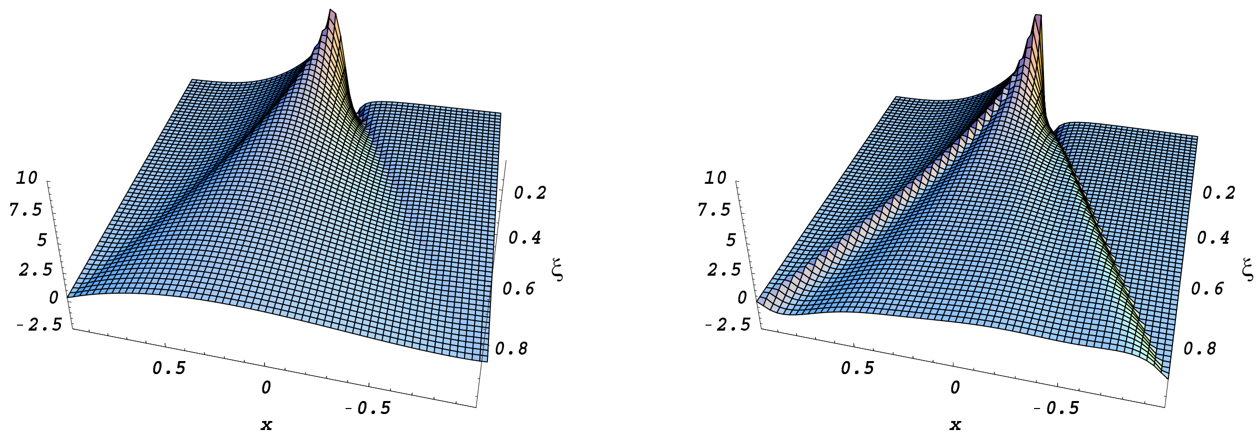


Figure 23: Two possible Generalized Parton Distributions [Vapc] that are consistent with available deep inelastic scattering data (*i.e.*, have identical values for $\xi = 0$) but contain very different quark-quark correlations (see text).

the cross sections can be determined experimentally.

There are thus reasons to be optimistic that either scaling will be achieved in these processes or that the scaling limits can be inferred by extrapolation from the behavior of the measured cross sections, so that the desired direct connection can be made with the wavefunction. Although this seems almost certain in the case of DVCS, as mentioned above, there are reasons to be cautious for other DES cross sections. For example, it is generally believed that the pion elastic form factor, which is asymptotically controlled by the upper part of the diagram of figure 22, is dominated by long-distance, confinement-based physics for $Q^2 < 10$ (GeV/$c$)$^2$. We also recall that determining the GPDs will require not only factorization, but also that the new wavefunctions being probed have evolved to their asymptotic form. However, there is some evidence from the decay characteristics of highly excited mesons that the $q\bar{q}$ sea is produced with a very hard spectrum [Ge93], so that the $qqqq\bar{q}$ component of the nucleon wavefunction may evolve much more slowly than the $qqq$ component to its $\beta \to 1$ limit.

In summary, it seems likely that the upgrade to 12 GeV will access the required conditions for a DVCS program. Whether, in addition, 12 GeV will be sufficient to determine all of the GPD's described here, to get a first glimpse of them, or only to define how the scaling regime is approached, is a question that awaits experiment. At the least, the upgrade will certainly provide important information necessary to define the energies and luminosities of a future machine required to complete this vital task.

### 3.1.3 Other New Research Thrusts

The 12 GeV upgrade will make a broad range of profound contributions to the study of nuclear matter beyond the two breakthrough programs described above. Many such examples of programs that the 12 GeV upgrade will support are described in the JLab White Paper; seven of them are highlighted here.

- *Pion and Nucleon form factors*

The high-$Q^2$ behavior of elastic and transition form factors probes the high-momentum components of the valence quark wavefunctions of the nuclear building blocks. Of particular interest in this regard is understanding when the dynamics of the valence quarks makes a transition from being dominated by the strong QCD [Cl95] of confinement to perturbative QCD. This transition should occur first in the simplest systems; in particular, the pion elastic form factor seems the best hope for seeing this transition experimentally. Figure 24 shows how well the proposed 12 GeV upgrade project can explore this transition.

- *Duality: the transition from a hadronic to a quark-gluon description of DIS*

At high enough energies, asymptotic freedom guarantees that the DIS cross section can be calculated based on nearly free electron-quark scattering as depicted in figure 21a. However, confinement guarantees that the experimentally observed final-state particles are hadrons. Thus in the scaling region, the equality of these two sets of cross sections is simply the statement that the results associated with figure 21a are rigorously proved; *i.e.*, that QCD is the correct theory of the strong interactions. In contrast, as one proceeds to kinematic conditions that are below the Bjorken limit (*e.g.*, $Q^2$ below 2 $\text{GeV}^2$), cross sections calculated assuming factorizing dynamics of the type depicted in figure 21a should be expected to fail to reproduce the hadronic cross sections, which when summed give *by definition* the true inclusive cross section. Low-energy quark-hadron duality suggests that hadronic cross sections, when averaged over an appropriate energy range, nevertheless coincide with the naïve leading twist quark-gluon calculations. Thus quark-hadron duality *at low energy* naturally examines the transition between strongly interacting matter and perturbative QCD. In the circumstances of the 12 GeV upgrade, both Bjorken scaling and the approach to scaling must arise from very few channels. One may therefore expect that the underlying mechanisms of quark-hadron duality may be determined by utilizing the spin/flavor selectivity of 12 GeV electron scattering in both inclusive and exclusive reactions.

- *Color transparency: The nature of hadronic interactions can be investigated via tests of the prediction of "color transparency"*

Transparency is an unusual QCD effect predicted to have its most counterintuitive manifestation in $(e, e'p)$ at very high energy. Under the right conditions, three quarks, each of which would have interacted very strongly with nuclear matter, pass right through it. This can happen because bound

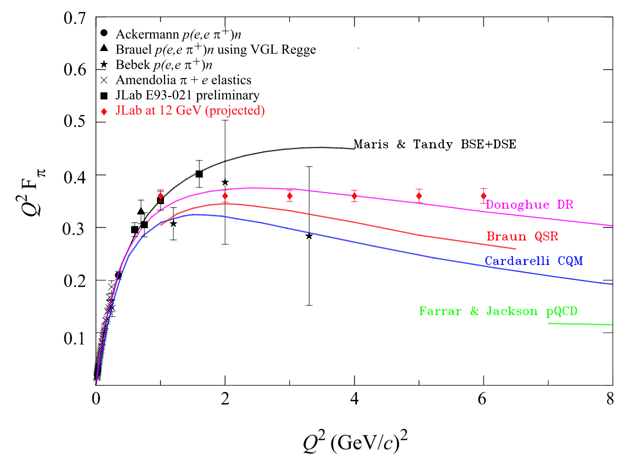


Figure 24: The projected measurements of the pion elastic form factor through the expected transition region from confinement-dominated dynamics to perturbative-dominated dynamics made possible by the proposed 12 GeV upgrade. Systematic errors are estimated to be comparable to the statistical errors shown for the projected 12 GeV data. Also shown are a few of the dozens of model predictions, all characterized by being confinement-dominated below about 2 $(\mathrm{GeV}/c)^2$ and making a transition to being perturbative-dominated with a value of $Q^2F_\pi \simeq 0.1$ $(\mathrm{GeV}/c)^2$ in the region of 10 $(\mathrm{GeV}/c)^2$.

states of three quarks must have zero net color charge by the "nonabelian" nature of charge and confinement in QCD, and they can also be arranged to have small color "dipole moments". While the nucleonic example is the more exotic, and such measurements may very well succeed, there is evidence that the electroproduction of vector mesons (where the fact that a quark-antiquark pair has zero net color charge seems much more mundane) may provide a more practical setting for observing this phenomenon. Indeed, the evidence suggests that this reaction may show transparency at much lower $Q^2$ and $\nu$ than quasielastic proton scattering, and that it may have its most pronounced experimental signature in just the energy range of the CEBAF upgrade.

• *Learning about the* NN *force by the measurement of the threshold* $\psi$ N *cross section and by searching for* $\psi$*-nucleus bound states*

Threshold $\psi$ photoproduction is a unique process since the small $c\bar{c}$ state will be produced by the interaction of its calculable small color dipole moment with a nucleon (in which it is presumed to *induce* a large, but uncalculable, color dipole moment). This simple color van der Waals–type force is a prototype for a possibly important component of the $NN$ force. It is quite possible that this interaction is sufficiently strong that $\psi N$ or $\psi$-nucleus bound states exist; such relatively long-lived objects might be detected in subthreshold $\psi$ production off nuclei. Based on the same picture, one could also look for $\phi N$ states.

• *Measuring short-range correlations in nuclei*

The higher-energy beams that will be available in Halls A, B, and C will support substantial extensions of CEBAF's current program measuring the high-momentum components of nuclear wavefunctions and of investigating short-range nucleon-nucleon correlations. In the rare regions of strong nucleon-nucleon overlap that drive these correlations, instantaneous densities of the order of four times nuclear densities (comparable to those in a neutron star and close to those at which the zero temperature quark-gluon phase transition could occur) are expected. Figure 25 gives an example of a DIS measurement that can be made to study short-range correlations in nuclei. With the variety of measurements that can be made in the three halls, the upgrade can be expected to fully answer this old question from nuclear many-body theory.

• *The spectroscopy of* $\mathrm{s\bar{s}}$ *mesons*

Figure 26a shows some of what we know about the spectra of $Q\bar{q}$ mesons for $q$ a light quark and $Q = b, c, s$, and $u$ or $d$. The rigorous results of Heavy Quark Effective Theory (HQET) should only be applied for $Q = b, c$, but these data suggest that there is a remarkable similarity between the dynamics of "true" heavy-light systems and those where $Q = s$ or even $Q = u$ or $d$: it appears that the creation of the constituent quark mass through spontaneous chiral symmetry breaking is enough to boost any quark into the heavy-quark world, at least qualitatively. Similar behaviour can be seen in the spectra of heavy quarkonia ($Q\bar{Q}$ systems) shown in figure 26b. Once again, even though there is no known rigorous explanation, there seems to be a great similarity between the spectra of the heavy quarkonia (which have a well-understood quark-model-like connection to

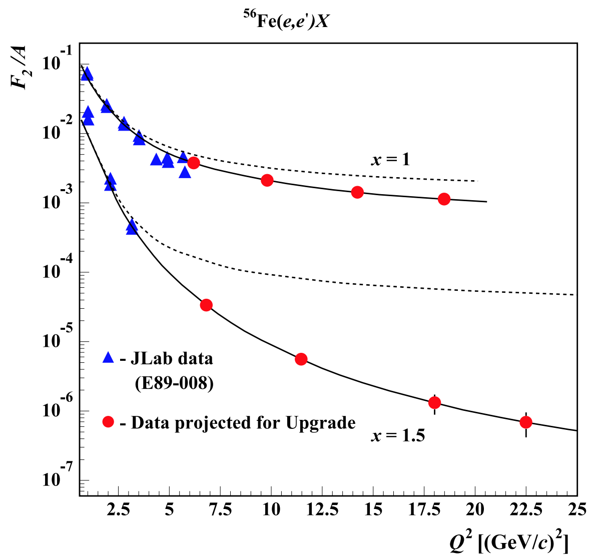


Figure 25: An example of the type of DIS measurement that can be made to study short-range correlations. The experiment is very sensitive to short-range correlations: solid lines are for two-body correlations only, while the dashed line shows the expected full effects of short-range correlations.

QCD) and light-quark systems.

These interesting data showing possible relationships between heavy- and light-quark systems exist because nature has presented us with an interesting selection of quark masses. Historically the quarks have been divided into two groups based on their masses: the light-quark $(u, d)$ world (or, by extension, the $u, d, s$ world of SU(3)) and the heavy-quark world. It is ironic that in many critical areas we know much more (both experimentally and theoretically) about the heavy-quark world than about our own. In this respect, these figures strongly suggest that it would be desirable to know much more about $s\bar{s}$ spectroscopy. Given that the photon is $s\bar{s}$ rich, a great deal of data will automatically be available from this sector as part of the planned Hall D program, creating the opportunity to correct this situation.

- *Primakoff production of light pseudoscalar mesons*

The existence of the pseudoscalar Goldstone bosons due to spontaneous breaking of chiral symmetry and the profound roles played in QCD by the chiral anomalies responsible for their two-photon decays and for the $\eta'$ mass are two basic phenomena of QCD. As a result, the system of three neutral pseudoscalar mesons, the $\pi^0$, $\eta$, and $\eta'$, contains fundamental information about low-energy QCD, including certain critical low-energy parameters, the effects of SU(3)- and isospin-breaking by the $u$, $d$, and $s$ quark masses, and the strengths of the two types of chiral anomalies. The 12 GeV upgrade will in particular allow a new and in many respects unparalleled series of measurements of

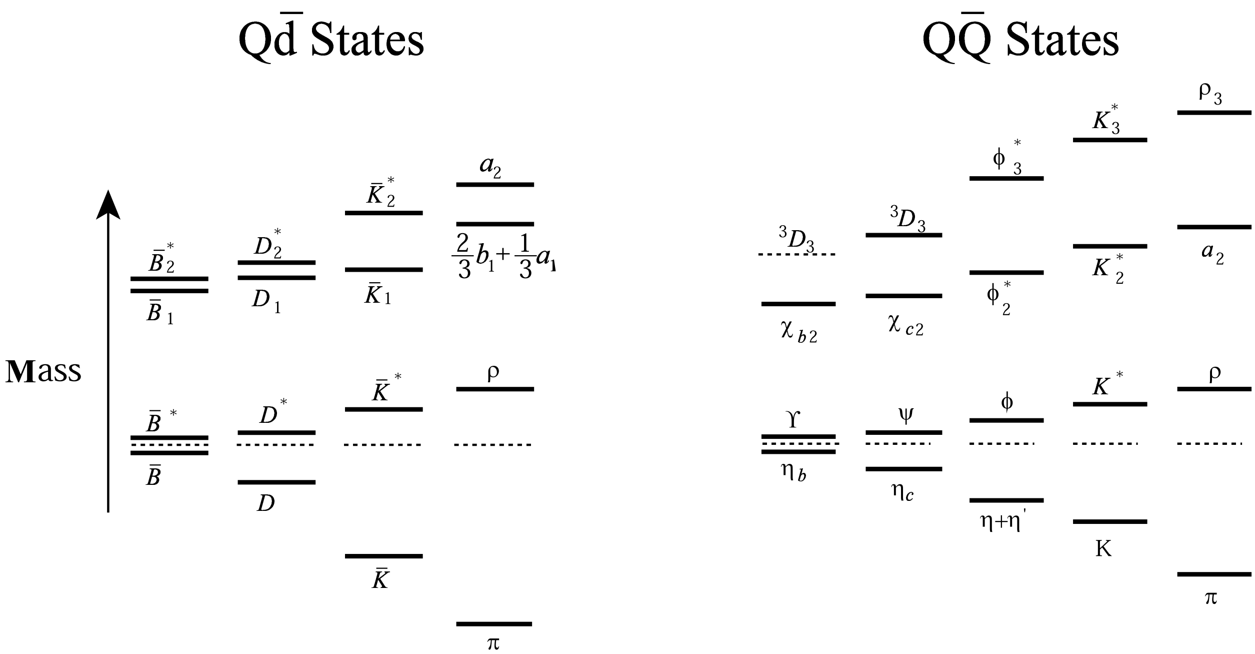


Figure 26: The relative splittings of the $Q\bar{d}$ states (left) and the $Q\bar{Q}$ states (right) are each shown to scale from the heaviest to the lightest with the center-of-gravity of the ground state multiplets aligned in each case. For the $Q\bar{d}$ states the $\bar{B}^*$ and $\bar{B}$ are the $J^P = 1^-$ and $0^-$ "ground state" multiplet with light-degrees-of-freedom spin-parity $s_\ell^{\pi_\ell} = \frac{1}{2}^+$, while $\bar{B}_2^*$ and $\bar{B}_1$ with $J^P = 2^+$ and $1^+$ are an excited heavy-quark spin multiplet with $s_\ell^{\pi_\ell} = \frac{3}{2}^+$ [Is91], etc. For the $Q\bar{Q}$ states we show the states in each sector with $J^{PC} = 0^-, 1^-, 2^+$, and $3^-$.

the radiative decay widths and transition form factors of these special mesons. In particular, the two-photon decay widths will provide the ultimate tests of the predictions of chiral perturbation theory for these chiral-anomaly-driven processes, and the $\gamma \rightarrow \gamma^*$ transition form factors at very small $Q^2$ will provide a model-independent extraction of the electromagnetic interaction radii of these mesons, answering fundamental questions about the relationship of these Goldstone bosons to QCD's other pseudoscalar mesons (recall figure 26).

The Primakoff mechanism of electro- and photo-production of neutral mesons in the Coulomb field of a nucleus provides a powerful tool to measure these fundamental quantities. The 12 GeV upgrade is required to reach much of the relatively high-mass $\eta$ and $\eta'$ part of this experimental program, while other properties can be studied as part of the current 6 GeV program.

### 3.1.4 The Upgrade Project Summary

In this section we summarize briefly Jefferson Lab's plans for the accelerator and experimental equipment upgrades necessary to carry out this research program. Details are presented in the Jefferson Lab White Paper [JL01], and in the 25 May 1999 internal JLab report, *Interim Point Design for the CEBAF 12 GeV upgrade.*

The key features of CEBAF that make the upgrade so cost-effective are easily defined. By the summer of 1994, CEBAF had installed the world's largest superconducting radio-frequency (SRF) accelerator: an interconnected pair of antiparallel linacs, each comprising 20 cryomodules, with each cryomodule in turn containing eight SRF accelerating cavities. On average, these cavities exceed their design specifications by 50% in both gradient and $Q$, the critical performance measures. It is the success of this technology that has opened up the possibility of a relatively simple and inexpensive upgrade of CEBAF's top energy. However, this technological success would not be so readily multiplied if considerable foresight had not also been exercised in laying out the CEBAF tunnel "footprint", which was designed so that the magnetic arcs could accommodate an electron beam of up to 24 GeV. The latent accelerating power of the installed SRF cavities has already brought CEBAF to 6 GeV, 50% above its design energy, and recent successes in SRF development have led to the production of two cryomodules that are more than a factor of 2 more powerful than the original design. With expected further improvements in SRF technology, with the production of a new, compact cryomodule (that contains higher-performing seven-cell cavities but fits in the same space as the original cryomodules based on five-cell cavities), and with the use of space available in the linac tunnels to install ten new cryomodules, 12 GeV can be attained at a modest cost.

In fact, the accelerator portion of the upgrade is straightforward. The basic elements can be seen in figure 27. The upgrade utilizes the existing tunnel and does not change the basic layout of the accelerator. There are four main changes: additional acceleration in the linacs, stronger magnets for the recirculation, an upgraded cryoplant, and the addition of a tenth recirculation arc. The extra arc permits an additional "half pass" through the accelerator to reach the required 12 GeV beam energy, followed by beam transport to the new Hall D that will be added to support

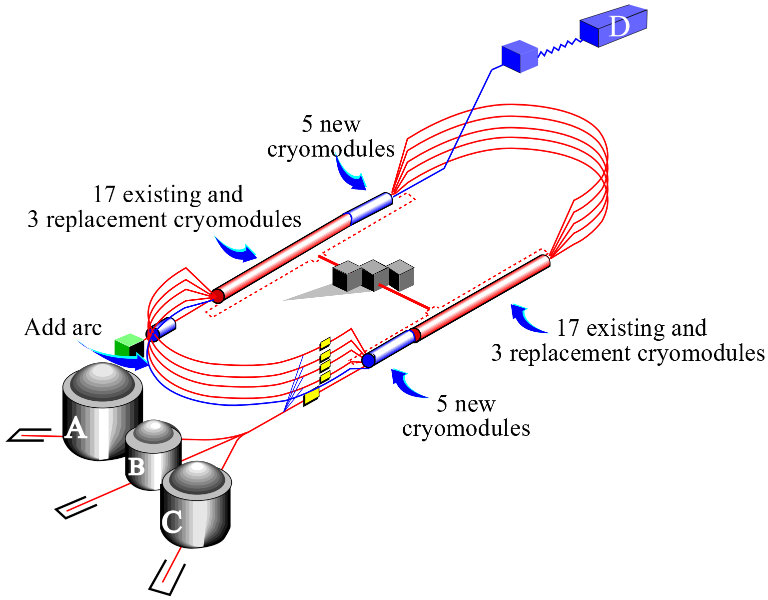


Figure 27: The configuration of the proposed 12 GeV CEBAF upgrade.

the meson spectroscopy initiative. Table 2 presents the key parameters of the upgraded accelerator.

Motivated by the science, the upgrade derives its name from the fact that it will deliver 12 GeV electron beams to the new end station, Hall D (where they will be used to produce 9 GeV polarized photons for the new gluonic and $s\bar{s}$ spectroscopies) while sending electrons of 2.2, 4.4, 6.6, 8.8, or 11.0 GeV to the existing Halls A, B, and C. Studies of the existing detectors have led to cost-effective plans for their upgrades. The increased physics power of the present halls comes from the qualitative jump in energy and momentum transfer that the upgrade brings, and from the enhanced instrumentation capabilities planned for the detector complements in each of them.

In Hall A, the upgrade will add a large-angular- and large-momentum-acceptance, moderate-resolution magnetic spectrometer (to be called the Medium-Acceptance Device, or MAD) together with a high-resolution electromagnetic calorimeter and a $^3$H target. The spectrometer will provide a tool for high-luminosity, high-$x$ studies of the properties of nucleons with an 11 GeV beam, and also be used for selected investigations of the GPD's, where high luminosity and good resolution are needed. In Hall B, the CEBAF Large Acceptance Spectrometer (CLAS), which was designed to study multiparticle, exclusive reactions with its combination of large acceptance and moderate momentum resolution, will be upgraded to optimize it for studying exclusive reactions (emphasizing the investigation of the GPD's) at high energy. Most importantly, the maximum luminosity will be upgraded from $10^{34}$ to $10^{35}$ cm$^{-2}$ s$^{-1}$. The present toroidal magnet, time-of-flight counters, Čerenkov detectors, and shower counter will be retained, but the tracking system and other details of the central region of the detector will be changed to match the new physics goals. In Hall C

Table 2: Selected key parameters of the CEBAF 12 GeV upgrade

| Parameter | Specification |
|---|---|
| Number of passes for Hall D | 5.5 (add a tenth arc) |
| Max. energy to Hall D | 12.1 GeV (for 9 GeV photons) |
| Number of passes for Halls A, B, C | 5 |
| Max. energy to Halls A, B, C | 11.0 GeV |
| Max. energy gain per pass | 2.2 GeV |
| Range of energy gain per pass | 2:1 |
| Duty factor | cw |
| Max. summed current to Halls A, C* (at full, 5-pass energy) | 85 $\mu$A |
| Max. summed current to Halls B, D | 5 $\mu$A |
| New cryomodules | 10 (5 per linac) |
| Replacement cryomodules | 6 (3 per linac) |
| Central Helium Liquifier upgrade | 10.1 kW (from present 4.8 kW) |

*Max. *total* beam power is 1 MW.

a new, high-momentum spectrometer (the SHMS, Super-High-Momentum Spectrometer) will be constructed to support high-luminosity experiments detecting reaction products with momenta up to the full 11 GeV beam energy. This feature is essential for studies such as the pion form factor, color transparency, duality, and high-$Q^2$ $N^*$ form factors. The spectrometer will be usable at very small scattering angles. Finally, in Hall D, a tagged coherent bremsstrahlung beam and solenoidal detector will be constructed in support of a program of gluonic spectroscopy aimed at testing experimentally our current understanding that quark confinement arises from the formation of QCD flux tubes.

### 3.2 The Electron Ion Collider

It has been over 25 years since the formulation of Quantum Chromodynamics (QCD), the theory which identifies colored quarks and gluons as the basic constituents of strongly interacting matter. In the intervening decades, a great amount of information has been obtained about the partonic (quark and gluon) structure of hadronic matter. However, our knowledge is still far from complete. Crucial questions in this field remain open:

- *What is the structure of hadrons in terms of their quark and gluon constituents?*
- *How do quarks and gluons evolve to form hadrons?*
- *Can nuclei be used to produce and study partonic matter under extreme conditions?*

The answer to these questions is the key to our ultimate understanding of the microscopic structure of matter. A high-luminosity electron-ion collider turning on at the end of this decade will be the ideal machine to address the above questions decisively. The Electron-Ion Collider (EIC) should have a luminosity $\geq 10^{33}$ cm$^{-2}$sec$^{-1}A^{-1}$ and a center-of-mass energy in the range of 30 to 100 GeV. It is crucial that the collider should allow collisions of electrons not just with protons, but with light and heavy ions, in order to explore the full ramifications of QCD. With the parameter space given in figure 28, EIC will provide a capability beyond anything presently existing.

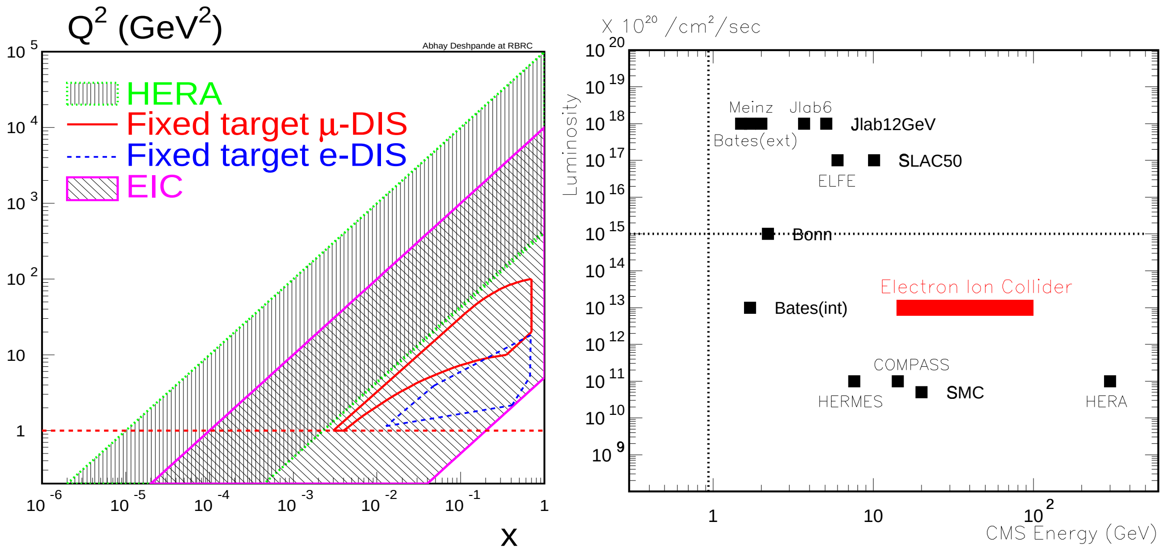


Figure 28: (a) The $x - Q^2$ range possible with EIC in comparison with the kinematic region presently explored by fixed target experiments and by HERA. (b) The plot of CM vs. Luminosity for EIC in comparison with the other experimental facilities around the world.

### 3.2.1 Polarized $\vec{e} \cdot \vec{p}$ studies with EIC

Much of our knowledge of nucleon spin structure is based on deep inelastic scattering (DIS) experiments carried out over the past three decades using charged lepton beams and fixed targets. These measurements were mainly *inclusive* in nature and determined the valence quark contribution to the nucleon spin precisely, but left the questions of the gluon spin ($\Delta G$) and the angular momentum ($L_q + L_G$) contributions to the nucleon spin almost completely open.

After exploring inclusive DIS, the recent fixed-target experiments have started to focus on semi-inclusive measurements, which, for the first time, allow quark-flavor decomposition of the nucleon spin. However, the "fixed target" geometry of these measurements inhibits full acceptance of the target fragments, and makes tagging on specific quark flavors difficult. Such semi-inclusive measurements do not necessarily require high beam energies, but they need good detector acceptance, excellent particle identification and high luminosity. The approved next-generation DIS fixed-target experiments (HERMES (II) at DESY, COMPASS at CERN) represent improvements in this direction. But only DIS measurements in a collider geometry with almost $4\pi$ acceptance, and a detector capable of excellent particle identification, can overcome all present limitations.

**EIC Physics at low CM Energies**

A program at low CM energies will use the high luminosity and collider geometry to study semi-inclusive and exclusive processes with high precision and much more detail than hitherto possible. Some examples of the physics issues are:

- The effect of the parton's intrinsic transverse momentum in hard processes where the resulting fast hadron contains the struck quark with high probability (so-called "current fragmentation"). The kinematic domain where the remainder of the hadronic debris can be found is known as the "target" fragmentation region.
- The mechanism of polarization transfer from incoming lepton to the final hadronic states.
- How does removal of a certain parton from a nucleon affect the probability that the residue decays into a particular hadron? Including spin, this would examine how the polarization of the initial state affects the quantum numbers of the final hadron.
- Comparison of the relative number of baryons and meson states in the target fragmentation region with those in the current fragmentation region, a region dominated by mesons. Polarization of both beams allows investigation of how spin affects these ratios.

A polarized electron-hadron collider with high luminosity is uniquely able to address the question: *How do partons evolve into hadrons?* The collider geometry allows clear separation of the current and target fragments. The study of fragments provides a window into the evolution of quarks into hadrons. Topics of interest are:

- Model independent studies of the parton structure of the neutron over a wide kinematic range using "tagged" structure functions, through the process $e + D \to e' + p + X$. This technique can provide accurate measurements of $d^p(x)/u^p(x)$ at large $x$, as well as proton and neutron spin asymmetries $A_1^N(x)$.

- Measurements of the $\pi^+$ structure function could be made by observing forward neutrons in the reaction $e + p \to e' + n + X$, determining the effects of sea quarks and gluons in the pion, and nuclear medium effects on meson structure functions. Similarly, kaon structure functions could be obtained by observing $\Lambda$ hyperons arising from the $e - p$ collisions.

- Transversity, the last unmeasured spin-related leading twist structure function, could be obtained using the azimuthal asymmetry of pion production.

- Hard exclusive processes using deeply virtual Compton scattering (DVCS) and meson electroproduction provide access to the generalized parton distributions (GPDs), which are a topic of intense current interest and debate.

- Comparison of elastic processes with inelastic excitations to the $N^\star$, the $\Delta$ or the hyperon provides information about spin-flavor correlations.

**Physics at high CM Energies**

On every occasion that DIS experiments (including those related to spin) have moved into new $x-Q^2$ territory surprising results about the structure of the nucleon have been produced. Figure 28 shows that the $x - Q^2$ range of a 250-GeV proton on 10-GeV electron polarized collider increases by more than an order of magnitude over fixed target experiments in both $x$ and $Q^2$. This allows addressing questions like: *What is the role of sea quarks and gluons in the nucleon's spin?* and *What is the quark-gluon structure of the photon?*

Specific inclusive and semi-inclusive measurements at high collider energies are:

- Spin structure functions $g_1^{\mathrm{p/n}}$ could be measured with high precision down to $x \sim 10^{-4}$ and at high enough $Q^2$ so that pQCD could be reliably applied.
- Low $x$ measurement with very good accuracy will reduce the present 10% uncertainty in the test of the fundamental Bjorken sum rule to significantly less than 1%.
- Perturbative QCD analysis at next-to-leading order of the spin structure function results in the first moment of the polarized gluon distribution $\Delta G$. Measurement of $\Delta G$ has been the principle motivation for the proposals and construction of major experimental facilities at CERN, DESY and BNL. EIC would reduce the uncertainty in this quantity by factors of 3-5.
- $\Delta G$ in the nucleon can also be accessed through partonic processes where the gluon appears in leading order. The photon gluon fusion process is one such example. Using the EIC data on di-jet production, the uncertainty in the gluon distribution can further be reduced by factors of 3 or more.
- If this method of constraining $\Delta G(x)$ is coupled with the pQCD analysis method mentioned before, the effective improvement factor is estimated to be about 10 or higher.
- At high energies the virtual photon can resolve itself into its partonic contents. Unpolarized structure functions of the photon have been measured at HERA. A polarized EIC would do the same for the polarized photon. This would be a unique measurement not planned at any other future approved facility.
- Measurements of $W^\pm$ production (charged current events) give access, at intermediate $x$ and high $Q^2$, to the parity violating spin structure functions $g_5^\pm$. These would be unique measurements: no other experimental facility plans to measure them.

- Inclusive measurements made with EIC at very low $Q^2$ values determine the contributions to the Drell-Hearn-Gerasimov spin sum rule integral in the high energy regime. This would be complementary to the JLAB measurements. Although the integral contribution in this kinematics is small, the data constrain the extrapolations that are necessary to evaluate the full sum rule.

The RHIC spin program, the first high energy collider with two polarized proton beams, will overcome some of the obstacles of the fixed target experiments and will pursue some of the same physics goals of the polarized electron-hadron collider in a complementary way. An elegant test of the universality of QCD and perturbative QCD (pQCD) dynamics would be provided by the consistency of the final results from both facilities.

### 3.2.2 $e \cdot A$ with EIC

DIS off large nuclei at high energies is ideal for studying QCD properties at small x. Following the discovery of asymptotic freedom in the early 70's, perturbative QCD has been enormously successful in describing the physics of very high momenta that probe phenomena at wavelengths that are small compared to the QCD scale: $Q^2 \gg \Lambda_{QCD}$. However, these very high $Q^2$ processes comprise only a small fraction of the total cross–section at high energies. The vast bulk of the cross–section, corresponding to soft and semi–hard processes, is still poorly understood in QCD.

Note that for a fixed momentum transfer $Q^2$, the high energy limit $s \longrightarrow \infty$ is also the limit $x \longrightarrow 0$ since $x \propto Q^2/s$. The physics of high-energy soft and semi–hard processes in QCD is therefore also the physics of small $x$. Understanding these small-$x$ processes within the framework of QCD is an outstanding challenge to both theory and experiment. In fact it is in this regime that entirely new many-body manifestations of QCD may become apparent.

In a large nucleus, there are $A^{1/3}$ more partons per unit transverse area and the struck quark will sample them all. Due to this nuclear amplification, the parton densities reached in $eA$ collisions at RHIC energies will be comparable to parton densities reached in *ep* collisions at $\sqrt{s} \approx 30$ TeV! Thus, EIC would have the same saturation scale $Q_s$ as might an *ep* collider at LHC energies. EIC therefore provides outstanding capabilities for answering the question: *How does partonic matter behave at extremes of low $x$?*

At very small $x$, the density of partons per unit area is large, and is characterized by a scale large compared to the QCD scale: $Q_s(x, Q^2) \gg \Lambda_{QCD}$. For $x$ and $Q^2$ values beyond this scale, parton distributions saturate. The properties of these saturated distributions are predicted to be those of a *Colored Glass Condensate*. *Colored* because it is a manifestation of QCD, *Glass* because the infrared behavior of these parton distributions bears a formal resemblance to that of a spin glass, and *Condensate* because the occupation number of gluons in the saturated state is large. Such a state has not yet been seen, and it lies in a regime of QCD that has yet to be explored.

The properties of matter in the colored glass condensate can be probed both in inclusive and exclusive processes. In this regime, for instance, one expects hard diffractive events (a hard final state accompanied by a rapidity gap that is not exponentially suppressed) to comprise about 30% to 40% of the total cross–section. It is a particularly attractive feature of DIS experiments with a collider with tunable energies of the proton and nuclear beams that longitudinal structure functions (in the small $x$ region) can be measured for the first time. This will provide a reliable gluon distribution at small $x$. Knowing the gluon distribution to high accuracy is very important for many applications.

EIC will be also very important for understanding the detailed properties of the hot and dense partonic matter (called the quark gluon plasma) expected at RHIC and LHC. Sophisticated simulations now show that the multiplicity and final state properties of partons produced in heavy ion collisions sensitively depend on the bulk scale $Q_s$ of the colored glass condensate. In heavy ion collisions the colored glass condensate is destroyed, resulting in large color field strengths that finally relax to form the plasma. Thus, both heavy ion collisions and deep-inelastic lepton scattering off nuclei provide crucial complementary information about a new regime of QCD. In this regime the coupling is weak, albeit the physics is non–perturbative, thus allowing accurate calculations. The study of the small-x regime in e-A collisions can resolve the long standing mystery of multi–particle production in QCD.

### 3.2.3 Accelerator & Detectors

The collider being proposed for the physics program above has exacting, but technically realistic, properties.

- It must be able to collide polarized electrons with polarized protons as well as light nuclei and heavy ions, with a center-of mass-energy range $\sqrt{s}$ from $14 \rightarrow 100$ GeV for polarized protons and $\geq 63$ GeV/A for ions.
- The luminosity is to be $\geq 10^{33}\text{cm}^{-2}\text{sec}^{-1}$ per nucleon over the entire energy range.

While this luminosity is unprecedented for such a collider and drives the machine design, it is achievable with a focused R&D program, and may in practice be exceeded with clever detector integration into the machine lattice.

Many details of the collider configuration need to be decided in a dialogue between experiment and accelerator designers:

- What electron/proton(nucleus) energy tuning range is required to address the full panoply of QCD studies?

- What is the minimum bunch spacing and what clear length in the interaction region is required for a detector?
- How can the synchrotron radiation loading onto the detector by the electron beam be accommodated?

**Accelerator physics issues**

The high luminosities mentioned above will drive some design parameters, e.g., the electron current, to extremes (although the modern B factories have demonstrated that it can be done). Synchrotron radiation in a high current high energy electron storage ring is a serious limitation on magnet design. It is also important in the e-p/A collision region and determines the minimum radius with which the beams can be joined.

Two options have been evaluated for the collision geometry: The *Ring-Ring option* draws on established technology and the experience of the B-factory. The *Electron Linac-Ring* option offers several important advantages, but pushes existing technology in terms of electron current ($\geq$ 200mA) and requires full beam energy recovery along the lines of the FEL accelerator now operating at Jefferson Laboratory. For the proton and ion ring RHIC demonstrates the required ring capability covering the full energy range. RHIC does have suitable interaction points available and collisions between an electron ring or linac have been studied. It appears that e-A and A-A operation would be entirely transparent to each other. However, achieving the large luminosity requires that any proton/ion ring design (including RHIC) will require electron cooling at colliding energy (except for the highest energy protons).

Electron cooling at these energies has not yet been demonstrated. An R&D effort will be required to address several technical challenges:

- High precision manufacturing and alignment of a long superconducting solenoid.
- Operate a 50 MeV high current ($\sim$ 100 mA) electron linac with full energy recovery.
- Generate, transport and match a "magnetized" beam without a continuous magnetic field.
- De-bunch (then re-bunch) the beam to obtain low energy spread
- An interesting question for the electron cooled collider: Will the electron cooling permit an increase in the tune shift parameter which would further increase the luminosity?
- High polarization, polarization time in the ring, and the strength of polarized sources, which have to be increased significantly above the presently achieved levels.

**Detector issues**

The development of detectors for EIC collisions can build upon the experience gained at Hermes for low energies, and at HERA for high energies. Some detector concepts have been considered. The geometry is of course highly asymmetric, consisting of a "hadronic component ", detecting reaction products emitted along the p/A beam direction; a central "parton detector", detecting transverse hadrons and DIS electrons; and a lepton side in the direction of the electron beam. Both forward elements will need to be incorporated into the collider magnetic lattice elements and the electron inflection magnets. The energy variability of the EIC electron beam makes it possible to tune the reaction so that the central detector may be quite modest. These aspects may reduce the costs of such detectors, but they require a vigorous R&D program to study tracking detectors and calorimeters that are suitable to operate close to the beam in a strong synchrotron radiation environment.

### 3.2.4 Summary

An electron-nucleon/nucleus collider with an energy range from 30 to 100 GeV and high luminosity will provide a capability unmatched world-wide to study QCD as a fundamental theory and its manifestations in the nuclear environment.

EIC will make possible precision studies of the partonic structure of mesons, nucleons and nuclei, and the evolution from partons to hadrons. It will also provide an unmatched capability to explore gluon saturation at low momenta, and to search for new many-body phenomena, such as the *Colored Glass Condensate* predicted by QCD.

First studies indicate that such a facility can be built at reasonable cost. A vigorous R&D program over 3 to 5 years will be required in order to prepare a full conceptual design.

- It is proposed that this R&D program begin right away with the goal of bringing EIC online at the turn of the decade.

## 3.3 The Lattice Hadron Physics Initiative

### 3.3.1 Motivation

Unlike the constituents of atoms, molecules, or nuclei, quarks are confined within hadrons. This remarkable feature renders QCD essentially nonperturbative and not amenable to the traditional analytical techniques of theoretical physics. As a result, the only known method to solve, rather than model, the structure of hadrons is large scale numerical solution of QCD on a lattice.

Now, for the first time, the confluence of advances in lattice field theory and computer technology makes lattice QCD a crucial tool for hadronic physics. Lattice field theory has developed dramatically from the initial demonstration of quark confinement into a controlled, quantitative tool of theoretical physics. The combination of algorithms that incorporate chiral symmetry exactly on the lattice, chiral perturbation theory to extrapolate reliably to the masses relevant to the physical pion mass, and terascale computational resources provide the unprecedented opportunity for controlled solutions that will have decisive impact on our understanding of hadron structure.

Large scale lattice calculations are now an essential tool to obtain the full physics potential of the investment in major accelerators and detectors. Experimental study of quark and gluon distributions by Jefferson Lab, SLAC, Hermes at DESY, CERN, Fermilab, and the RHIC Spin Collaboration, measurements of the strange quark content of the proton at Bates and CEBAF, the exploration of transitions to excited nucleon states at Jefferson Lab, and the search for meson states with exotic quantum numbers at BNL and Jefferson Lab can all be confronted with the predictions of QCD using lattice calculations. The cost of definitive lattice QCD calculations is very small compared to the overall cost of these experimental results, and yet crucial for reaping the full physics benefit of the investment in these frontier experimental efforts.

### Physics Goals

The overarching physics goal is to achieve a quantitative, predictive understanding of the structure and interactions of hadrons.

The internal structure of the nucleon is a defining problem for hadron physics just as the hydrogen atom is for atomic physics. The wealth of probes exploited by experimentalists provides rich and precise measurements of the quark and gluon structure of the nucleon that can be directly calculated on the lattice. In particular, lattice theorists will calculate electromagnetic form factors, characterizing the distribution of charge and magnetization, the axial charge relevant to $\beta$ decay, the contribution of strange quarks to the charge radius and magnetic moment measured in parity violating electron scattering, and moments of the structure functions characterizing the light cone distribution of quarks and gluons.

Spectroscopy is the classic tool for discovering the relevant degrees of freedom of a physical system and the forces between them. Lattice calculations will study the number and structure of hadronic excited states, as well their transition form factors. The presence or absence of hadrons with exotic quantum numbers, the nature of glueballs, and the overlap between model trial functions and exact hadron states will provide insight into the role of flux tubes, dibaryons, and other degrees of freedom and into the inner workings of QCD.

Currently, there is no fundamental understanding of the very foundation of nuclear physics, the nucleon-nucleon interaction. Significant insight into the role of gluon exchange, quark exchange, meson exchange, and the origin of short range repulsion will be obtained by lattice calculations of the adiabatic potential between heavy-light systems, that is, mesons or baryons containing a single heavy quark in addition to other light quarks or antiquarks.

In addition to calculating observables to compare with experiment, lattice calculations are also invaluable in obtaining insight into fundamental aspects of QCD. Current lattice techniques enable study of the role of instantons and their associated zero modes in chiral symmetry breaking, the role of center vortices and magnetic monopoles in confinement, and calculation of the parameters entering chiral perturbation theory. The lattice also allows theorists to answer interesting theoretical questions inaccessible to experiment, such as how the properties of QCD change with the number of colors, quark flavors, or quark masses. New techniques under development may also enable study of the phases of dense hadronic matter and the transitions between them.

The Lattice Hadron Physics Collaboration, founded in 1998 and presently including 22 theorists beyond the postdoctoral level from 13 institutions, is actively engaged in beginning this research program and developing the computational facilities to bring it to fruition.

**Cost-Performance Optimized Lattice QCD Clusters**

Whereas conventional supercomputers such as a Cray T3E cost approximately $500 per sustained Megaflops, clusters of commodity processors using commodity interconnects judiciously designed for lattice QCD presently cost less than $10 per sustained Megaflops. This cost is below that of replicating the present QCDSP special purpose QCD machines at Columbia and Brookhaven and affords all the advantages of standard operating systems and compilers, compatibility with workstations, and the flexibility of the rich and highly competitive marketplace.

MIT and Jefferson Lab are undertaking an aggressive program to develop Alpha-based clusters that are optimized for cost/performance on lattice QCD and that scale to the multiteraflops range required for definitive calculations. MIT currently has a 64 Gflops prototype cluster of twelve four-processor ES40's. Jefferson Lab has a 16 Gflops cluster of sixteen single-processor XP1000's and a 21 Gflops cluster of 8 dual-processor UP2000's. QCD currently runs at one-third of the theoretical peak speed on these clusters and the efficiency is being improved still further.

In March, 1999, Jefferson Lab, MIT, and the Lattice Hadron Physics Collaboration jointly proposed funding the first phase of production clusters for QCD [La00a]. This phase would increase the clusters to include 256 processors at Jefferson Lab and provide a total peak speed of one half Teraflops. The cost at the time of the proposal was $1.42M for hardware and $420K for one year of manpower.

The second phase is to utilize emerging technology in which the processor, memory, and communications controller are all on a single chip to build a cluster with ten Teraflops sustained performance. Interactions with vendors and initial performance analysis indicates that QCD will scale excellently on this architecture and that the cost will be of the order of $ 1-2 per sustained Megaflops, comparable to that projected for special purpose machines.

### 3.3.2 Lattice QCD Resources available Nationally and Internationally

Currently, U.S. hadronic physics researchers are at a striking disadvantage relative to their international competitors. For ease of comparison, all resources will be stated in Gflops-yrs, that is, dedicated use of a computer that sustains 1 Gflops executing QCD code for one year.

A current state-of-the-art quenched QCD calculation typically requires 50 Gflops-yrs. For comparison, the largest NERSC allocation in FY00 for QCD was 2 Gflops-yrs. According to a recent study [La00b] by the Lattice QCD Executive committee appointed by the DOE, the total resources openly available for lattice QCD in the US in FY00 (excluding the special purpose machines used exclusively by Columbia and RIKEN) is 20 Gflops-yrs, when for comparison, there are 264 Gflops-yrs in Germany, 554 in Italy, 980 in Japan, and 41 in UK. The European Committee for Future Accelerators recently recommended acquisition of several 10 Tflops computers in FY03, and the UK has already contracted to purchase one of these.

**Meeting the Needs of the Hadronic Physics Community**

To exploit the outstanding physics opportunities provided by lattice QCD and to compete effectively with Europe and Japan, the U.S. hadronic community needs to build up its computational resources to 0.5 Tflops sustained in FY01-02 and continue to 10 Tflops sustained in FY03-05.

This is one component of a coordinated national plan [La00b] in which the resources for QCD thermodynamics ( which should be addressed in the BNL Town Meeting for Relativistic Heavy Ion Collisions) and weak matrix elements relevant to the B factory would also be developed comparably.

It is possible and highly desirable that some of these resources will be provided by the new program Scientific Discovery through Advanced Computation (SDAC). However, to bring the full power of lattice QCD to bear on the national nuclear physics program, nuclear physics will also have to be a partner. In particular, FY01-02 is crucial and may well need substantial nuclear physics support.

Because lattice QCD has needs that are much more similar to those of experimental programs than to traditional theoretical physics efforts, the nuclear physics community needs to begin thinking about lattice facilities the way it thinks about experimental facilities, with manpower and budgets to match. As with other new initiatives, support of manpower and bridge positions is also important.

Coupled with the frontier experimental program, lattice QCD provides an unprecedented opportunity for fundamental understanding of hadronic physics.

## 3.4 The Theory Infrastructure Initiative

Theoretical research plays an essential role in formulating the fundamental research directions of nuclear physics. We want to know how the phenomena of nuclear physics can be understood directly from Quantum Chromodynamics (QCD). This requires a better understanding of confinement, exploitation of the chiral symmetry that provides an effective theory at low energies, and numerical solutions of strong QCD. Answers to these fundamental questions will have a deep impact on particle physics, astrophysics and cosmology. These key theoretical problems are manpower intensive and require a new balance between the theoretical and experimental effort. The full potential of our investments in world-leading experimental facilities cannot be realized without the work of theoretical physicists. To ensure the vitality of theoretical research, we must be able to recruit and provide career paths for the best young people. The prime goal of nuclear theory, to show how the nucleon and the few- and many-body nuclear problems can be understood directly from QCD, will then be attainable. In so doing we will also provide the crucial theoretical support needed for major experimental initiatives.

### 3.4.1 Recent accomplishments

Nuclear theory has made major advances since the last Long Range Plan. The nuclear theory community in the US initiated some of these advances but presently there is insufficient theory manpower for the US to maintain its world leadership. To exemplify the breadth and depth of nuclear theory, three of the many recent theoretical advances are presented; one of these (the last) was not even envisioned at the time of the last long range plan.

- A major breakthrough has been made in solving the non-relativistic many-body problem numerically. Using phenomenological potentials that accurately reproduce nucleon-nucleon scattering data, together with modest three-nucleon forces that are consistent with chiral symmetry, theorists have been able to reproduce the binding energies of all light nuclei with A≤10 and the low energy scattering observables for $N-d$ scattering reactions. The work has demonstrated that nuclei arise in nature primarily because of the strong two-nucleon interaction. These efforts required the close collaboration of many theorists from a number of institutions. A key missing link between the bulk of nuclear physics and QCD is the understanding of the origins of the nuclear force from QCD. Other exciting opportunities abound, doing precise calculations of electromagnetic observables in light nuclei, for example, or cross sections important to astrophysics. These efforts will require both enhanced support for young researchers at all levels as well as dramatically increased access to the most advanced computational facilities.

- A new theoretical avenue with much promise is the development of effective field theories [EFT], including chiral perturbation theory. An EFT is the most general description that exists consistent with all underlying symmetries and physical principles of QCD. The EFT allows one to calculate perturbatively away from the symmetry limit, e.g., the almost perfect chiral symmetry of QCD. The uncertainty associated with a calculation of any observable in an EFT can be estimated and controlled. An example from the *Highlights of Scientific Achievement* section is the 1% calculation of the $n-p$ radiative capture cross section which plays a central role in predicting the abundance of elements from Big-Bang nucleosynthesis. The development of EFT for particle and nuclear physics is a global effort. The US has strong groups which focus on EFT for multi-nucleon systems, and this focus is one successful example of fruitful theory collaborations growing out of the INT during the last few years. Continuing this successful effort requires a sizeable increase in manpower as recommended.

- A recent and significant development is the identification of the Generalized Parton Distributions (GPD), a new class of parton distributions. The GPD are primarily probed in exclusive measurements and describe hard scattering processes that involve *correlations* between partons, as described in the *Highlights of Scientific Achievement* section. In order to be maximally exploited, these QCD properties of GPD, which go beyond the naive picture of collinear non-interacting quarks, have to be investigated via QCD inspired models in the next few years. For example, GPD have a direct connection to the unknown parton orbital angular momentum, which is an essential contribution to the total spin of the nucleon and to the impact parameter dependence of parton distributions. Again the theory manpower to explore the GPD is inadequate. This development was proposed and is led by US theorists. It will require collaborations among several well-supported theoretical groups to further investigate these initial GPD successes.

Although these three major advances in nuclear theory illustrate the high quality of the current theoretical effort, the manpower and the fraction of resources devoted to theory are insufficient to insure that the US will maintain its world leadership role.

**The role of theory and the balance between theory and experiment**

Historically we know that a strong and *balanced* community of theorists and experimentalists is needed to open new frontiers, to discover new directions and novel approaches, and to interpret the multitude of precision data streaming from our world class experimental facilities. What constitutes the correct balance between theory and experiment cannot be easily or objectively estimated. The following considerations may be helpful:

- Based on the 1999 DOE manpower survey, the current distribution of effort in nuclear physics in terms of experimentalists and theorists (after renormalization by fraction of effort from the original head count census) shows the following ratio for permanent DOE supported staff:

$$\text{experimentalists:theorists} \simeq 550/140 \simeq 4{:}1.$$

- From the direct manpower census the ratio for permanent university nuclear physicists is about 5:2. By comparison, this ratio is 4:3 for university based high energy physicists.
- The DOE manpower survey also shows that the number of theorists at national labs has not grown since 1986. In contrast, the number of laboratory based experimentalists has increased by $\simeq 30\%$ . The ratio of experimentalists to theorists is 6:1.

It seems likely that there is an imbalance in nuclear physics between the experimental and the theoretical manpower. It is recognized in the budgeting process that without adequate (experimental) manpower and resources one cannot make effective use of the investment in facilities. For the field to flourish, an investment in nuclear theory, both in manpower and resources, is needed to provide the necessary theoretical effort to analyze the implications of the experimental results and motivate new investigations.

The current and near term JLab programs are driven by such concepts as the Bjorken and GDH sum rules, generalized parton distributions and QCD inspired models of hadron spectra. The search for the quark-gluon plasma is the primary goal for RHIC and the polarized proton program at RHIC promises a profound understanding of the nucleon's structure. Without an enhanced investment in the next generation of nuclear theorists, nuclear physics may well fail to generate the intellectual leadership for the future. Neither effective field theory nor generalized parton distributions were highlighted in the last Long Range Plan, and these novel developments testify to the high quality of the current nuclear theory community. However, the size of the community is too small to follow up on these successes.

Looking at the future, important opportunities that would benefit from enhanced manpower and resources include: developing consistent nuclear currents which are fully consistent with the modern two- and three-body nuclear force models used to calculate nuclear structure and reactions; developing a fully relativistic approach to modeling few-nucleon systems' response to high energy electromagnetic probes at JLab and Bates; to develop QCD based quark models of hadron structure and branching ratios that supercede the naive valence quark picture; developing an understanding of the methods required to extract hadron resonance properties from nuclei of two and more nucleons; and developing realistic models to describe the dynamics of the quark/gluon sea of nucleons as observed in deep inelastic scattering.

In addition, interpreting the hypernuclear structure that will be explored in the electromagnetic production of hypernuclei requires theoretical understanding of kaon dynamics as well as numerous model calculations. For lack of two-body scattering data, hyperon-nucleon interaction models must be constrained by exact calculations of the ground- and excited-state properties of light hypernuclei. Model calculations to correlate the JLab and AGS hypernuclear spectroscopy data are needed, as are model calculations to support the AGS program to measure weak decays and to confirm the existence of $\Lambda\Lambda$ hypernuclei. The latter bears significantly on the existence of the **H** dibaryon and the strangeness content of neutron stars. A significant effort in understanding the QCD origin of the short-range properties of $NN$ and $NNN$ forces, which, e.g., drive the equation of state and neutron star properties, is lacking for want of adequate manpower and resources.

We suggest that a plan to increase the number of nuclear theorists by 20% over the next six years is an appropriate yet modest goal. This clearly cannot be accomplished easily, but the plan outlined below describes a broad program of about the right size to accomplish this goal.

### 3.4.2 Nuclear Theory Plan

To solve these problems, nuclear theory requires an increase in manpower, resources, and funding of the necessary infrastructure. Such a recommendation should be included in the 2001 Long Range Plan. In order to recruit and retain the best young theorists and to support the theory needs of major experimental programs, annual expenditures should be ramped up over a six year period as suggested in the following infrastructure initiative.

**MANPOWER/RESOURCES**

**1. Pre-doctoral Program**
Establish a national pre-doctoral fellowship competition to fund 10 new graduate students per year (renewable for 5 years) who choose to study nuclear theory at universities with Ph.D. programs. This will attract the best and brightest undergraduates from throughout the U.S. ($ 1M)

**2. Post-doctoral Program**
Strengthen the postdoctoral program in nuclear theory by funding 12 new positions at the six current national lab/facilities plus 12 new positions at universities. This would provide manpower crucial to solve the current shortage and provide enhanced career opportunities for our most talented Ph.D. graduates in diverse settings. To foster a vibrant community, a *Young Physicist Panel* similar to the one in the high energy community should be established. The national lab program would increase the national labs involvement in the process of educating post-docs. ($ 2M)

**3. Laboratory Staff**
Increase the staff in the current national lab/facility nuclear theory groups by up to twelve over a six year period. This would drive needed diversification into new areas and approaches to research. This is also a key part of the strategy to provide appropriate career paths for the people we propose to recruit to the field. ($ 3M)

**4. Faculty Positions**
Offer faculty bridge positions at universities that agree to hire a nuclear theorist into a tenure-track position. This should expand the role of nuclear physics in the academic community and provide career paths for the new blood. ($ 2M)

**5. Resources**

Enhanced resources for theorists are key elements in increasing research productivity. It is essential to provide increased funding for theoretical collaborators to meet and interact, for theorists to acquire state-of-the-art computing equipment and for theorists to travel to conferences and workshops to present ideas and results for peer review prior to publication. An investment of the order of 1% of the current nuclear physics budget would provide a highly leveraged return. ($ 4M)

**6. Research Centers**

Create six topical research centers with funding of the order of $500K per year over a period of up to six years at universities willing to commit a tenured faculty position to head such a center. This is designed to make progress on specific hot topics and to promote research in the academic community requiring a team focus. ($ 3M)

The program outlined would cost $\simeq$ $15M per year at the end of the six year ramp up period.

*Table 1.* Possible funding profile for increased resources and manpower.

| | Year | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Theory enhancement: | $M | 2.5 | 5.0 | 7.5 | 10.0 | 12.5 | 15.0 |

**Recommendation**

We strongly recommend that the resources devoted to nuclear theory be substantially increased through the initiatives outlined above. The scientific opportunities created by the significant investment in the JLab, RHIC, and other experimental programs demand a comparable initiative to strengthen nuclear theory in order to exploit these opportunities. We recommend a plan to create a new program to attract the best and brightest of the nation's undergraduate students into the field; to increase post-doctoral opportunities for our most talented graduates; to provide career paths by adding staff positions at national labs/facilities and universities; to use the established mechanism of bridge positions for new faculty at universities; to increase funds for collaboration and computing costs to enhance research effectiveness; and to establish new topical research centers at universities.

# 4 Education, Outreach and Societal Impact

## 4.1 Education and the Role of Universities

### Introduction

A strong nuclear physics program is of strategic importance to the United States. It is essential that our field train the young scientists necessary to maintain the world leadership of the country in this important field of science. Strong university research groups and laboratories in nuclear physics are vital to achieve this. They attract the young talent which is the seed corn for our field.

### Current Status and Trends

Over the last decade, the field of nuclear physics in the United States has seen increasingly complex experiments requiring more sizable resources in an essentially static funding environment. There has been an increasing centralization of facilities. At the universities, undergraduate and graduate enrollments have declined in science in general, but particularly in physics. Further, because of tight funding, there has been a general deterioration in the research infrastructure at universities.

Enrollment of first year graduate students in physics has declined by about 25% since 1991. Furthermore, enrollment of first year US graduate students has declined by about 40% in the same period. Thus, at present, foreign students comprise approximately 50% of the first year physics graduate student class in the United States. Students studying nuclear physics account for about 7% of all physics graduate students in Ph.D. granting departments in the U.S.

The universities continue to be the intellectual driving force of our field with approximately 70% of all publications originating in academic institutions. University-based laboratories continue to be important attractors for students, both undergraduate and graduate, and provide a unique environment for young people to acquire 'hands on' training.

### Important Issues for the Long Range Plan

**The highest priority must be to attract students in greater numbers into nuclear physics at both the undergraduate and graduate levels.** University research groups and laboratories should be strongly supported so that students can experience nuclear physics research on their campus. A student's first taste of research can often develop into a lifelong career. It is vital that the nuclear physics university infrastructure be adequately maintained so that we can compete successfully for students with the other subfields of physics. In particular, unique university-based facilities carrying out frontier research should be strongly supported.

The critical importance to the field of maintaining a healthy equilibrium between the university and the national laboratory programs must be made clear. The significant scientific, financial, and manpower contributions of university programs in nuclear physics should be explicitly recognized in the Long Range Plan. In particular, the funds invested in universities are highly leveraged.

Finally, it must be noted that a significant fraction of Ph.D.s trained in nuclear physics now enter private industry and are playing an important role in the high technology economy. Our students are educated not only to think critically but also acquire highly marketable skills in data analysis, computing, and equipment design and construction. This important societal contribution should be highlighted in the Long Range Plan.

**Acknowledgements**

This contribution borrowed greatly from the presentation of Dr. J. Natowitz at the Oakland Town Meeting, November 2000.

## 4.2 Impact of Nuclear Science

In a report to Congress[Eld98] in 1998, *Unlocking our Future*, the House Committee on Science stated that in developing this report their guiding principles were:

*The United States of America must maintain and improve its pre-eminent position in science and technology in order to advance human understanding of the universe and all it contains, and to improve the lives, health, and freedom of all peoples.*

Within this section we now address the second of these two major missions - that of the impact of science, particularly nuclear science, on society. Indeed, public investment in scientific research is mainly justified by its contributions to improvements in the quality of life, long-term national growth, national security, and global stability. The investment in nuclear science has provided in the past, and will provide in the future, a substantial return on our investment in this mission.

The impact of nuclear science on society was most recently addressed in a report completed by the National Research Council[Sch99]. This report discussed the contributions of nuclear science to medicine, environment, industry, energy, and national security. In addition, nuclear science also impacts other fields such as information technology. Specific examples are prolific, although little quantitative data is available. However the report from the National Research Council concludes:

*It is appropriate to ask whether these contributions are likely to continue ... Many of the items* *discussed above seem likely to have still greater importance in the future, and new applications will certainly arise from new technical developments in nuclear physics.*

Thus there is every expectation that the presently large impact of our field on society will increase rather than diminish.

### 4.2.1 Medicine

In the 3500 hospital-based nuclear medicine departments in the US, approximately 10 million nuclear procedures, and 100 million laboratory tests are performed each year. In the 1600 radiation oncology departments, 2100 linear accelerators are used, treating about 10 thousand patients daily[Bag94]. Nuclear medicine and radiation oncology each generate income of about \$10 billion annually, while instrumentation produces an annual income of about \$3 billion[Sch99]. New cancer therapies using protons, neutrons, and heavy ions are under development which will provide higher linear energy transfers(LET), and these are more effective in dose deposition and lethality, especially to oxygen deficient cells.

Other medical procedures use radio-isotopes to trace in-vivo functionality of various organs and bodily systems. An interesting outgrowth of polarized target research has provided the only means to visualize lung function. This technique uses polarized $^{3}$He or $^{129}$Xe and MRI. The development of MRI itself is based on fundamental studies of nuclear spin. Most recently improvements in superconducting magnet technology, which was initially developed for use at nuclear accelerators, has advanced the application of MRI[Ros01] by 10 years. Superconducting magnets produce a large-volume, stable magnetic field, ideal for MRI imaging. Finally radioactive tracers allow researchers to follow biochemical processes, and to develop new drugs targeted to specific diseases or body systems.

Positron emission tomography (PET) is an excellent example of the application of sophisticated nuclear science techniques to medical diagnosis. PET is made feasible due to the production "in-house" of short-lived radio-isotopes by medical accelerators, to new data acquisition and fast signal processing of thousand channel detector arrays, and to graphic displays of the resulting data. This technology is a direct "spin-off" from modern experimental nuclear science.

Diagnostic imaging of medical data is a particularly interesting application. The figure shows an axial view of the brain with intensification indicating areas involved in a listening task. Similar displays of data can be shown in various 3 dimensional projections, and each of the 156 whole-brain images is acquired in 2 seconds[Dze94].

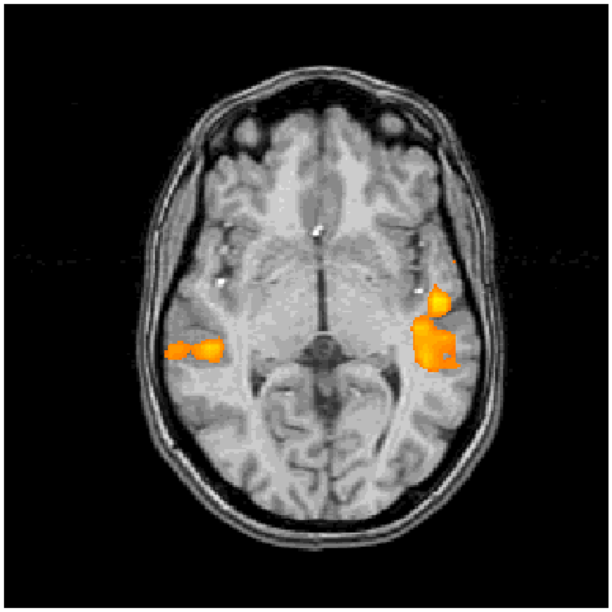

Figure 29: A graphic display of data showing areas of brain activity involved in a listening task.

### 4.2.2 Environment

Accelerator-based mass spectroscopy (AMS) has been used to study the concentration of various elements in the environment by measuring isotopic abundance ratios. As this technique is more sensitive than radioactive counting, and can also use stable nuclei, it has broad applications. Carbon-14 dating is well known, but the use of other isotopes such as $^{81}$Kr and $^{41}$Ca is now feasible, allowing studies of climatic change, ground-water dating, and the uptake by the body of hazardous chemicals. As one example, present AMS studies of the exchange of atmospheric $CO_2$ with the ocean are vital to understanding the impact of fossil fuels on the environment. In another application, the measurement of $^{41}$Ca can be used to investigate long-term osteoporosis, replacing a previous technique which was not very sensitive and involved large X-ray radiation dose.

### 4.2.3 Industrial Applications

Ion implantation is used to dope layers in semiconductors and to harden surfaces for bearings, cutting surfaces, and artificial joints. Beams of electrons and gammas are used for sterilization of foods and to cure epoxies. One interesting new application is the use of particle beams to pin the magnetic flux in high $T_c$ superconductors[Wei01], increasing the possible current densities and thus

Table 3: Enhancement of Current Densities In High $T_c$ Superconductors

| Beam Particle | Reaction[1] | Improvement in $J_c$ |
|---|---|---|
| $n_{thermal}$ | none | none |
| $n_{fast}$ | n + Y123 or Nd123 | $\times$ 10 |
| $p_{200\ MeV}$ | p + Y123 | $\times$ 10 |
| $Au_{5\ GeV}$ | Au + Y123 | $\times$ 50 |
| $Au_{50\ GeV}$ | Au + Y123 | $\times$ 100 |
| Fission[2] | n + U + Y123 or Nd123 | $\times$ 100 |

[1] Y123 is $YBa_2Cu_3O_7$ Nd123 is $NdBa_2Cu_3O_7$

[2] Fission of U in the material under neutron bombardment

the resulting magnetic fields. Table 1 shows the improvement in $J_c$ after irradiation by various particles. Magnets made of irradiated material can produce usable fields up to 5T in gaps of 5 X 5 X 3 $cm^3$, and presently 18T fields have been produced in laboratory materials.

Rutherford backscattering and neutron resonance fluorescence are used to measure material composition and thicknesses. In addition, beams from low energy accelerators are used to ionize atoms which then radiate characteristic X-rays. The detection of these mark the presence of specific elements in the target. These techniques are used whenever non-destructive elemental analysis is demanded, such as in the fields of geology, archaeology, and environmental science.

Power supplies developed for accelerators are widely used in industrial applications. These have found use in the production of silicon wafers and pollution control.

### 4.2.4 Energy

Nuclear reactors generate about 22% of our nation's power, and several states obtain more than 50% of their energy from fission. Presently there are no plans to add more nuclear capacity, although problems with global warming, air quality, and acid rain may eventually require society to re-evaluate this position. Electrical energy use in the US is expected to increase by 40% in the next two decades and require replacement of at least 25% of our current generation capacity[Wol01]. However, before widespread acceptance of nuclear power occurs, problems involving nuclear waste and safety will need to be better resolved. These will be addressed in large measure by nuclear scientists. For example research on the accelerator transmutation of nuclear waste and accelerator driven reactors may provide the required solutions. In any event, maintaining safely the present plants as they age is also an important concern, and in part, this is accomplished by testing and evaluation using nuclear techniques.

The production and use of fossil fuels is also influenced by nuclear science. Electric utility industries have installed on-line analyzers which determine the composition of coal by nuclear techniques, and monitor quality to sort and blend the composition of the fuel. These techniques are also used to monitor and reduce air pollution at the utility plants.

On a smaller scale nuclear "batteries" provide power for heart pacemakers and space probes. Accelerator technology is used in oil well logging, and to monitor the quality of the oil produced. In well logging a compact accelerator is inserted into a well and must operate in an extremely hostile environments[Bai01].

Finally it is interesting to note that a material, aerogel, developed commercially for use as a particle detector, now can be used as a high quality thermal insulator. One inch of aerogel is an equivalent insulator to 10 inches of fiberglass.

### 4.2.5 National Security

Nuclear science lies at the heart of the technology required to maintain our national security. As our country is no longer involved in nuclear testing, the maintenance of the existing nuclear stockpile involves computer simulation. This requires an understanding of the decay of, and particle emission from, fission reaction fragments - i.e. knowledge of a complex set of nuclear physics problems. In addition, the reliability of present weapons must be determined by non-destructive means. In this regard, a new technique, proton radiography, has been developed. This technique can also test the dynamics of non-nuclear explosives, which are used to trigger atomic weapons. The technology, now only in its infancy, will allow precise observation of of extremely fast chemical reactions.

As one additional component of stockpile stewardship, it is necessary to continually replace the tritium contained in thermonuclear warheads. This material was previously obtained from weapons reactors, but with the closure of these plants, new techniques, such as accelerator generation of tritium must be explored.

Stewardship also entails the monitoring of the nuclear capabilities of other countries, including the non-proliferation of nuclear materials. Gamma-ray imaging can be used to locate and identify nuclear materials, helping to verify treaty protocols and violations.

Finally, explosives can be detected using a technique similar to MRI, quadrupole resonance, and this can be applied to the detection of land mines as well as hidden bombs.

### 4.2.6 Information Technology

Nuclear science also pushes computer technology from computation facilities to data acquisition. RHIC requires unprecedented data acquisition capabilities including signal density, rate handling, and real-time analysis. To meet these requirements distributed signal processing and optical signal transmission techniques were developed to provide the needed bandwidth.

Computer initiatives[Neg01] in QCD computation propose to have machines capable of 10 tera-flops in 5 years. There is great interest in the computer industry to develop such machines, and a partnership has been arranged between JLab/MIT and a commercial computer manufacturer to push this technology.

Finally the World Wide Web, initiated by particle physicists, continues to be developed to provide information and communication.

## 4.3 Summary

More than half of our GNP growth in the past 50 years has been attributed to technology fueled by science. Today this number is closer to 70%. This fact was acknowledged by Federal Reserve Chairman Allen Greenspan in the statement[Gre99]:

*Something special has happened to the American economy in recent years ... a remarkable run of economic growth that appears to have its roots in ongoing advances in technology.*

However, while public funding for science as a whole has increased by a little over 50% in constant dollars during the past 30 years, funding for the physical sciences has remained approximately constant. Only funding for life sciences has increased, about a factor of 3, during this period, so that it now comprises about 50% of the total funding portfolio. This imbalance[Var00] was noted by Harold Varmus, Nobel prize winner in Medicine in 1989 and former NIH director.

*...But Congress is not addressing with sufficient vigor the compelling needs of the other science agencies* (i.e., other than NIH) *, especially the National Science Foundation and the Office of Science at the Department of Energy... Medical science can visualize the inner workings of the body at far higher resolution with techniques that sound dazzlingly sophisticated... These techniques are the workhorses of medical diagnostics. And not a single one of them could have been developed without the contributions of scientists, such as mathematicians, physicists and chemists supported by agencies currently at risk...*

Nuclear science has traditionally made major contributions to high-tech innovation including, but not exclusively, medical technology. It attracts some of the best minds pushing scientific frontiers, and it educates a knowledgeable workforce in high-tech fields. nuclear science is a major pillar underpinning our new, high-tech economy.

# 5 Facilities

The progressive evolution of nuclear physics depends critically on the availability and advancement of instrumentation for probing systems at distance scales less than 1 fm. A variety of particle accelerators are needed to illuminate and excite nuclear systems over a wide range of wavelengths and energy scales. The investigation of new phenomena and novel theoretical concepts compels the parallel push of accelerator and detector technologies. Most of our knowledge of nucleon structure and the strong interaction of fundamental particles comes from probing nuclear systems with electromagnetic and hadronic beams. This section provides brief descriptions of accelerator facilities available for carrying out the very ambitious research program in hadronic physics presented in this report. The emphasis is on accelerator facilities, with a facility being the accelerator complexes, the associated detector systems, the data acquisition systems, and the technical infrastructure required to operate the facility. An overview of the current U.S. facilities is given first, followed by a review of the foreign facilities, and then concluded with a global perspective. The facilities are divided into to general categories according to the type of beam delivered, either electromagnetic or hadronic (including only nucleons and mesons).

## 5.1 U.S. Facilities

The U.S. investment in facilities for the study of strongly interacting matter with medium- and high-energy electromagnetic and hadronic beams is primarily at six facilities: MIT-Bates, LEGS, JLab, the nuclear-physics program at SLAC, the fixed target program at Fermilab, and the proton-proton program at RHIC. Since the last long-range plan, the decision was made to gradually phase out support for the Indiana University Cyclotron Facility (IUCF) as a nuclear-physics user laboratory. This decision marks the end of the capability in the U.S. to offer medium-energy hadron beams to the nuclear-physics user communities. In this same period, production running started at JLab, the first beams collided at RHIC, and funds for the construction of the 1.2-GeV booster injector for the High-Intensity Gamma-Ray Source (HIGS) at Duke University were approved.

The electromagnetic-beam facilities are presented first and then the hadron-beam facilities are described. Only facilities with active nuclear-physics programs are included. The facilities are discussed in order of increasing maximum energy. Detailed descriptions of the facilities can be obtained from the facility web sites, which can be found by following the links at (*http://nucth.physics.wisc.edu/dnp/nplinks/labs.html*).

### 5.1.1 Electromagnetic beam Facilities

The electromagnetic-beam facilities in the U.S. with active nuclear-physics programs are HI$\gamma$S at Duke University, LEGS at BNL, MIT-Bates, JLab and SLAC. All facilities, with the exception of

SLAC, provide continuous beams of electrons and/or photons. The facilities that deliver photon beams produce the beams either by bremsstrahlung or by Compton backscattering. The facilities that use bremsstrahlung to produce photon beams use tagging systems to obtain high energy resolution, circularly polarized photons are produced with polarized electrons, and linearly polarized photon beams are generated by coherent bremsstrahlung. At Compton-backscattering facilities both polarizations are available by using either circularly or linearly polarized laser light. A brief description, the accomplishments and activities since the last long-range plan, and the near-term outlook are presented for each active facility.

**High Intensity $\gamma$-Ray Source (HI$\gamma$S):**

The High Intensity $\gamma$-Ray Source (HIGS) is a facility at the Duke University Free Electron Laser Laboratory (DFELL) in Durham, NC. The storage-ring FEL is used to produce a high-intensity (in excess of $10^7$ photons/s/MeV) gamma-ray beam in the energy range from 2 to 225 MeV by intracavity Compton backscattering. The present accelerator configuration is a 280-MeV linear accelerator for injection into the 1.2-GeV electron storage ring. The ring is designed to store a current up to 155 mA. The stored beam can be ramped to an energy of 1.2 GeV. The ring is an oval with a circumference is 108 m, and one of the straight sections is equipped with an optical klystron, the OK-4, at the center of an optical cavity to produce tunable laser light in the ultraviolet wavelength range. Gamma rays are produced by injecting two electron bunches that are 180° out of phase with each other into the storage ring. The more intense bunch (about 110 mA) is the source for lasing and the other bunch (about 10 mA) is the target for Compton backscattering. The collision between the target electron bunch and the reflected light bunch occurs in the drift space between the two wigglers of the OK-4. The energy resolution and intensity of the $\gamma$-ray beam is determined by collimation. The $\gamma$-rays are nearly 100% linearly polarized. The proposed research at this new facility includes: selected measurements in nuclear astrophysics, nucleon polarizabilities, nucleon spin polarizabilities, the Gerasimov-Drell-Hearn (GDH) sum rule on the deuteron and $^3He$, near threshold photo-pion production studies to test predictions of Chiral Perturbation Theory, low-energy photofission and nuclear structure studies of high-spin isomeric isotopes.

Since the last long-range plan, the technique of producing $\gamma$-rays by intracavity Compton backscattering in a FEL was demonstrated at HI$\gamma$S, the polarization of the $\gamma$-rays at HI$\gamma$S was empirically verified to be above 95%, and the first experiment was done at the HI$\gamma$S facility. A number of facility upgrades are scheduled for the next two years. The 280-MeV LINAC will be replaced with a 1.2-GeV booster injector to enable injection at the maximum energy of the ring. The OK-4 will be replace with a helical undulator, the OK-5. The helical undulator will give the capability of delivering either linearly or circularly polarized photon beams and will permit operation of the optical cavity at a higher power level by reducing mirror damage. The nuclear-physics target area will be instrumented for the first-generation experiments over the next two years. The facility upgrades will cost \$4M (\$3M from a special instrumentation grant from DOE/NP, \$0.65M from Duke University, and \$0.35M from redirected funds at TUNL). The upgrade is scheduled to be completed by 2003. In the meantime, experiments requiring only linearly polarized photons and energies below 40 MeV will run during the upgrade period. The cost of the annual 1000 hours of operations will be paid for by redirected funds from the DOE grant to TUNL.

**Laser Electron Gamma Source (LEGS):**

The Laser Electron Gamma Source (LEGS) is a facility at the National Synchrotron Light Source at Brookhaven National Laboratory (BNL). Gamma ray beams are produced by Compton backscattering of laser light from electrons circulating in the 2.5 - 2.8 GeV X-Ray Ring. Fluxes of $10^7$ gammas/sec are obtained but vary depending on the laser used, electron current and ring energy. Photons are tagged by detecting the scattered electrons in a spectrometer incorporated into the storage ring (tagging efficiency = 100%). Linear and circular polarization of >75% are available. The maximum $\gamma$-ray energy available at the facility is 470 MeV. The facility has an assortment of detector systems, including: a high energy gamma spectrometer (4 MeV resolution at 300 MeV), liquid hydrogen, oxygen, $^3$He and $^4$He targets, a 400-element sodium iodide array (XTAL-BOX), and a 1.5-$m^2$ 24-element phoswich scintillator array for TOF measurements. The FY2001 budget at LEGS for operations, capital equipment and support for resident physicists is $2.64M ($2.05M from DOE/NP to BNL, $0.23M from DOE/NP to collaborators, $0.24M from NSF/NP to collaborators, and $0.12M from foreign collaborators).

The research program at LEGS is devoted to carrying out sensitive new tests of models describing the internal structure of protons, neutrons and light nuclei, particularly properties associated with their spin. Questions addressed include: the intrinsic deformation of the nucleon and its first excited state, the $P_{33}$ $\Delta$ resonance; the strength of transient dipole moments (nucleon spin-polarizabilities) generated by the rearrangements of constituent spins during photon scattering; spin sum rules, such as the Gerasimov-Drell-Hearn, which ultimately test the structure of the Compton spin-flip amplitude at infinite energy; $NN$ tensor forces and the $N\Delta$ interaction in deuterium; and three-body forces in light nuclei.

Future LEGS experiments will focus mainly on beam-target double-polarization experiments with polarized photon beams on polarized $p$, $n$ and $D$. The two energy-weighted spin-structure sum rules (SR), the forward spin-polarizability SR ($\gamma_0$) and the Gerasimov-Drell-Hearn SR (GDH), are of considerable interest. The LEGS energy range (up to 470 MeV) covers the largest contributions to these integrals (90% for $\gamma_0$ and 60% for GDH), and these will be measured for both polarized protons and neutrons. The LEGS program is complementary to other facilities in the U.S. and abroad with very little overlap in energy. The capabilities of magnetic analysis and a Strongly Polarized Hydrogen-deuteride Ice targe (SPHICE), which is free of extraneous unpolarizable nuclei, make LEGS a unique facility for photo-nuclear physics with polarized neutrons below 0.5 GeV. While proton-GDH measurements are on-going at Mainz and Bonn in Germany, only the combination of magnetic analysis and SPHICE targets at LEGS and JLab can provide the needed capabilities for the neutron-SR measurements.

**MIT-Bates Linear Accelerator Center:**

The Bates Linear Accelerator at MIT provides high-quality electron beams up to an energy of 1 GeV. The pulsed linac and the isochronous recirculator provides currents in excess of $80\mu$A at a duty-factor of up to 1%. The accelerator-recirculator system feeds the recently completed South Hall Ring (SHR). The 190-m circumference ring will operate in the energy range up to 1 GeV at peak circulating currents of up to 200 mA for internal-target experiments and extracted currents of up to $20\mu$A with duty factors of 85%. The facility has two experimental halls in addition to the internal target area in the SHR. The North Hall receives beam directly from the LINAC recirculator system and is equipped with a high-resolution spectrometer system. The SAMPLE detector for parity-violating electron-proton and electron-deuterium scattering is set up in this hall. The South Hall has three medium-resolution, large solid-angle acceptance magnetic spectrometers and a set of four newly commissioned out-of-plane magnetic spectrometers (OOPS). There are four central research thrusts at this facility: the flavor structure, charge distribution, shape, size and polarizability of the nucleon; the spin and electromagnetic structure of light nuclei; the origin of the elements; and the studies with polarized beams in the SHR. The FY2001 budget for the MIT-Bates facility from the DOE/NP is $14.1M for 2000 hours of operation, capital equipment projects and research. In addition, MIT contributes $0.5M towards the operation of Bates. An additional $0.5M has been requested from DOE to run the SAMPLE experiment in the summer 2001.

There have been a number of significant achievements at this facility since the last long-range plan. Measurements of parity violating elastic scattering from the nucleon at an energy of 200 MeV were completed by the SAMPLE collaboration. Their results indicate that the *strange* quark-antiquark pairs contribute less than 5% to the proton's magnetism. The SHR was commissioned for a peak stored beam of over 200 mA and a high-duty factor extracted beam of 7 $\mu$A. The OOPS were completed, and the first data were taken with this unique spectrometer system.

In the next year, construction of the Bates Large Acceptance Spectrometer Toroid (BLAST) will be completed and commissioning will start in 2002. The initial BLAST experimental program is expected to run through 2005. In addition, one experiment will be run each year using the OOPS system after 2002. Faculty at MIT-Bates has taken a leadership role in the planning and design efforts of the proposed Electron Ion Collider (EIC), described in an earlier section of this report. They plan to request funds to conduct R&D on design aspects of the EIC over the next several years.

**Jefferson Laboratory (JLab):**

Jefferson Laboratory (JLab) is a national user facility located in Newport News, VA. The laboratory has two independent accelerator complexes, the continuous electron beam accelerator facility (CEBAF), which provides beams for nuclear-physics research and a Free-electron laser (FEL) that supplies tunable high-intensity coherent light in the infrared wavelength region for interdisplinary and applied research. Our interest in this report is CEBAF. The accelerator at CEBAF is a superconducting continuous wave electron accelerator with a maximum energy of 5.5 GeV and 100% duty factor. The racetrack-shaped accelerator consists of two parallel superconducting linear accelerator sections joined at each end by 9 isochronous magnetic arcs which allow the electron beam to be recirculated up to five times. A Radio-frequency separator allow extraction of beam with different energies to the three circular-shaped experimental areas. Three electron beams with a combined maximum current of 200$\mu$A can be simultaneously injected into the accelerator for beam delivery to the three experimental areas. The FY2001 requested budget to the DOE/NP for JLab is \$74.7M to operate the accelerator for 4500 hours and for capital equipment.

Hall A, with a diameter of 53 m, is the largest of the three experimental areas. The primary base equipment is two 4-GeV/c high-resolution ($10^{-4}$) magnetic spectrometers (HRS). The detector packages have been optimized differently; one for detecting electrons and one for detecting hadrons. The hadron spectrometer is equipped with a focal plane polarimeter. The experimental program in Hall A is broad and mainly ultilizes the two HRS to make $(e, e'p)$ and $(\vec{e}, e'\vec{p})$ coincidence measurements. The program includes precision measurements of the nucleon electromagnetic form factors, determinations of the strange-quark contributions to the charge and magnetization distributions of the nucleons via parity-violating electron scattering experiments using both H and $^4$He targets, detailed studies of spin observables in the $N \rightarrow \Delta$ transition region, and selected few-nucleon and nuclear structure studies.

Hall B has a diameter of 30 m and is equipped with the CEBAF Large Acceptance Spectrometer (CLAS) and a bremsstrahlung tagging system. The CLAS is based on a toroidal magnetic field produced by six superconducting magnetic coils. The six sectors between the coils are instrumented with drift chambers, Cerenkov counters, scintillation hodoscopes, and electromagnetic calorimeters which identify and determine the momentum of several, simultaneously-emitted, charged particles. The CLAS combines large solid angle acceptance with excellent particle tracking, identification and momentum resolution. Together with the bremsstrahlung tagging system, the CLAS facility provides special capabilities for studying the structure of nucleons by electro- and photo-excitation.

Hall C, 46 m in diameter, supports a broad research program including the study of strange matter, parity-violation measurements, and high $Q^2$ form-factor measurements. This varied program requires a flexible set of instrumentation. The primary base equipment in the Hall consists of a medium-resolution ($10^{-3}$) high-momentum magnetic spectrometer (HMS) and a short-orbit magnetic spectrometer (SOS). The HMS serves as a hadron spectrometer for high $Q^2$ measurements and as an electron spectrometer both for inclusive scattering experiments and for coincidence experiments in combination with the SOS.

Impressive scientific and facility achievements have been made at JLab since the last long-range plan. Among the facility highlights are the completion and commissioning of the base instrumentation in the three experimental areas and the efficient running of the experimental program in each hall; the acceleration of the electron beams up to 5.5 GeV, exceeding the original design specifications of the cryo cavities; and the delivery of high-current polarized electron beams with polarization up to 70%. Many of the results from the initial experiments are noted in the highlights section of this report.

The plans for the next three years are to continue running the programs in the three halls and in parallel to make incremental increases in the accelerator maximum energy to reach 6 GeV by reconditioning some accelerator cavities. The ambitious polarized electron source R&D program will continue for some time. Modest instrumentation improvements and additions to the base equipment in all three halls are planned to meet the needs of the approved experiments. For example, a photon calorimeter will be installed in Hall A for a real-photon Compton-scattering experiment. In addition to the normal changes, instrumentation for two major experiments will be installed in Hall C: a polarized deuterium target and a shielded neutron-detector array for electric form-factor measurements of the neutron, and the G0 detector system for determining the strange content of the nucleons by parity-violating elastic electron scattering. The plans beyond the next three years is to perform an energy upgrade to reach 12 GeV. The proposed upgrade is described earlier in this report.

**Stanford Linear Accelerator Center (SLAC):**

The SLAC is a high-energy accelerator facility located at Stanford University. A very impressive program in nuclear physics co-exists with the main missions in pariticle physics at this facility. A newly developed coherent bremsstrahlung (polarized) photon beam with energies from 5 to 48 GeV makes possible a number of extremely exciting and important experiments for the next five years. The EPAC at SLAC has recently approved three nuclear physics experiments: *Proposal to Measure* $\Delta\sigma^{\gamma N}(k)$ *and the High-Energy Contribution to the Gerasimov Drell Sum Rule* (E159), *Proposal to Measure the A-Dependence of* $J\psi$ *and* $\psi'$ *Photoproduction* (E160), and *Proposal to Measure the Gluon Spin Distribution Using Polarized Charm Photoproduction* (E161). The first of these experiments will likely run in the next two to three years, and each subsequent experiment should follow in about one to two years. The cost of running this program to the DOE/NP is the support cost of the users and the funding of instrumentation for the experiments.

### 5.1.2 Hadron Beam Facilities

The hadron-beam facilities in the U.S. with active nuclear-physics programs are IUCF, AGS/BNL, RHIC/BNL and Fermilab. At both RHIC and Fermilab only a limited fraction of facility operation time is dedicated to hadron physics experiments. An initiative is proposed to continue use the AGS at BNL to run a limited fixed-target program in hadronic spectroscopy. The programs at the four U.S. hadron-beam facilities are described below.

**Indiana University Cyclotron Facility:**

The IUCF is a medium-energy nuclear physics user facility located on the campus of the

Indiana University in Bloomington. For more that two decades the research program at IUCF has significantly contributed to nuclear physics in the area of medium-energy hadron physics. It is now the only facility in the U.S. with the capability to provide users with proton and deuteron beams in the energy range from 100 to 500 MeV. The facility has two accelerator complexies, a set of coupled cyclotrons that are used for interdisciplinary research and an electron-cooled storage ring that receives beam from a synchrotron injector system. The nuclear physics program is carried out using the electron-cooled storage ring (the Cooler). Proton or deuteron beams are injected into the Cooler ring at energies between 100 and 240 MeV and ramped to energies up to 500 MeV. Polarized proton beams with polarizations up to 70% and gaseous polarized targets are available. The fiscal year 2001 budget to run the Cooler program is approximately $6.4M of which $5.3M is from the NSF and $1.1M is contributed by the University of Indiana.

Since the last long-range plan the results of experiments conducted at IUCF have contributed significantly to the precise modeling of the nucleon-nucleon (NN) interaction, to the resolution of discrepancies in the magnitude on the pion-nucleon coupling constant, and to new insights about the short-range nature of the NN interaction by studies of pion production near threshold. The details of many of these findings are presented in the highlights section of this report. In addition, a number of technical achievements were made over the same period. The construction of the Cooler Injector Synchrotron (CIS) and the Polarized Ion Source (CIPIOS) were completed, and both were commissioned. The new source and injector system gives a factor of about 100 increase in the stored beam intensity in the Cooler ring over the previously used cyclotron injector and results in much more reliable operation. The upgraded system provides stored currents of up to 10 mA of unpolarized and up to 2.5 mA of 70% polarized proton beams. A laser-driven polarized gaseous target was developed and installed in the Cooler ring. The first Polarized Internal Target EXperiments (PINTEX) were installed in the Cooler ring and commissioned, and the first data were taken with this pioneering facility. These new data are setting standards in the level of precision and variety of observables in medium-energy polarization measurements.

The plan is to run the approved Cooler experiments through the end of 2002. In preparation for the last two years of the running, a number of facility developments, in addtion to the ones above, has been made. For example, a neutron tagger has been constructed and commissioned, and development of storing deuteron beams is underway. The three major thrust of the Cooler program are: study of three-nucleon forces via measurement of polarizaion observables in $pd$ elastic scattering and breakup, measurement of $g_{\pi NN}$ via a precision measurement of $np$ elastic scattering, and study of charge symmetry breaking via the $d + d \to \alpha + \pi^{\circ}$ reaction.

**Fixed-Target Program at the AGS:**

The Alternating Gradient Synchrotron (AGS) at BNL has become the injector for RHIC. However, since the RHIC rings require only two fills each day, the AGS remains available to provide a proton beam during RHIC operation approximately 20 hours per day. The cost of the fixed-target program is reduced to the costs associated with the fixed-target beam lines plus the incremental costs of running the AGS during the periods it would otherwise be kept in an idle state. This mode of running will be initiated during the 2001 running period.

The current program uses the existing secondary separated-beams of kaons, pions, and antiprotons to access physics not available at any other facility. The D6 line is capable of delivering 1.8 GeV/c kaons at a flux of more than $10^7$ kaons/s. This energy and flux are used to create systems containing one and two strange-quarks. Combining this line with the Japanese built Germanium "Hyperball", which detects coincident $\gamma$-rays, has recently produced missing-mass resolutions of a few keV and these observed hypernuclear level splittings provide insight into the nature of the baryon-baryon force. In another experiment, the first study of strangeness -2 systems was performed by observing their mesonic weak-decays using the Cylindrical Drift chamber System (CDS). The Crystal Ball detector package has been successfully utilized for meson and baryon spectroscopy.

For the future, it is proposed that the fixed-target program continue to run for 10 weeks per year, concurrent with the running of RHIC, and that the AGS deliver beam to two concurrently-running experiments. The continuation of the AGS fixed-target program would provide necessary complementary data to the N* program at JLab as well as allow meson spectroscopy and hyperon physics not otherwise accessible. This program would provide a bridge to the start of the recently approved Japan Hadron Facility. It is also proposed that a second high-quality separated beam line in the 2 GeV/c momentum regime be constructed and instrumented. When running concurrently with the RHIC operation, the cost to deliver beam to the fixed target experiments is about $2.5M per year. The estimated cost to build and instrument the second beam line is $10M ($5M for the beamline and $5M for detectors and electronics).

**Fixed-Target Program at Fermilab:**

The main injector at Fermilab provides proton beams for fixed-target programs in three dedicated areas, the meson, neutrino and proton areas. The momentum of the primary beam delivered to the fixed-target areas is 120 GeV/c. Among the current topics investigated at the meson and proton areas are: searches for CP violation in the decays of hyperons, measurement of the anti-quark content of the proton, studies of charm baryon physics, and studies of heavy-quark states with one or more charm quarks interacting with light quarks (strange, up, down). The running of the already approved experiments will certainly last through the period of this long-range plan.

**Spin-Physics Program at RHIC:**

The Relativistic Heavy-Ion Collider (RHIC) is a major nuclear physics facility at the BNL. The main accelerator at RHIC consists of two concentric rings of superconducting dipole and quadrupole magnets together with RF accelerating systems and corrector magnets. The rings are 3.9-km in circumference and have six intersection points, four of which are instrumented for nuclear-physics experiments. The accelerator complex at RHIC is capable of producing proton-proton ($pp$) collisions up to a c.m. energy of 500 GeV and heavy-ion collisions up to a c.m. energy of 200 GeV per nucleon pair. The anticipated luminosities are $2 \times 10^{28}/cm^2/s$ for heavy-ion collisions and up to $10^{31}/cm^2/s$ for $pp$ collisions. During production running the tandem-Booster-AGS complex is used to fill the rings about twice each day. The injection energy is 26 GeV, and the time required to fill both rings is about one hour. Protons can be longitudinally and traversely polarized. There are two major collider detectors, STAR and PHENIX and two smaller scale detectors, PHOBOS and BRAHMS. The main components of the physics program at RHIC are: the search for and study of the quark gluon plasma (QGP), the study of hot compressed hadronic matter, and hadronic spin physics. The design of the accelerator and the two major detectors are optimized to pursue the central mission of the facility, the search for the QGP. The STAR detector design emphasizes detection of global features of hadrons and jets as the signature for QGP formation. The focus of the PHENIX detector is on detection of leptons, photons, and hadrons in selected angle ranges to find electromagnetic signatures of QGP formation. Upgrades to the STAR and PHENIX detectors are underway to improve their capabilities for hadron-spin-physics measurements.

The commisioning of the RHIC accelerators and detectors started in the first quarter of 2000 and progressed with great success throughout the year. The first collisions of heavy ions were achieved in June 2000. Commissioning associated with the RHIC spin program has also been very impressive. The first test of the Siberian Snake with high-energy beam was done and control of the proton spin was demonstrated. Also, polarized protons have been stored and accelerated in the RHIC rings. The acclerator complex is technically ready to start the RHIC spin program. The hadron spin part of the RHIC program will operate about 10 weeks out of the 37 weeks of operations per year. The FY2001 requested budget to the DOE/NP for RHIC operations and equipment is \$119M. By prorating the part of the RHIC program dedicated to hadronic physics, the estimated annual cost to run the pp collision program at RHIC is \$32M.

**Summary of U.S. Medium- and High-Energy Accelerator Facilities:**

The U.S. has strategically invested in facilities that will enable an effective pursuit of the key issues in the scientific plan presented at this town meeting. The continuous flow of modest amounts of funds for capital equipment to the major user facilities enables the flexibility needed to respond to new physics opportunities and provides the means to keep the facilities modern. The estimated annual cost in FY2001 to run the hadron-physics programs at the medium- and high-energy facilities described in this section is \$131.54 M. This estimate is the full annual cost of the facility including capital equipment and funding for approved upgrades. The funding for the HI$\gamma$S upgrade is prorated over three years, and only the cost of running the $pp$ collision part of the RHIC physics program is included. Also, user support is not included in this estimate.

Combining the capabilities at the U.S. facilities with those offered at foreign facilities gives an impressive array of tools for probing subnucleonic degrees of freedom. However, there are some noticeable gaps in the kinematic phase space accessible at existing facilities with sufficient luminosities to meaningfully probe these regions, and there is a lack of medium-energy hadron beam types needed to conduct the detailed nucleon spectroscopy required to gain real insight about confinement issues. New facilities and upgrades to existing facilities are being proposed by both the U.S. hadron-physics communities and by foreign communities to remedy the critical short falls. These initiatives are described in an earlier section of this report.

## 5.2 Foreign Facilities

In this section we describe the major electro-magnetic and hadron beam facilities outside the U.S. that are currently being used to conduct the research described in the scientific sections of this report.

### 5.2.1 Electromagnetic beam Facilities

The major electromagnetic beam facilities outside the U.S. with active nuclear-physics research programs are listed in Table 4. All facilities in Table 4, with the exception of COMPASS, provide continuous beams of electrons and/or photons. In the five years since the last Long Range Plan the MAMI and ELSA facilities have provided polarized electron beams on a routine basis. The facilities that deliver photon beams produce the beams either by bremsstrahlung or by Compton backscattering. All electron-beam facilities can produce photons. However, only those facilities that provide photon beams with high energy resolution are listed in Table 4. The facilities that use bremsstrahlung to produce photon beams use tagging systems to obtain high energy resolution. At these facilities circularly polarized photons are produced with polarized electrons, and linearly polarized photon beams are generated by coherent bremsstrahlung. At Compton-backscattering facilities both polarizations are available by using either circularly or linearly polarized laser light.

In the five years since the last Long Range Plan the nuclear-physics programs at the AmPS facility at NIKHEF (in 1998) and the SAL facility at Sasakatchewan (in 1999) were discontinued. However, new facilities were constructed in that period: GRAAL, DA$\Phi$NE, the LNS stretcher ring and SPring-8. A brief description of the facility capabilities and the research programs are given here. More complete descriptions can be obtained from the facility web sites, which can be reached from links at (*http://www-elsa.physik.uni-bonn.de/accelerator_list.html*).

**Superconducting DArmstadt LINear ACcelerator (S-DALINAC):**

The facility at the Technical University of Darmstadt utilizes the superconducting recirculator S-DALINAC with a maximum energy of 130 MeV, which can also be operated as a FEL. There are three experimental areas for nuclear physics: 1) a low-energy ($<$ 10 MeV) bremsstrahlung facility for Nuclear Resonance Fluorescence studies of mainly scissor-mode excitations, 2) a 180° scattering facility for similar studies and 3) a high-resolution magnetic spectrometer for coincidence studies

Table 4: Overview of foreign electromagnetic-beam facilities, ordered according to their maximum energies. The facilities listed in bold type are approved upgrades to existing facilities.

| Energy Range | Electrons | | Real Photons | |
|---|---|---|---|---|
| | Facility | Location | Facility | Location |
| < 150 MeV | S-DALINAC | Darmstadt | MAX-Lab | Lund |
| | LNS-LINAC | Sendai | **SPring-8** | Harima |
| < 1 GeV | MAMI-B | Mainz | MAMI-B | Mainz |
| | | | **MAX-LabII** | Lund |
| < 10 GeV | LNS-STB | Sendai | GRAAL | Grenoble |
| | **MAMI-C** | Mainz | **MAMI-C** | Mainz |
| | ELSA | Bonn | ELSA | Bonn |
| | DAΦNE($e^-e^+$) | Frascati | SPring-8 | Harima |
| > 10 GeV | COMPASS ($\vec{\mu}$) | Geneva | | |

of nucleon knock-out from Giant Resonances.

**MAX-Lab:**

The tagged photon facility of Max-Lab, at the University of Lund, utilizes the almost continuous electron beam with an energy of up to 80 MeV, extracted from one of its storage rings. The nuclear physics research program is presently focused on establishing which reaction mechanisms are important in the absorption of photons in a variety of nuclei. In the immediate future the Max-Lab SR facility will be upgraded by installing a 700-MeV recirculating accelerator and a new storage ring. The photon tagging spectrometer from Saskatchewan will be installed in the extraction line of the 250-MeV storage ring.

**Laboratory of Nuclear Science at Tohoku University (LNS):**

The Laboratory of Nuclear Science at Tohoku University has had a low duty factor 300-MeV linac (LNS-LINAC) for a long time. Recently, a stretcher/storage ring (LNS-STB) has been commissioned, in which the stored beam can be ramped to 1.2 GeV. With this combination a variety of experimental facilities is being conceived: real photons and internal targets at 1.2 GeV and a CW extracted electron beam at 300 MeV.

**MAinz MIcrotron Facility (MAMI):**

The MAMI-B facility at the University of Mainz is a three-stage room-temperature microtron, producing a maximum energy of 850 MeV. The beam can be delivered to three experimental halls.

The first, used for electron beams, has three magnetic spectrometers; the second, used for photon beams with a high-resolution tagger system, utilizes a variety of large-acceptance non-magnetic detectors; and the third, again using electron beams, is available for special experiments. Previously, the three hall was used for measurements of the neutron electric form factor with non-magnetic detectors, now a large array of $PbF_2$ crystals has been installed for a measurement of the electroweak form factor of the proton. Highlights of the research program are pion photo- and electro-production near threshold, the neutron electric form factor, proton and two-nucleon knock-out, the E2/M1 and C2/M1 ratios in the excitation of the $\Delta$ resonance and the GDH sum rule. At present a fourth microtron is being installed which will increase the maximum energy to 1.5 GeV. The future research will focus on studies of small amplitudes in resonance production with the aid of the Crystal Ball detector and on hypernuclear spectroscopy.

**ELectron Stretcher Accelerator (ELSA):**

The ELSA facility at the University of Bonn is comprised of a 1.6-GeV booster synchrotron and a 3.5-GeV stretcher ring, which can produce low-intensity electron beams and tagged photon beams. Recent research used a large-array of scintillator detectors (PHOENICS) and a large-acceptance dipole magnet (SAPHIR) to study meson (mainly $\eta$ and $\omega$) photo-production. At present a program has been initiated to measure the GDH sum rule and the Crystal Barrel has been installed.

**DAΦNE at Frascati National Laboratory:**

At the Frascati National Laboratory a $\phi$-factory, DAΦNE, has been constructed. In this facility $\phi$-mesons are produced in abundance by colliding the beams from a positron and an electron storage ring, each with an energy of 0.51 GeV. The main research program at DAΦNE is a detailed study of CP violation in the decay of $\phi$- and K-mesons with the KLOE detector. A second detector, FINUDA, will be used for studies of the spectroscopy and decay modes of $\Lambda$-hypernuclei, which will be produced by stopping K-mesons inside nuclear targets.

**GRenoble Anneau Accelerateur Laser (GRAAL):**

GRAAL, installed in 1997, is focused on the study of the Gerasimov-Drell-Hearn sum rule and of meson photo-production off the proton in an energy range between 500 and 1500 MeV. The photon beam is produced by Compton backscattering off the 6-GeV electron beam, circulating at the European Synchrotron Radiation Facility. The main component of the detector system is a large-acceptance BGO-array.

**Super Photon Ring - 8 GeV (Spring-8):**

A new facility for photon beams has recently been completed at the SPring-8 facility of the

University of Osaka. Photon beams in an energy range of 1.5 to 3.5 GeV are produced by Compton scattering light from an Argon laser off the 8-GeV electron beam stored at the SPring-8 synchrotron radiation facility. The initial instrumentation, with the main components being a large-aperture dipole magnet and a large TOF scintillator array, is designed for the detection of charged decay products at forward angles. In the near future a low-energy ($< 10$ MeV) photon facility will be added, which will use Compton scattering from a far-infrared laser.

#### COMPASS:

The COmmon Muon Proton Apparatus for Structure and Spectroscopy (COMPASS) at CERN is designed to operate in two modes. In the first mode 100 and 200 GeV polarized muons are used mainly to study the gluonic spin contribution to the proton spin through open charm production. The second utilizes 100 to 280 GeV beams of $\pi$, K and protons for the production of exotic hybrid mesons and studies of hadron polarizabilities through Primakoff scattering off a heavy nuclear target. The experiment is presently in its commissioning phase.

#### Summary of the Foreign Effort using Electromagnetic Probes

The information given in this section clearly indicates that there is a very active and advanced (and thus competitive) research program with electromagnetic probes outside the US with electron beams in an energy range up to 1.5 GeV and with photon beams up to 3 GeV. At higher energies, however, there are at present only plans, and any decision about such plans is not expected before 2005.

### 5.2.2 Hadron Beam Facilities

In this section a brief review of foreign (non-US) facilities where hadron physics is studied with hadronic beams is given. The facilities are listed in Table 5 in order of increasing maximum particle energy. The facilities that offer momentum analyzed secondary beams are indicated.

#### The Research Center for Nuclear Physics (RCNP):

The Research Center for Nuclear Physics at Osaka University is a multi-site facility consisting of three major laboratories: the Cyclotron Laboratory in Osaka, the Oto Cosmo (underground) Observatory in the Tentsuji tunnel, and SPring-8 in Harima. The accelerator at the cyclotron laboratory (RCN-CL) consists of a AVF injector cyclotron with K=140 MeV and a ring cyclotron with K=400 MeV. Polarized proton beams are available. The main detectors are a high-resolution ($\Delta p/p = 3 \times 10^{-5}$) two-arm magnet spectrometer, an array of neutron detectors for TOF measure-

Table 5: Overview of foreign hadron-beam facilities, ordered according to their maximum energies. Availability of momentum analyzed secondary beams is indicated.

| Energy Range | Facility | Location | Accelerated Beams | Secondary Beams |
|---|---|---|---|---|
| < 1 GeV | RCNP-CL | Osaka | p,d | mesons |
| | TRIUMF | Vancouver | p,d | mesons |
| | PSI | Zürich | p,d | mesons |
| < 10 GeV | TSL-CELSIUS | Uppsala | p | |
| | COSY | Jülich | p | |
| < 30 GeV | KEK | Tsukuba | p | mesons, $\bar{p}$ |
| | | Damstadt | p, $\bar{p}$ | |
| < 100 GeV | IHEP | Protvino | p | mesons, $\bar{p}$ |
| < 600 GeV | COMPASS | Geneva | p | mesons |

ments and a neutron polarimeter. The research program includes studies of the nucleon-nucleon interaction, few-nucleon studies, investigations of hyperon interactions and flavor nuclear physics.

**TRI-University Meson Facility (TRIUMF):**

The TRI-University Meson Facility (TRIUMF) is located on the campus of the University of British Columbia in Vancouver, Canada. The accelerator at TRIUMF is a six-sector isochronous cyclotron that can accelerate $H^-$ ions to a maximum kinetic energy of 520 MeV. Two proton beams are extracted simultaneously to feed two experimental areas, the proton hall and the meson hall. The energies of the beams may be varied independently between 183 and 520 MeV. A laser optical-pumped ion source provides high-intensity polarized proton beams for injection into the cyclotron. The research program includes studies of decay modes and other fundamental properties of pions and muons, precision measurements of symmetries in the nucleon-nucleon system, parity violation measurements, and muon spin resonance studies of solids, liquids and gases. An Isotope Separator and ACcelerator (ISAC) facility is under construction. This new facility will be used for nuclear astrophysics and nuclear spectroscopy research with rare isotopes.

**Paul Scherrer Institut (PSI):**

The Paul Scherrer Institut (PSI) is a multidisciplinary research center located in northern Switzerland, approximately midway between Zürich and Basel. The cyclotron provides proton beams up to an energy of 590 MeV for the nuclear-physic program. Polarized proton beams with intensities up to 10 $\mu$A and 75% polarization are available. The research program in nuclear physics includes studies of: pionic and muonic atoms, muon-catalyzed fusion and muon-induced fission, pion-nucleon and pion-nuclear interactions, nucleon-nucleon and few-nucleon physics with polarized beams and polarized targets.

**The Svedberg Laboratory (TSL):**

The Svedberg Laboratory (TSL) is a national research facility located in Uppsala, Sweden. Protons can be accelerated up to an energy of 1360 MeV with a momentum dispersion of ($\Delta p/p = 2 \times 10^{-3}$) in the CELSIUS storage ring at TSL. The momentum dispersion in the stored protons can be reduced to ($\Delta p/p = 2 \times 10^{-4}$) by electron cooling up to a proton energy of 500 MeV. The experiments use either a gas jet target or a very innovative and unique hydrogen pellet target in the ring. There are currently two major detectors, WASA for hadron physics and CHICSI for heavy ion physics. The WASA detector, which is operative now, has $4\pi(96\%)$ acceptance and consists of a central and a forward detector. The central detector consists of a drift chamber, a scintillation counter barrel, an ultra-thin wall superconducting solenoid (0.18 rad length), and a 1020 element CsI calorimeter. The physics program with WASA intends to concentrate on threshold and subthreshold production of $\pi, 2\pi, \eta, \omega, \eta'$, and $\phi$, using p, d, and $^3$He targets, and the study of rare decays of $\eta$ which will enable tests of C and CP invariances, and chiral perturbation theory at the $10^{-9}$ level, as compared to the $10^{-4} - 10^{-5}$ level currently in the literature.

**The COoler SYnchrotron (COSY):**

The COoler SYnchrotron (COSY) is at the Institute for Nuclear Physics in Jülich, Germany. Protons are accelerated, cooled and stored in the COSY in the momentum range 0.3 to 3.3 GeV/c. It is planned to replace the old cyclotron injector with a LINAC to obtain better beams and more control over polarization degrees of freedom. There are several operating detectors at COSY for internal-target and extracted-beam experiments. A very wide ranging program of physics is actively pursued at COSY including: study of nucleon-nucleon scattering with polarization and spin correlations, threshold and sub-threshold production of mesons, modifications of hadron structure in nuclear medium, and search and study of exotic structures such as dibaryons and glueballs. A number of important and very difficult experiments have been successfully conducted at COSY. For example, measurements of meson production cross sections to within 300 keV of threshold, and the successful identification of subthreshold kaon production in nuclei in the reaction $pp_{nucl} \rightarrow p\Lambda K^+$ with 1.0 GeV incident protons represent tour de force (threshold with free protons in 1.58 GeV) achievements.

**The NUCLOTRON/Synchrophasotron Facility (Dubna)**

The year 2000 saw the first extracted beam from the NUCLOTRON ring at the Joint Institute of Nuclear Research Laboratory of High Energies in Dubna. The accelerator complex including the

Synchrophasotron and the NUCLOTRON can deliver beams of high intensity polarized protons and deuterons as well as a range of heavy ions with kinetic energy 4.2 GeV/u. The design of the low-cost miniature superconducting magnets in the NUCLOTRON should have wide applications. With severe budget restrictions, several physics exeriments per year have been carried out in recent years with internal targets. Equipment from laboratories in the West has been welcome: a polarized proton target (Argonne, Saclay, Dubna) is operational, the Medium Resolution Spectrometer from Los Alamos is expected soon, and the polarimeter POMME from Saclay will be installed this summer. The physics program includes spin effects in the few nucleon system, cumulative (kinematically "forbidden") particle production and multi-nucleon fragmention in nucleus-nucleus collisions. International collaborations are invited.

**Koh-Ene-Ken (KEK):**

The KEK facility is located in Tsukuba, Japan. It has a 12-GeV proton synchrotron built for high-energy physics that is now being used for both particle and nuclear physics experiments. The facility has several well designed and well instrumented beam lines for transport of secondary particles like pions, kaons and antiprotons. There are four well-instrumented magnetic spectrometers at the facility: KURAMA is a medium acceptance spectrometer with a scintillation fiber active target; BENKEI is a multiparticle spectrometer with an emphasis on neutral meson detection; TOROIDAL is a large acceptance superconducting toroidal spectrometer for stopped-K experiments; and SKS is a high-resolution large-acceptance superconducting spectrometer for nuclear spectroscopy. The main emphasis of the research program are K-decay studies, hadron spectroscopy, hypernuclear spectroscopy, pion physics, and the K2K experiment (a tagged neutrino measurement done with the Super-Kamiokande detector).

**Institute for High-Energy Physics (IHEP):**

The 70-GeV proton accelerator facility, which is located in Protvino in the Moscow region in Russia, has a distinguished past. The GAMS, VES, and SPHINX Collaborations have made notable contributions in the spectroscopy of light hadrons and in searches for exotics and glueballs. Unfortunately, they have great difficulties in finding the financial resources to run the accelerators for more than a couple of months per year. Nevertheless, they have been able to do a modest upgrade of the VES spectrometer and squeeze in a 5 to 6 week long run each year, one in 1999, one in 2000, and hopefully one in 2001 and 2002. Their physics objectives include: Primakoff production of light hadron resonances, diffractive production of charmed mesons, and study of rare decays using 23-GeV/c and 46-GeV/c proton and kaon beams. They suffer from manpower shortage and invite international collaboration.

**COMPASS:**

Several CERN experiments have made notable contributions to hadron spectroscopy in the past. These include: Crystal Barrel, Obelisk, and JETSET at LEAR, and GAMS(II) and WA102 at the SPS. The LEAR experiments, GAMS and WA102 are finished taking data. The only remaining experiment at the SPS that is at least half devoted to hadron spectroscopy is COMPASS. The 400-GeV proton beam from SPS is used to produce secondary muon, pion, kaon and antiproton beams for the two main components of the COMPASS experiment. In one part polarized *muon* beams are used to study deep inelastic scattering, in particular, the gluon contribution to the proton spin problem. This part is essentially operative now. In the second part *hadron* beams are used to study Primakoff scattering (electric and magnetic polarizabilities of incoming hadrons and ChPT), central production of gluonic systems, and charm physics. COMPASS is proceeding to implement its muon and hadron physics programs, as part of the high priority that CERN assigned to COMPASS as the only CERN fixed target experiment approved to run during the pre-LHC era.

**Summary of the Foreign Effort using Hadronic Probes**

It is clear that hadron physics is being pursued at foreign hadron-beam facilities with vigor and that the use of strongly interacting probes is firmly in the future of these nations, as evidenced by their proposals for two very versatile new hadron-beam facilities, the GSI upgrade in Germany and the Japan Hadron Facility. In sharp contrast, despite very notable achievements in the US (the discovery of the first hybrids at Brookhaven, precision spectroscopy of charmonium, and unraveling of the nature of sea-quarks in the nucleon at Fermilab) there are presently no hadron-beam experiments active, or even approved, at either Brookhaven or Fermilab that address the physics topics presented above. However, opportunities exist for reviving the program at Brookhaven, and starting new experiments in hadron physics at the new Main Injector at Fermilab. The U.S. nuclear physics community would be greatly remiss if it does not take advantage of these opportunities which can restore our leadership position in hadronic physics with a minimum expense.

## 5.3 Foreign Facility Initiatives

Four major foreign facility initiatives were presented at the town meeting. Each is described below.

**European Laboratory For Electrons (ELFE):**

Since the early 1980's the European electromagnetic hadronic physics community has been discussing the design of a 30-GeV fixed-target high-luminosity facility. The research program would be focused on a systematic study of Generalized (or Skewed) Parton Distributions. Designs for the ELFE at two sites, DESY and CERN, are being considered. The proposed plan for the DESY site is to return the electron beam from the Tera electron volt Energy Superconducting Linear Accelerator (TESLA) at the 30-GeV point for injection into the HERA storage ring. The stored beam would then be extracted to a fixed-target facility. The CERN proposal comprises a recirculating accelerator, similar to the JLab design, using the LEP cavities.

Table 6: Overview of international electron-accelerator and photon facilities. The maximum energy, $E_{max}$, is the maximum laboratory kinetic energy of the electron or photon on a fixed target. The facilities are listed in order of $E_{max}$. The horizontal lines are drawn at each decade in $E_{max}$. The facilities listed in bold-face type are upgrades or new facilities that are either (1) approved or (2) being considered.

| Facility | Beam Species | $E_{max}$ (MeV) | Expt. Type | Country |
|---|---|---|---|---|
| **SPring-8**$^{(1)}$ | $\gamma$ | 10 | FT | Japan |
| MAX-Lab | $\gamma$ | 80 | FT | Sweden |
| S-DALINAC | e | 130 | FT | Germany |
| HI$\gamma$S | $\gamma$ | 225 | FT | USA |
| **MAX-LabII**$^{(1)}$ | $\gamma$ | 250 | FT | Sweden |
| LNS-LINAC | e | 300 | FT | Japan |
| LEGS | $\gamma$ | 470 | FT | USA |
| MAMI-B | e, $\gamma$ | 850 | FT | Germany |
| MIT-Bates | e | 1000 | FT | USA |
| DA$\Phi$NE | $e^-$,$e^+$ | 1020 | COL | Italy |
| LNS-STB | e | 1200 | FT | Japan |
| **MAMI-C**$^{(1)}$ | e, $\gamma$ | 1500 | FT | Germany |
| GRAAL | $\gamma$ | 1500 | FT | France |
| SPring-8 | $\gamma$ | 3500 | FT | Japan |
| ELSA | e, $\gamma$ | 3500 | FT | Germany |
| JLab | e, $\gamma$ | 6000 | FT | USA |
| **JLab-12**$^{(2)}$ | e, $\gamma$ | 12000 | FT | USA |
| **ELFE**$^{(2)}$ | e | 30000 | FT | Germany |
| SLAC | e, $\gamma$ | 48000 | FT | USA |
| **EIC**$^{(2)}$ | e,p, ions | 100000 | COL | USA |
| **TESLA-N**$^{(2)}$ | e | 250000 | FT | Germany |
| COMPASS | p, ($\mu$, $\pi$,K, $\bar{p}$) | 400000 | FT | Switzerland |
| **HERA-N**$^{(2)}$ | e | 820000 | FT | Germany |

**Proposals for High CM Energy Accelerations:**

Two design projects that focus on extremely high CM energies are underway. Both projects are motivated by the need for more complete studies of transversity and of the distributions of quark, antiquark and gluon helicity inside nucleons. In the TESLA-N design additional electron pulses will be accelerated in the TESLA to the full energy of 250 GeV and then extracted for

Table 7: Overview of international hadron-beam accelerator facilities. The maximum energy, $E_{max}$, is the maximum laboratory kinetic energy of the primary accelerated particle incident on a fixed target. The facilities are listed in order of $E_{max}$. The horizontal lines are drawn at each decade in $E_{max}$. Separated secondary beams are listed in parentheses. The facilities listed in bold-face type are upgrades or new facilities that are either (1) approved or (2) being considered.

| Facility | Beam Species | $E_{max}$ (MeV) | Expt. Type | Country |
|---|---|---|---|---|
| RCNP-CL | p,d ($\pi$) | 400 | FT | Japan |
| IUCF | p,d (n) | 500 | FT | USA |
| TRIUMF | p,d (n, $\pi$) | 520 | FT | Canada |
| PSI | p,d ($\pi$) | 590 | FT | Switzerland |
| TSL-CELSIUS | p | 1360 | FT | Sweden |
| COSY | p | 2490 | FT | Germany |
| KEK | p ($\pi$, K, $\bar{p}$) | 12000 | FT | Japan |
| **GSI-future**$^{(2)}$ | $\bar{p}$, p | 14000 | FT | Germany |
| **BNL/AGS**$^{(2)}$ | p, ($\pi$, K, $\bar{p}$) | 39000 | FT | USA |
| **JHF**$^{(2)}$ | p, ($\pi$, K, $\Lambda$, $\Sigma$) | 50000 | FT | Japan |
| IHEP | p, ($\bar{p}$, $\pi$) | 70000 | FT | Russia |
| Fermilab | p, $\bar{p}$ | 119000 | FT | USA |
| COMPASS | p, ($\mu$, $\pi$,K, $\bar{p}$) | 400000 | FT | Switzerland |
| RHIC-spin | p | 500000 | COL | USA |

fixed target experiments involving polarized targets. The HERA-N proposal is to store a beam of 820-GeV (polarized) nucleons in the HERA ring which would interact with an internal polarized target.

**Gesellschaft für Schwerionforshung (GSI):**

GSI, located in Darmstadt, Germany, has had a distinguished past as a heavy-ion laboratory. However, there is a proposal to extend the mission of the facility to include research in radioactive ion and hadron physics. In hadron physics they have opted for uniqueness by deciding to offer antiproton beams. The same accelerator complex will be used to produce and accelerate rare isotopes. The main accelerator is the SIS 200, which is a high intensity superconducting synchrotron capable of accelerating protons to 60 GeV (and $U^{92+}$ to 23 GeV/amu). The plan is to use high-energy protons from the SIS 200 to produce antiproton beams. Antiprotons are produced at 3 GeV, collected, cooled, and accumulated in a complex of of two rings (CR and ESR). They are reinjected into SIS 200 where they are accelerated to energies up to 14 GeV (up to 4.4 GeV/amu for $U^{92+}$ ions). After acceleration, the antiprotons are injected into a final ring where they are stored and cooled for use in internal-target experiments. The planned facility represents significant improvement over the fixed-target program at Fermilab, and opens possibilities for physics not accessible at Fermilab.

Among the physics topics that can be vigorously studied at this proposed facility are QCD exotics (glueballs and hybrids), charmonium spectroscopy, and charmonium attenuation in the presence of the quark-gluon plasma.

**Japan Hadron Facility (JHF):**

The Japan Hadron Facility (JHF) is a proposed new multi-purpose accelerator facility to be built on the KEK site in Tsukuba, Japan. The accelerator complex will consist of a 200-MeV proton linac, a 3-GeV Booster proton ring and a 50-GeV main proton synchrotron ring. Its aim is to provide to an international user community the highest beam intensity among accelerators of such energies in the world. In addition to the high-energy hadron-beam physics program, the facility will have a rare isotope facilty. Some of the physics areas made assessible by the high-intensity high-energy hadron beams are hypernuclear spectroscopy, hyperon-nucleon scattering, vector mesons in nuclei, hadron spectroscopy, neutrino oscillations, rare K decays and muon lepton flavor violation. The JHF has been recognized as the most important accelerator construction project in the future in Japan. The project has not yet been officially approved by the Japanese government. However, the last major review of the project was in May 2000, and many are optimistic that approval will be within the next few years.

## 5.4 An International Perspective

The international nuclear physics community is vigorously pursuing deeper understanding of fundamental questions in hadron physics. Hadronic physics covers a broad scope of phenomena that are observed over wide energy and distance scales. The complexity of the phenomena and systems arise from the dynamical nature of the strong interaction between fundamental constituents. Progress on this scientific front has and continues to critically depend on having a wide variety instruments for probing different aspects of hadronic systems over wide energy and distance scales. The core instruments are particle accelerators and detector systems. Many nations have made significant investments in these core tools for nuclear physics over the last three decades. The accelerator facilities with active or proposed programs in hadron physics are listed in Tables 6 and 7. The tables include existing, approved and proposed facilities. The facilities in bold-face type are either approved or being considered. For electromagnetic-beam facilities, $\gamma$-ray beams are listed only when there is good energy resolution capabilities. Secondary hadron beams are only listed when there is good species separation and momentum analysis of the secondary beams at the facility. Experiments at the facilities are divided into two gross types, fixed target (FT) and collider (COL).

# References


[Abo00] D. Abbott *et al.*, Phys. Rev. Lett. **84**, 5053 (2000).

[Ack00] K. Ackerstaff *et al.*, Phys. Lett. **B475**, 386 (2000).

[Ad91] Fermilab E704 Collaboration, D.L. Adams *et al.*, Phys. Lett. **B264**, 462 (1991); Phys. Rev. Lett. **77**, 2626 (1996).

[Adl00] C. Adler *et al.*, nucl-ex/0008005 (2000).

[Ad99] C. Adloff *et al.*, Eur. Phys. J. **C6**, 587 (1999).

[Ai86] T.A. Aibergenov et al., Czech. J. Phys. **36**, 948 (1986).

[Ai00] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett. **84**, 4047 (2000).

[Ald90] D. M. Alde *et al.*, Phys. Rev. Lett. **81**, 2479 (1990).

[Ale99] L. C. Alexa *et al.*, Phys. Rev. Lett. **82**, 1374 (1999).

[Ani99] K.A. Aniol *et al.*, (HAPPEX Collaboration), Phys. Rev. Lett. **82**, 1096 (1999).

[Ani00] K. A. Aniol, *et al.*, (HAPPEX Collaboration), nucl-ex/00060002.

[Ank94] H. Anklin *et al.*, Phys. Lett. **B336** (1994) 313.

[Ank98] H. Anklin *et al.*, Phys. Lett. **B428** (1998) 248.

[An00] P. Anthony, *et al.*, Phys. Lett. **B493**, 19 (2000), and references therein.

[An85] Yu. M. Antipov et al., Z. LPhys. **C26**, 495 (1985).

[An83] Yu. M. Antipov et al., Phys. Lett. **B121**, 445 (1983).

[Ar99] C. S. Armstrong, *et al.*, Phys. Rev. **D60**:052004 (1999).

[Ar00] Jlab experiment E00–114 (R. Michaels and D. Armstrong, contacts).

[Arr00] J. Arrington, spokesperson, JLab E00-101.

[Ba77] Exotic hybrids were apparently first described in a bag model context by T. Barnes, Ph.D. thesis, California Institute of Technology, 1977 (unpublished).

[Ba92] D. Babusci et al., Phys. Lett. **B277**, 158 (1992).

[Ba97] G. Bali *et al.* [SESAM Collaboration], Nucl. Phys. Proc. Suppl. **63**, 209 (1997).

[Ba00] G. S. Bali *et al.* [SESAM/TCL Collaboration], *Static potentials and glueball masses from QCD simulations with Wilson sea quarks*, hep-lat0003012 (2000).

[Bag94] N. Bagget, private communication; Projected from a 1994 survey: J. Owen, *et al*, Int. J. Radiation Oncology Biol. Phys., **39**(1994)179.

[Bai01] E. Baird, CEO, Schlumberger Inc., private communication.

[Bea00] S. R. Beane, P. F. Bedaque, W. C. Haxton, D. R. Phillips and M. J. Savage, Essay for the Festschrift in honor of Boris Ioffe, to appear in the 'Encyclopedia of Analytic QCD', edited by M. Shifman, to be published by World Scientific. `hep-ph/0008064`.

[Bec91] Jlab "G0" experiment (D. Beck, contact).

[Bec97] R. Beck *et al.*, Phys. Rev. Lett. **78**, 606 (1997).

[Bec99] J. Becker *et al.*, Eur. Phys. J. A **6**, 329 (1999).

[Be91] Jlab experiment E01–004 (E. Beise, contact).

[Be99] S. Belostotski for the HERMES Collaboration, Nucl. Phys. Proc. Suppl. **79**, 526 (1999).

[Ben98] O. Benhar *et al.*, JLAB-THY-98-12.

[Be95] *Chiral Dynamics: Theory and Experiment*, ed. A.M. Bernstein and B.R. Holstein, Springer-Verlag, New York (1995).

[Be98] *Chiral Dynamics: Theory and Experiment*, ed. A.M. Bernstein, D. Drechsel, and T. Walcher, Springer-Verlag, New York (1998).

[Be00B] *Chiral Dynamics 2000*, JLab, July 2000 (to be published).

[Ber93] JLab experiment E93–050, spokespersons: P.Y. Bertin, P.A.M. Guichon, and C.E. Hyde-Wright.

[Bi96] W. Bietenholz and U. J. Wiese, Nucl. Phys. **B464**, 319 (1996).

[Bie00] R. Bieber *et al.*, Phys. Rev. Lett. **84**, 606 (2000).

[Bj66] J. Bjorken, Phys. Rev. **148**, 1467 (1966), Phys. Rev. **D1**, 1376 (1970).

[Bl69] E. D. Bloom *et al.*, Phys. Rev. Lett. **23**, 930 (1969), and M. Briedenbach *et al.*, Phys. Rev. Lett. **23** 935 (1969)

[Bla97] G. Blanpied *et al.*, Phys. Rev. Lett. **79**, 4337 (1997).

[Boc98] C. Bochna *et al.*, Phys. Rev. Lett. **81**, 4576 (1998).

[Bro94] W. Brooks, private communication; JLab experiment E94–017, contacts: W. Brooks and M. Vineyard.

[Br00] C. N. Brown *et al.*, hep-ex/0011030 (2000).

[Bru95] E.E.W. Bruins *et al.*, Phys. Rev. Lett. **75** (1995) 21.

[Bul00] H.J. Bulten, private communication.

[Bu00] M. Butler and J.-W. Chen, *Nucl. Phys.* **A675**, 575 (2000); M. Butler, J.-W. Chen, and X. Kong, (2000), `nucl-th/0008032`.

[Ca98] S. Capitani *et al.*, Nucl. Phys. Proc. Suppl. **73**, 294 (1999)

[Cad00] R. V. Cadman *et al.*, submitted to Phys. Rev. Lett., (2000).

[Ch99a] N. Christ, Review talk at CHIRAL '99, Taipei, Sep. 13-18, (1999).

[Ch99b] S. Chandrasekharan and U.-J. Wiese, Phys. Rev. Lett. **83** 3116 (1999).

[Cl95] F. E. Close, private communication, advocates using the *positive* term "strong QCD" instead of the negative "nonperturbative QCD".

[Co93] J. Collins, Nucl. Phys. **B396**, 161 (1993).

[De97] L. Del Debbio, M. Faber, J. Greensite, S. Olejnik, Phys. Rev. **D55**, 2298 (1997).

[Do98] S.J. Dong, K.F. Liu, and A.G. Williams, Phys. Rev. **D58**, 074504 (1998).

[Do00] D. Dolgov *et al.*, hep-lat/0011010, to appear in Nucl. Phys. B (Proc. Suppl.) (2000)

[Don93] See, *e.g.*, J.F. Donoghue and B.R. Holstein, Phys. Rev. **D48**, 137 (1993).

[Dr66] S.D. Drell and A.C. Hearn, Phys. Rev. Lett. **16**, 908 (1966).

[Dze94] M. Dzemedic, Indiana Medical School, private communication.

[Ed99] R.G. Edwards, U.M. Heller and R. Narayanan, Nucl. Phys. **B540**, 457 (1999).

[Ef99] A.V. Efremov, O.G. Smirnova and L.G. Tkatchev, Nucl. Phys. Proc. Suppl. **74**, 49 (1999), hep-ph/9812522.

[Ef00] A.V. Efremov, K. Goeke, M.V. Polyakov, D. Urbano, Phys. Lett. **B478**, 94 (2000).

[EF98] Proceedings of the Joint Caltech/INT workshop on *Nuclear Physics with Effective Field Theory*, edited by R. Seki, U. van Kolck and M. J. Savage, published by World Scientific (1998), ISBN 981-02-3596-8; Proceedings of the INT workshop on *Nuclear Physics with Effective Field Theory II*, edited by P. F. Bedaque, M. J. Savage, R. Seki and U. van Kolck, published by World Scientific (1999), ISBN 981-02-4181-X.

[Eld98] *Unlocking Our Future - Toward a New National Science Policy*, Report to Congress by the House Committee on Science, Sept., 1998.

[Fl00] See, *e.g.*, R. Flores-Mendieta et al., Phys. Rev. **D62**, 034001 (2000).

[Fo99] J. L. Forest, V. R. Pandharipande, and A. Arriaga, Phys. Rev. C**60**, (1999) 014002.

[Fra00] L. L. Frankfurt *et al.*, Phys. Rev. Lett. **84**, 3045 (2000).

[Fre93] S.J. Freedman *et al.*, Phys. Rev. **C48**, 864 (1993).

[Fri83] B. L. Friman *et al.*, Phys. Rev. Lett. **51**, 763 (1983).

[Fro99] V.V. Frolov *et al.*, Phys. Rev. Lett. **82**, 45 (1999).

[Gao00] MIT-Bates proposal PR-00-02, Spokespersons: H. Gao, J.R. Calarco.

[Ga82] J. Gasser and H. Leutwyler, *Ann. Phys.* **158**, 142 (1984); *Nucl. Phys.* **B250**, 465 (1985).

[Ga99] See, *e.g.* J. Gasser and M.E. Sainio, Eur. Phys. J. **C6**, 297 (1999).

[Ge66] S.B. Gerasimov, Sov. J. Nucl. Phys. **2**, 598 (1965).

[Ge93] P. Geiger and N. Isgur, Phys. Rev. D **47**, 5050 (1993); D **44**, 799 (1991).

[Gi82] P.H. Ginsparg and K.G. Wilson, Phys. Rev. D25, 2649 (1982).

[Go96] M. Gökeler *et al.*, Phys Rev. **D53**, 2317 (1996).

[Gre99] A. Greenspan, Statement before the Joint Economic Committee, June 14, 1999.

[Gu99] S. Gusken *et al.* Phys. Rev. D **59**, 114502 (1999).

[Gu00] W. Guryn *et al.*, Nucl. Phys. **A663**, 1115 (2000).

[Ha00] O. Hanstein *et al*, Nucl. Phys., **A632**, 561 (1998); L. Tiator *et al*, nucl-th/0012046.

[Ha00] R. Hasty, *et al.*, Science **290**, 2117 (2000).

[Ha98] E. H. Hawker *et al.*, Phys. Rev. Letts. **80**, 3715 (1998); J. C. Peng *et al.*, Phys. Rev. **D58**, 092004 (1998); R. S. Towell *et al.*, to be published (2000).

[He98] K. Ackerstaff *et al.*, Phys. Rev. Letts. **81**, 5519 (1998).

[He96] K. Heller, Proc. of Spin 96, Amsterdam, World Scientific, p. 23 (1997).

[He00] See, *e.g.* T.R. Hemmert et al., Phys. Rev.**D62**, 014013 (2000).

[Her99] C. Herberg *et al.*, Eur. Phys. Jour. **A5**, 131 (1999).

[Is85] N. Isgur, and J. Paton, Phys. Rev. D **31**, 2910 (1985); N. Isgur, R. Kokoski and J. Paton, Phys. Rev. Lett. **54**, 869 (1985).

[Is91] N. Isgur and M. B. Wise, Phys. Rev. D **43**, 819 (1991).

[Iv98] T. L. Ivanenko and J. W. Negele, Nucl. Phys. B (Proc. Suppl.) **63** 504 (1998).

[Jac00] H. E. Jackson, Sixteenth Int'l Conf. on Few-Body Physics, Taipei, 2000.

[Ja77] R.L. Jaffe, Phys. Rev. Lett. **38**, 195 (1977).

[Ja92] R.L. Jaffe and X. Ji, Nucl. Phys. **B375**, 527 (1992).

[JM91] E. Jenkins and A. V. Manohar, *Phys. Lett.* **B255**, 558 (1991); *Phys. Lett.* **B259**, 353 (1991); Talks presented at the *Workshop on Effective Field Theories of the Standard Model*, Dobogoko (1991).

[Ji97] X. Ji, Phys. Rev. Lett. **78**, 610 (1997); Phys. Rev. D **55**, 7114 (1997).

[Ji99] X. Ji and J. Osborne, hep-ph/9905410.

[Ji00] X. Ji, C. Kao and J. Osborne, Phys. Lett. **B72**, 1 (2000).

[Jia00] X. Jiang and R. Ransome, Jlab Hall-A proposal, PR-00-115 (2000).

[Jl91] JLAB experiments E91–023, E93–009,and E97–117.

[JL01] *The Science Driving the 12 GeV Upgrade of CEBAF*, Jefferson Lab Internal Report, Feb. 2001.

[Jon00] M. Jones *et al.*, Phys. Rev. Lett. **84**, 1398 (2000).

[Ju99] K.J. Juge, J. Kuti, and C.J. Morningstar, Phys. Rev. Lett. **82**, 4400 (1999).

[Ka92] D.B. Kaplan, Phys. Lett. **B288**, 342 (1992).

[Ka99] S.S. Kamalov and Shin Nan Yang, Phys. Rev. Lett., **83**, 4494 (1999); S.S. Kamalov. S.N. Yang, D. Drechsel, O. Hanstein, L. Tiator, nucl-th/0006068.

[Ka00] A. Ali Khan *et al.* HEP-LAT 0010078; Phys. Rev. Lett. **85**, 4674 (2000).

[Ko96] B. Kopeliovich, J. Nemchik and E. Predazzi, Proc. of the Workshop on Future Physics at HERA, Edited by G. Ingelman, A. De Roeck and R. Klanner, DESY, vol. 2, p. 1038 (1996), nucl-th/9607036.

[Kol98] D. S. Koltun, Phys. Rev. **C57**, 1210 (1998).

[Kr87] A.S. Kronfeld, M.L. Laursen, G. Schierholz, U.J. Wiese, Phys. Lett. **B198**, 516 (1987).

[Kr95] B. Krusche, *et al.*, Phys. Rev. Lett. **74**, 3736 (1995).

[La00a] The Lattice Hadron Physics Proposal is in LatticePropFinal at ftp://www-ctp.mit.edu/pub/negele/LatProp/

[La00b] The Lattice QCD Executive Committee Whitepaper is in whitepaper at http://quark.phy.bnl.gov/www/qcdocworkshop.dir/

[Lee00] T.-S. H. Lee, Argonne National Laboratory, private communication.

[Le00] M. J. Leitch *et al.*, Phys. Rev. Letts. **84**, 3256 (2000).

[Lh99] JLab experiment E99–115 (K. Kumar and D. Lhuillier, contacts).

[Lu81] M. Luscher, Nucl. Phys. **B180**, [FS2], 317 (1981).

[Ma96] R. Machleidt *et al.*, Phys. Rev. C**53**, (1996) R1483; R. B. Wiringa *et al.*, Phys. Rev. C**51**, (1995), 38; V. G. Stoks *et al.*, Phys. Rev. C**49**, (1994) 2950.

[Ma94] K. Maltman and M. Schmatikov, Proc. of the 5th Conf. on the Intersections between Particle and Nuclear Physics, AIP Proc. 338, 601 (1994).

[Man96] See, *e.g.* D. Kaplan, *Effective Field Theories*, in Proc. 7th Summer School in Nuclear Physics, `nucl-th/9506035`; H. Georgi, *Effective Field Theory*, in *Ann. Rev. Nucl Sci.* **43**, 209 (1995); A. Manohar, *Effective Field Theories*, in *Schladming 1996: Perturbative and Nonperturbative Aspects of Quantum Field Theory*, `hep-ph/9606222`.

[Ma98] L. E. Marcucci, D. O. Riska, and R. Schiavilla, Phys. Rev. **C**58, 3069 (1998).

[Ma00] L. E. Marcucci, et al., Phys. Rev. Lett. **84**, 5959 (2000).

[Ma99] M. A. Vasiliev *et al.*, Phys. Rev. Letts. **83**, 2304 (1999).

[Me00] U. -G. Meißner, Essay for the Festschrift in honor of Boris Ioffe, to appear in the 'Encyclopedia of Analytic QCD', edited by M. Shifman, to be published by World Scientific. `hep-ph/0007092`.

[Me99] C. Mertz *et al*, nucl-ex/9902012.

[Mer00] C. Mertz *et al.*, submitted to Phys. Rev. Lett.

[Mil00] G. A. Miller *et al.*, Phys. Lett. **B475**, 245 (2000).

[Mo97] C. J. Morningstar and M. Peardon, Phys. Rev. D **56**, 4043 (1997).

[Mo99] C.J. Morningstar and M. Peardon, Phys. Rev. **D 60**, 34509 (1999).

[Mu00] V. Muccifora for the HERMES Collaboration, Proc. of the 38th International Winter Meeting on Nuclear Physics, January 2000, Bormio, Italy (available from http://hermes.desy.de/notes/)

[Mu97] B. A. Mueller, *et al.*, Phys. Rev. Lett. **78**, 3824 (1997).

[Na70] Y. Nambu, Univ. of Chicago Report No. 70-70 (1970) (unpublished); lectures at the Copenhagen Summer Symposium (1970) (unpublished).

[Na95] R. Narayanan and H. Neuberger, Nucl. Phys. **B443**, 305 (1995).

[Na00] V. G. S. Nakamura, T. Sato and K. Kubodera, *Private Communication.*

[Ne98] "Hadron Physics in the 21st Century," (unpublished), B. Nefkens, editor (1998).

[Neg98] J.W. Negele, in Unfolding the Matter of Nuclei, Course CXXXVIII, Varenna, Italy, July (1998).

[Ne99] J. W. Negele, A. Pochinsky, and B. Scarlet, Nucl. Phys. B (Proc. Suppl.) **73**, 225 (1999).

[Neg01] J. Negele, this report, http://www-ctp.mit.edu/ negele/

[Ni00] I. Niculescu, *et al.*, Phys. Rev. Lett. **85**, 1186 (2000).

[No00] K. Nollett and R. B. Wiringa, nucl-th/0006064 and private communication.

[Ost99] M. Ostrick *et al.*, Phys. Rev. Lett. **83**, 276 (1999).

[Pan94] V. R. Pandharipande *et al.*, Phys. Rev. **C49**, 789 (1994).

[Pas99] I. Passchier *et al.*, Phys. Rev. Lett. **82**, 4988 (1999).

[Pd96] Particle Data Group, Phys. Rev. **D54**, 1 (1996).

[Pe00] J. C. Peng *et al.*, hep-ph/0007341 (2000).

[Per99] Jefferson Lab experiment E99–007, contacts: C. Perdrisat, E. Brash, M. Jones, V. Punjabi.

[Po99] M. V. Polyakov and C. Weiss, Phys. Rev. D **60**, 114017 (1999).

[Pos00] Th. Pospischil *et al.*, submitted to Phys. Rev. Lett.

[Pr98] B. V. Przewoski, *et al.*, Phys. Rev. C**57**, 1897 (1998).

[Ra96] A. V. Radyushkin, Phys. Lett. **B380**, 417 (1996); Phys. Lett. **B385**, 333 (1996); Phys. Rev. D **56**, 5524 (1997).

[Ra99] A. V. Radyushkin, Phys.Rev.D **59**, 014030 (1999).

[Re99] M. C. M. Rentmeester, et al., Phys. Rev. Lett., **82**, 4992 (1999).

[Ri00] D. G. Richards, hep-lat/0011025, to appear in Nucl. Phys. B, (Proc. Suppl.) (2000).

[Roc00] J. Roche *et al.*, Phys. Rev. Lett. **85**, 708 (2000).

[Roh99] D. Rohe *et al.*, Phys. Rev. Lett. **83**, 4257 (1999).

[Ros01] Carl Rosner, CEO, Intermagnetics General; private communication.

[Sak00] H. Sakai *et al.*, Phys. Rev. Lett. **84**, 5288 (2000).

[Sar00] JLab experiment E91–011; see A. Sarty, contributed abstract.

[Sa00] T. Sato and T.-S.H. Lee, Phys. Rev., **C54**, 2660 (1996) and T.-S.H. Lee, private communication, 2000.

[Sch98] C. Schlichter, G. S. Bali and K. Schilling, Nucl. Phys. Proc. Suppl. **63**, 519 (1998).

[Sch99] *Nuclear Physics - The Core of Matter, The Fuel of Stars*, Committee on Nuclear Physics, National Research Council, National Academy Press, Washington, D.C., 1999.

[Sc98] R. Schiavilla, et al., Phys. Rev. **C**58, 1263 (1998).

[Sc99] H. Schmieden, nucl-ex/9909006.

[Sch00] E. Schulte *et al.*, preprint, 2000.

[Sha97] Bates experiment 97–03, spokespersons: J. Shaw and R. Miskimen.

[Si99] A. Silva, D. Urbano, T. Watabe, M. Fiolhais and K. Goeke, hep-ph/9905326.

[Si90] D. Sivers, Phys. Rev. **D41**, 83 (1990).

[So99] J. Soffer, Proc. of Hyperon 99, Batavia, USA, hep-ph/9911373.

[Sp00] D.T. Spayde, *et al.*, Phys. Rev. Lett. **84**, 1106 (2000).

[Tapc] H. Tamura, private communication.

[Th01] R. Thompson, *et al.* (CLAS Collaboration), Phys. Rev. Lett. **86**, 1702 (2001).

[To97] JLAB experiments E99–117, E97–103,and PR00–113.

[Vapc] M. Vanderhaeghen, private communication. The calculations were done using the double distribution of Radyushkin [Ra99] with and without the $D$"-term of Polyakov and Weiss [Po99].

[Var00] H. Varmus, *Squeeze on Science*, Washington Post, op-ed column, 4 Oct., 2000.

[Ve00] J. J. Verbaarschot and T. Wettig, Ann. Rev. Nucl. Part. Sci. **50**, 343 (2000).

[Wa90] M. Warns, H. Schroder, W. Pfeil and H. Rollnik, Z. Phys. C, **45**, 627 (1990).

[We67] S. Weinberg, *Phys. Rev. Lett.* **18**, 188 (1967); *Phys. Rev.* **166**, 1568 (1968); *Physica* **A96**, 327 (1979).

[We90] S. Weinberg, *Phys. Lett.* **B251**, 288 (1990); *Nucl. Phys.* **B363**, 3 (1991); *Phys. Lett.* **B295**, 114 (1992).

[Wei01] R. Weinstein, private communication.

[Wi74] K Wilson, Phys. Rev. **D10**, 2445 (1974).

[Wij00] K. Wijesooriya, private communication.

[Wipc] R. B. Wiringa and R. Schiavilla, private communication.

[Wir98] R. B. Wiringa and R. Schiavilla, Phys. Rev. Lett. **81**, 4317 (1998).

[Wir00] R. B. Wiringa, Steven C. Pieper, and J. Carlson, Phys. Rev. **C**014001 (2000), and private communication.

[Wit98] H. Witala *et al.*, Phys. Rev. Lett. **81**, 1183 (1998).

[Wol01] B. Wolfe and C. Starr, Outlook, Houston Chronicle, Jan. 7, 2001.

[Xu00] W. Xu *et al.*, Phys. Rev. Lett. **85**, 2900 (2000).

[Yi89] S. Ying, W. C. Haxton and E. M. Henley, *Phys. Rev.* **D40**, 101 (1989); *Phys. Rev.* **C45**, 1982 (1992).

[Zh00] S.-L. Zhu *et al.*, Phys. Rev. **D62**, 033008 (2000).

# Appendix A

Guidance from NSAC in the Long Range Plan Process

- What scientific question(s) is this sub-field trying to answer?
- What is the significance of this sub-field for nuclear physics and for science in general?
- What are the achievements of this sub-field since the last long-range plan?
- What are the theoretical and experimental challenges being addressed by this sub-field (a) in the immediate future (<3 years) and (b) over the duration of the next long-range plan (10 years)? Identify the new opportunities which will contribute to this scientific endeavor.
- What resources, including manpower, will be needed throughout the duration of the next long-range plan (with some attempt at priorities)?
- How does the U.S. effort in this sub-field compare to the rest of the world and how do U.S. studies fit into the global picture?
- What will the impact of the proposed program be on other fields and on society?