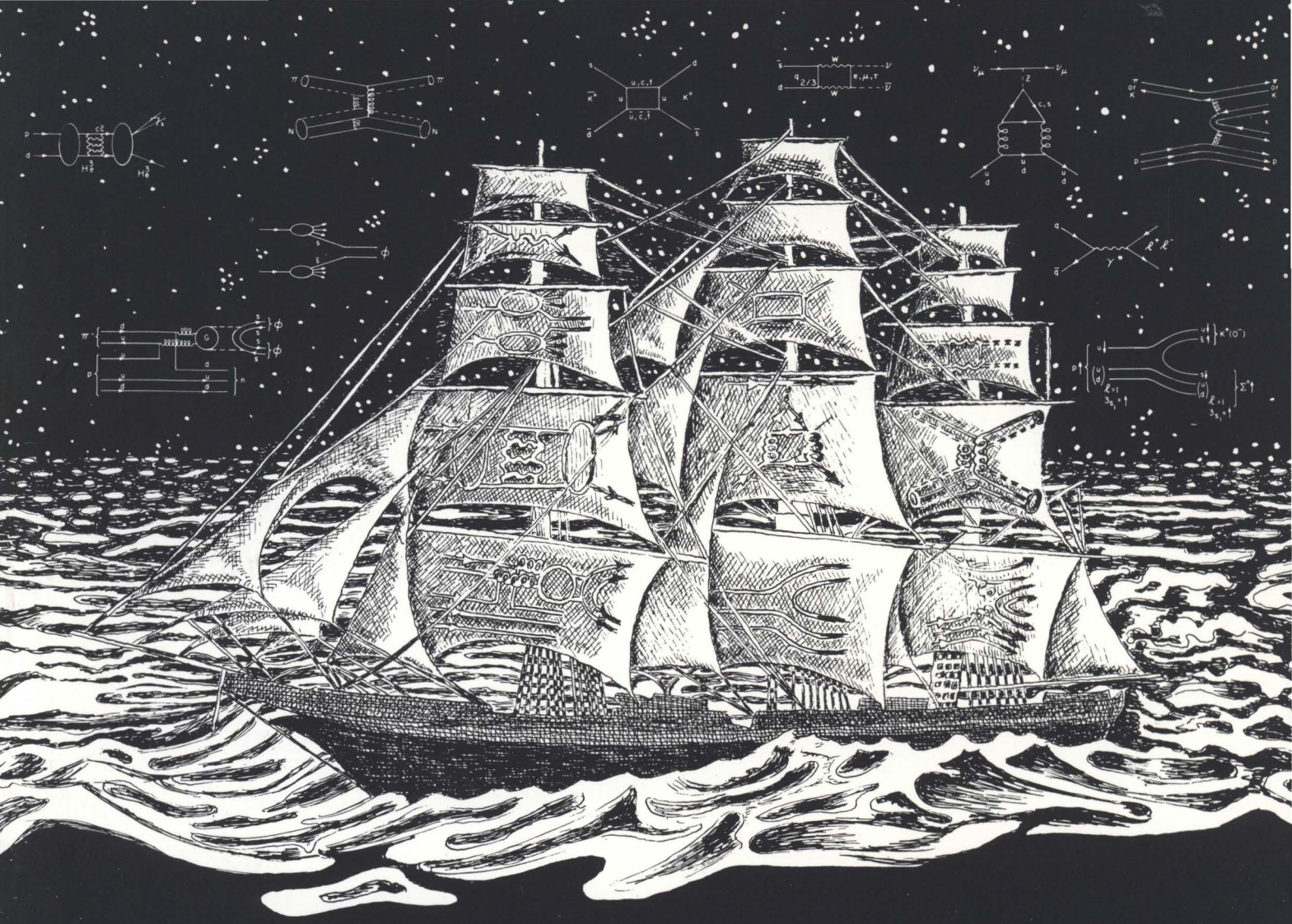

# Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities

**December 2-3, 1994**

# Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities

A White Paper from the Workshop Held at
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# Executive Summary

Through the efforts of particle and nuclear physicists over the past four decades, we now have a theoretical framework, the Standard Model, which encompasses all of the known forces in nature except gravity. Yet with all of the successes of the Standard Model, many fundamental questions at the very foundations of particle and nuclear physics remain to be answered. For instance, astrophysical evidence suggests that we do not know what form more than 90% of the mass in the universe takes, leading to much speculation that massive neutrinos or other subatomic particles may hold the key to this mystery. We do not convincingly know the source of the violation of the CP symmetry which is related to the excess of matter over antimatter in the universe. We do not know whether exotic forms of matter, containing perhaps six quarks rather than the usual three — or perhaps none at all, may exist. We do not fully understand the source of the spin angular momentum of the protons and neutrons that make up the nuclei in the matter that surrounds us. We cannot calculate the short and intermediate range parts of the force that binds nucleons inside a nucleus. We do not know why nucleons are different when they are inside a nucleus. And the list goes on. Many of these questions can be studied most effectively, and in some cases only, through experiments at multi-GeV hadron accelerators which can provide highly intense beams of protons, pions, kaons, hyperons, muons, and neutrinos, or hadron beams with special properties — such as polarized protons.

In spite of the importance of studies utilizing such beams, recent developments have created an uncertain future for research at multi-GeV hadron beam accelerators. The primary U.S. hadron facility for nuclear physics for the past two decades, the Los Alamos Meson Physics Facility (LAMPF), will cease to operate as a nuclear physics facility after the 1995 fiscal year. The Brookhaven AGS, operated as a high energy physics facility, currently provides the highest intensity multi-GeV external hadron beams of any accelerator in the world, but progress on many experiments has been slow there due to limited beam time and limited funds for capital equipment for detectors. The cancellation by the Canadian government of the KAON project, a very high-intensity hadron accelerator which had been planned at the TRIUMF lab, has cut off many exciting avenues for progress for both the nuclear and high energy physics communities.

Looking ahead, we find uncertain plans for the Brookhaven AGS during the RHIC era, an unknown level of opportunities for running at RHIC with beams other than heavy ions, and the still undefined plans for external beams from the Fermilab Main Injector. Still, the physics program which can be built around such facilities is central to the fundamental issues in both particle and nuclear physics, and with the completion of current construction projects, the U.S. will have the best complement of accelerators in the world — the AGS, Main Injector, RHIC, and Tevatron — to proceed with this program. Consequently, it is of the utmost importance for the U.S. high energy and nuclear physics communities, with the support of their funding agencies, to achieve effective utilization of these facilities. And in the absence of very high intensity beams from a facility like KAON, it is important for well-conceived upgrades to these facilities to be given serious consideration.

This white paper represents the interests and aspirations of a significant community of researchers at the forefront of particle and nuclear physics, brought together by shared concerns for the future viability of the tools needed for this research. To address the concerns of this community, a series of three workshops, titled "Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities," was conducted. The final meeting

of this series was held at Fermilab on December 2-3, 1994. In considering the facilities needed to conduct this program over the next five to ten years, a few common themes clearly emerged. These provide the impetus for the following conclusions and recommendations:

- Hadron beam accelerators of medium to high energy, with very high intensity external beams, or beams with special properties, are required to address some of the most fundamental questions in particle and nuclear physics. Stable, long-term support of these facilities must be established if a viable program in this field is to proceed.

- The Brookhaven AGS and the Fermilab complex, augmented by the Main Injector now under construction, provide the best opportunities in the world for conducting much of the research outlined in this white paper. They should be regarded as the primary facilities in the U.S. for conducting this research in the foreseeable future. Exploitation of these opportunities requires sufficient funding for effective utilization of these facilities in the near future, and support for well conceived upgrades in the long-term.

- Special opportunities will exist to address key questions in particle and nuclear physics at other accelerator facilities, such as the polarized beam capability at RHIC. Other opportunities may include polarized beams at the Main Injector/Tevatron, neutrino experiments at LAMPF, or muon experiments at TRIUMF or LAMPF. When deemed cost-effective and consistent with the missions of those facilities, experiments to exploit these opportunities should be allowed to compete for resources on an even footing with experiments at the primary facilities.

- To ensure timely progress and efficient utilization of accelerator facilities, equipment funds and support for university-based and laboratory-based user groups must be given high priority.

Finally, it is important to stress that many fundamental issues are of interest to members of both the high energy physics and nuclear physics communities. Consequently, collaborations on experiments will frequently include members from both communities. While this makes the boundary between these fields harder to locate, it is ultimately a healthy sharing of skills and resources which should be encouraged where a natural overlap of interests occurs. An important corollary of this is that the funding agencies responsible for funding high energy and nuclear physics (DOE and NSF) need to have good communication between their internal divisions which fund research in these two fields.

- Administrative barriers to funding high-energy/nuclear physics collaborative projects should be lowered. The funding agencies should encourage better communication between their advisory committees (such as HEPAP and NSAC), for example by conducting joint meetings on an regular basis.

# 1 Introduction

As we approach the end of the millennium, our understanding of the subatomic world is at once amazingly successful and frustratingly incomplete. On the one hand, we have the spectacularly successful "Standard Model," which consists of two different, but intimately related theories, based on the ideas of gauge invariance for fundamental interactions: the electroweak theory of Glashow, Salam, and Weinberg, and the strong interaction theory known as Quantum Chromodynamics. No established experimental result so far is inconsistent with this picture. On the other hand, there are several missing pieces in our understanding: we have strong theoretical reasons for believing the Standard Model is incomplete, in essence an approximation to a more complete underlying theory; we do not understand the mechanism of electroweak symmetry breaking that gives elementary particles their mass; indeed, astrophysical evidence suggests that we do not even know what form more than 90% of the mass in the universe takes, leading to much speculation that massive neutrinos or other subatomic particles may hold the key to this mystery; we do not convincingly know the source of the violation of the CP symmetry which is related to the excess of matter over antimatter in the universe; we do not know whether exotic forms of matter, containing perhaps six quarks rather than the usual three — or perhaps none at all, may exist; we do not fully understand the source of the spin angular momentum of the protons and neutrons that make up the nuclei in the matter that surrounds us; and the list goes on.

Particle accelerators have proven over time to be our most incisive tools for probing the questions of particle and nuclear physics. Several types of particle accelerators exist in the world today and some new ones are under construction. These include high energy colliders to probe the mysteries of the super-massive top quark and ultimately to uncover the source of the electroweak symmetry breaking. With the cancellation of the Superconducting Supercollider (SSC), the United States has ceded the high energy frontier to Europe where the Large Hadron Collider (LHC) will be built at CERN. Clearly the high energy frontier is crucial to continued progress in understanding the basic laws of nature. But some important questions are not accessible to these big machines and many important questions can best be addressed in other venues. In particular, hadron accelerators, which can provide highly intense hadron beams or beams of hadrons or other particles with special properties, are needed to address many of these profound questions. The beam energies required span a wide range and cannot be provided by any single existing facility. In this white paper we sometimes use the term "multi-GeV" to describe these hadron beams, but this should be understood to include beams from about 1 GeV up to nearly 1 TeV.

This white paper represents the interests and aspirations of a significant community of researchers at the forefront of particle and nuclear physics, brought together by shared concerns for the future viability of the tools needed for this research. The primary U.S. hadron facility for nuclear physics for the past two decades, the Los Alamos Meson Physics Facility (LAMPF), will cease to operate as a nuclear physics facility after the 1995 fiscal year. The Brookhaven AGS, operated as a high energy physics facility, currently provides the highest intensity multi-GeV external hadron beams of any accelerator in the world, but progress on many experiments has been slow there due to limited beam time and limited funds for capital equipment for detectors. The cancellation by the Canadian government of the KAON project, a very high-intensity hadron accelerator which had been planned at the TRIUMF lab, has cut off many promising avenues for progress in both nuclear and high

energy physics.

The physics program which can built around multi-GeV hadron beam facilities is central to the fundamental issues in both particle and nuclear physics. Without KAON, we must redefine the future of existing facilities to carry forth this program. Looking ahead, we find uncertain plans for the Brookhaven AGS during the RHIC era, an unknown level of opportunities for running at RHIC with beams other than heavy ions, and still undefined plans for external beams from the Fermilab Main Injector. Yet, with the completion of current construction projects, the U.S. will have the best complement of accelerators in the world — the AGS, Main Injector, RHIC and the Tevatron — to proceed with this program. It is of the utmost importance for the U.S. high energy and nuclear physics communities, with the support of their funding agencies, to achieve effective utilization of these facilities. And in the absence of very high intensity beams from a facility like KAON, it is important for well-conceived upgrades to these facilities to be given serious consideration.

This white paper is the product of a series of three workshops titled "Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities." The workshops were organized and attended by members of both the high energy physics and nuclear physics communities. The third and final meeting of the series was held at Fermilab in December, 1994. This white paper describes the important physics issues that can best be addressed using multi-GeV hadron accelerators which provide external beams or hadron beams with special properties. These issues fall naturally into two broad areas: (1) the electroweak Standard Model and beyond and (2) the strong interaction. The major facilities now existing in North America are also described. Finally, the conclusions and recommendations which emerged from the workshop series are presented. Five technical appendices prepared by separate working groups provide more detailed expositions of the physics issues than the body of the white paper.

# 2 Physics Issues

## 2.1 Introduction

Physicists have made enormous strides in understanding the fundamental forces, or interactions, of nature during this century. At the beginning of this century, we knew of two — gravity and electromagnetism. One hundred years ago, we discovered radioactivity, which soon led to the introduction of the weak interaction. The existence of a strong interaction also was recognized early in the century as the force through which protons and neutrons bind together to form a nucleus. To study the strong interaction, physicists developed a variety of particle accelerators that act much like a microscope to probe the nucleus and its constituent particles, the nucleons, at smaller and smaller distance scales. As technologies evolved, beam energies increased and a new array of previously unknown particles, mesons and baryons, were produced. Particle physics developed as a new discipline, in part to study the source and extent of these new objects. Nuclear physicists continued to study the remarkable spectrum of phenomena displayed by the many-body system of the nucleus and kept as an underlying goal the development of a theory of the nucleon-nucleon interaction. Indeed the existence of the first of the mesons, the pion, was predicted from the properties of the nucleon-nucleon interaction.

The decade of the 1950's and into the 1960's witnessed an explosion of new particles and new ideas on the forces of nature. New experimental tools — both accelerators and ancillary equipment — provided the means to study the production and decay of many of these particles. In an attempt to give order to this new array of particles, Gell-Mann and Zweig in 1960 introduced the quark model which provided a natural explanation for the known 'elementary particles,' including the nucleons, by using three quarks as fundamental building blocks. Later Glashow, Salam, and Weinberg, using gauge theory, were able to unify the electromagnetic and weak interactions into one electroweak theory.

Over two decades ago, particle physicists demonstrated that the proton and neutron are composed of smaller constituents. Other experiments at high energy accelerators also showed that the meson models developed to understand nuclear interactions at low energy do not work when the nucleus is probed with high energy particles. Around this time, Quantum Chromodynamics (QCD) was introduced as a theory of the strong interaction of quarks with the force being carried by a new elementary field, the gluons. QCD was coupled with the electroweak model to form the Standard Model which is based on the gauge symmetry $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$.

For more than two decades, particle and nuclear physicists have worked to test both the electroweak and strong interaction sectors of the Standard Model. Through these efforts we have a better understanding of the successes of the Standard Model, but many open physics questions remain. Below we discuss how experiments at multi-GeV hadron facilities can play a crucial role in this important undertaking.

## 2.2 The Electroweak Standard Model and Beyond

The remarkable phenomenological success of the standard electroweak theory has led to its universal acceptance. However, there are many questions left unanswered. Why, for example, are there three groups, or generations, of quarks and leptons with very different masses but otherwise similar properties? Is there some fundamental relationship between the quarks and leptons that appear to belong to the same generation? Are some of these

leptons, specifically the neutrinos, truly massless and hence very special particles? What leads to mixing between the quarks? These are just a few of the problems leading most physicists to conclude that the electroweak theory is incomplete, that a deeper and more satisfactory understanding can only be gained by uncovering some still undiscovered physics "beyond" the current theory.

There are three ways to search for new physics — through experimentation at higher energy, through higher precision measurements for allowed processes, or through higher sensitivity to rare or forbidden processes. Some issues can only be addressed effectively at higher energies. For example, the electroweak theory contains a mechanism, known as electroweak symmetry breaking, which is responsible for generating the masses of the fundamental particles. Although the details of the electroweak symmetry breaking are not fully understood, a possible scenario invokes the existence of one or more particles called the Higgs. Elucidating such issues as the number and kinds of Higgs particles, or what replaces them to achieve electroweak symmetry breaking, was to be the primary mission of the SSC, which would have provided proton-proton collisions with center of mass energies of 40 TeV. For the foreseeable future, the high energy frontier has shifted to CERN, where the LHC will be built, with a design energy of 14 TeV. It remains to be seen whether the LHC has sufficient reach to succeed, or whether a higher energy machine may not in the end still be needed. In any case, with the current LHC schedule, major progress on this frontier is at least a decade away.

Many opportunities to address some of the most fundamental questions in particle and nuclear physics, and to possibly observe new physics beyond the present electroweak theory, depend on the other two approaches — high precision and high sensitivity — through experiments which typically require specialized beams, such as kaons, pions, muons or neutrinos, derived from hadron accelerators. These experiments often require beams with very high intensities and good quality, such as high purity. Frequently the energy of the beam is not a chief figure of merit. Some examples of measurements, featuring high precision and high sensitivity, which probe the limits of the electroweak theory are highlighted below. A more detailed discussion of these and other important experiments that test the electroweak theory can be found in the appendices.

### 2.2.1 Precision Tests of the Electroweak Theory

Prior to the introduction of the electroweak theory, a large number of experiments in particle and nuclear physics had been carried out to understand the character of the weak interaction. We knew, for example, that the beta decay of a nucleus and the beta decay of a muon were linked by a common interaction. Also, of the five possible interactions that could produce beta decay — scalar, pseudoscalar, vector, pseudovector (axial vector), and tensor — only two, the vector ($V$) and axial vector ($A$) appeared to contribute. The electroweak theory provides a firm theoretical basis for these results. According to it, the elementary couplings of the quarks and leptons are pure $V - A$ and these couplings are universal, which simply means they are the same for quarks and leptons from generation to generation. One important way of testing the theory is to push those basic experiments, many of which predated its introduction, to higher precision. Several approaches have been used to determine if the actual form of the electroweak interaction is pure $V - A$ with the best constraints to date coming from muon decay experiments. New experiments in neutron, muon, pion and kaon decay are being planned to search with higher precision for deviations from a pure $V - A$ theory. A complete test of lepton universality requires comparisons

between measurements of several different processes. For example, $e$-$\mu$ universality has been best tested by comparing the branching fractions of $\pi^+ \rightarrow e^+\nu$ and $\pi^+ \rightarrow \mu^+\nu$ and further improvement is still possible, since theoretical uncertainties in the comparison are well below the level of experimental uncertainty.

The electroweak theory introduced some new features such as the weak mixing (or Weinberg) angle, new bosons — the $W$ and the $Z$, and a mechanism for quark mixing that provided a framework for understanding weak decays involving quarks. Precise measurements of the weak mixing angle from neutrino experiments, when combined with the values of the $W$ and $Z$ boson masses, provide an important test of the theory. At the current level of precision, agreement is good provided the top quark mass is about 170 GeV/c$^2$ — a value consistent with indications from the CDF experiment at Fermilab. Measurements at LEP and SLC will continue to improve the results at the $Z$ pole and the Fermilab collider will refine the measurements of the $W$ mass. A neutrino experiment in preparation at Fermilab should improve the measurement of the weak mixing angle by a factor of 2.5 in the next few years. Further significant improvements will be possible once the Fermilab Main Injector is in operation.

A key test of the electroweak theory is whether the quark mixing matrix (known as the Cabibbo-Kobayashi-Maskawa or CKM matrix) is unitary — that is, whether certain mathematical relationships between the elements of the matrix are satisfied. A failure of unitarity would herald new physics. Current measurements are consistent with unitarity, but some CKM elements are still either poorly determined or undetermined. Because these elements appear in the amplitudes for various weak decay processes, it is possible to test the unitarity of the matrix by a series of measurements which overdetermine the values of the matrix elements. While straightforward, this is very challenging, since it requires very good measurements in a wide variety of processes. For example, a precise measurement of the pion beta decay rate is the best way to determine the CKM element coupling the first generation $u$ and $d$ quarks. Several kaon decays, some of them very rare and difficult to observe, are important to this effort. It is perhaps surprising that the best information on the CKM elements associated with the top quark are likely to come from kaon decays, since precision studies of direct top decays are impossible for the foreseeable future. For example, the rare decay $K^+ \rightarrow \pi^+\nu\overline{\nu}$ (with expected branching fraction in the neighborhood of $10^{-10}$) occurs through a second-order weak process and is sensitive to the CKM element coupling $t$ and $d$ quarks. A major effort is underway at the AGS to make the first measurement of $K^+ \rightarrow \pi^+\nu\overline{\nu}$. Information on $B$ meson decays is also important, particularly due to their sensitivity to the CKM elements involving second generation $c$ and third generation $b$ quarks. Clearly, a complete test of the unitarity of the CKM matrix relies on continued progress in refining experiments on the decays of $\pi$'s, $K$'s, and $B$'s. The first two of these depend on obtaining high intensity secondary beams from hadron accelerators with external target capabilities, such as the Brookhaven AGS and Fermilab complex, or from meson factories (for $\pi$'s).

As a final example, a very precise determination of the anomalous magnetic moment of the muon, usually referred to simply as muon $(g-2)$, when compared to its theoretical value, is a sensitive test of the Standard Model, as well as a probe for new physics — such as a new interaction or muon or W boson substructure. It was last measured in a classic experiment at CERN in the 1970's. An experiment under construction at the AGS should improve upon the CERN result by a factor of 20 or more and even further improvement may be possible in the future, if required facilities are available.

### 2.2.2 CP Violation

CP violation — that some processes are not invariant under the combined transformations of charge conjugation and parity — was discovered in 1964 in $K$ decays. While CP violation is a subtle concept, it has profound consequences. Since all evidence indicates invariance under CPT (that is, when the time-reversal transformation is applied along with C and P), it means that there is a difference, even on the subatomic scale, between going forward and backward in time. This, in turn, provides experimental distinctions between a world made of matter and a world made of antimatter. Indeed, CP violation is now believed to be an essential ingredient in the evolution of the dominance of matter over antimatter in our universe. But 30 years after its discovery, the effect is not fully understood.

The electroweak theory permits CP violation in a natural way because the CKM matrix may have a complex phase. However, the value of the complex phase is not predicted by the theory and current measurements do not firmly establish the phase as the source of the CP violation observed in $K$ decays. Consequently, an experimental thrust today is the measurement of $\epsilon'/\epsilon$, a parameter which is sensitive to the "direct" CP violation in the decay amplitude of kaons which would result from a non-zero complex CKM phase. Major experimental programs to measure $\epsilon'/\epsilon$ have been and continue to be underway at both Fermilab and CERN. The experiments strive for a standard of precision that is rare in high energy physics and as a result they are among the most difficult, challenging, and beautiful in the field. Hyperon decay experiments in principle can also provide an indication of direct CP violation. A first generation search for CP violation in hyperon decays will be undertaken at Fermilab in the next few years. Other experiments sensitive to some aspects of CP violation are ongoing at LEAR and Frascati, but they will not be able to match the precision on $\epsilon'/\epsilon$ of those with $K$ beams at Fermilab and CERN. The $\epsilon'/\epsilon$ experiments, while a critical step in our study of CP violation, are only part of a larger program in the $K$ system. The $B$ meson system will also provide a rich testing ground for models of CP violation. Dedicated $e^+e^-$ collider "$B$ factories" are now under construction at SLAC and KEK in Japan and should be running by the end of the decade. Also, it may be practical to study CP violation using hadronically produced $B$'s from some combination of the Fermilab collider, HERA, RHIC, and ultimately the LHC. There is, however, a significant learning curve to be surmounted in studying $B$ decays and the $K$ system has not been explored to its full potential.

For example, decays of the type $K_L^0 \to \pi^0 l\bar{l}$, where $l$ indicates a lepton, are promising probes of direct CP violation. The branching fractions of all such modes are very low, of roughly the order $10^{-11}$. The decay $K_L^0 \to \pi^0\nu\bar{\nu}$ is of special interest since it can provide a measurement of the complex CKM phase with almost no theoretical uncertainty. Unfortunately, it is so far beyond the reach of current experiments that the feasibility of observing it is uncertain. The modes with charged leptons, $K_L^0 \to \pi^0 e^+e^-$ and $K_L^0 \to \pi^0\mu^+\mu^-$, while less theoretically simple and harder to interpret in terms of CP violation, are almost certainly tractable at Fermilab with the Main Injector. The potential for progress on these modes warrants serious effort. Innovative ideas for attacking the $K_L^0 \to \pi^0\nu\bar{\nu}$ mode have been advanced and can only be tested against experience. Also, polarization measurements in some $K$ decays probe non-Standard Model CP violation. Indeed, it appears that the maximum CP violation possible from the complex CKM phase is insufficient to account for the baryon-antibaryon asymmetry in the universe. That is, there may be a cosmological indication of another source of CP violation beyond the standard electroweak theory. Experiments measuring muon polarization in $K$ decays, where non-Standard Model CP

violation could be observed, appear well suited to the low-energy $K$ beams of the AGS.

### 2.2.3 Lepton Flavor Violation

No reaction has ever been observed which changes the net quantum number associated with each generation of leptons. Indeed, the conservation of this quantum number — lepton flavor conservation — is formalized in the standard electroweak theory. However, its origin is not understood in terms of a gauge symmetry, suggesting that the conservation is probably not exact. Dedicated searches for lepton flavor violation are most often conducted in muon and kaon decays, or related processes such as muon-electron conversion in the field of a nucleus ($\mu^- A \rightarrow e^- A$), owing to the advantages of working with long-lived particles (e.g., it is possible to create muon and kaon beams) and the enhanced sensitivity to small effects arising from the relatively small total decay rates. Experiments currently searching for lepton flavor violation in muon decays at LAMPF and kaon decays at the AGS are sensitive to branching ratios of order $10^{-12}$.

In contrast, the current experimental sensitivity to lepton flavor violation in other particle decays is much less stringent — roughly $10^{-6}$ in $\tau$ and $B$ decays. The higher masses of the $\tau$ and $B$'s only partially compensate for the much longer lifetimes of the $\mu$ and $K$'s, so that in simple extensions to the electroweak standard theory, the $\mu$ and $K$ decay experiments are often much more sensitive to new physics. A natural way to parametrize the physics reach of these searches is in terms of the mass scale of a new interaction which could be responsible for the decay. The existing limits in muon and kaon decays are sensitive to mass scales of about 100 TeV — far beyond the reach of direct production in foreseeable accelerators — and future searches will continue to push this frontier as the intensity and quality of muon and kaon beams improve. An example where rapid progress may be possible is the development of specialized muon beams. The current limit on muon-electron conversion is $4 \times 10^{-12}$ from TRIUMF and PSI experiments, but a new experiment at PSI has a goal of a $10^{-14}$ measurement. At the same time, innovative ideas for reaching the $10^{-16}$ level are being explored at TRIUMF and elsewhere.

### 2.2.4 Neutrino Oscillations

Neutrinos are assumed massless in the electroweak theory, but they may have small masses. Experimental upper limits on the masses of the three neutrino flavors ($\nu_e$, $\nu_\mu$, $\nu_\tau$) are about 7 eV, 270 keV, and 31 MeV, respectively. It is very difficult to improve these limits significantly by direct measurement, but if neutrinos do indeed have non-zero masses, then neutrinos of different flavor are expected to mix, leading to a potentially observable phenomenon called neutrino oscillations. For example, if a pure beam of $\nu_\mu$'s is produced, then at some distance away from the production region $\nu_e$'s and/or $\nu_\tau$'s may be found. The details of the oscillation will depend on the differences in the squares of the neutrino masses and on the strength of the mixing. Observing neutrino oscillations would prove that neutrinos have mass.

There are a number of reasons for suspecting that neutrinos may have mass. More than 90% of the mass in the universe is now believed to be "missing" — that is, unobserved except by its gravitational effect. Part of the missing mass (or dark matter) may be massive neutrinos. Indeed, some "hot" dark matter — exactly what massive neutrinos would constitute — may be needed to account for the structure and density variations seen in the universe. Also, there are indications that too few solar neutrinos reach the earth, implying

that some of the $\nu_e$'s produced in the sun may oscillate to another species en route. Finally, a set of experiments sensitive to neutrinos produced by cosmic ray interactions in the upper atmosphere have reported a low number of $\nu_\mu$'s relative to $\nu_e$'s, again hinting at a possible oscillation. However, convincing evidence for neutrino oscillations can only come from accelerator- or reactor-based experiments where it is possible to understand, in detail, the properties of the initial neutrino beam and control systematic uncertainties.

A number of accelerator-based searches for neutrino oscillations have been conducted — with negative results so far. Others are in progress now, for example at LAMPF and CERN. The range of mass differences for which any given experiment is sensitive depends on the ratio of the distance traversed by the neutrinos to their energy. No single experiment can cover the whole range. A new round of "long-baseline" experiments — experiments where the detectors are tens or even hundreds of miles from the accelerator — is now being planned to probe very small mass differences. These experiments require very intense neutrino beams and appear to be possible using the Brookhaven AGS and the Fermilab Main Injector.

## 2.3 Strong Interactions

For many decades the strong interaction frustrated nuclear and particle physicists who struggled to understand it. Successful phenomonological models were developed which worked in specific and limited domains. But with the advent of Quantum Chromodynamics, the challenge of achieving fundamental understanding seems within our grasp. QCD provides a common framework for all processes involving the strong interactions — both at the particle and nuclear (many-body) level. However, because QCD differs from the electroweak theory in dramatic ways, many problems are computationally much more challenging and we do not yet have all the tools to solve them. In QCD, the bosons which carry the force, the gluons, can interact strongly with each other. Furthermore, the strength of the QCD force, rather than decreasing with distance, actually increases with distance — a feature necessary for the confinement of quarks and gluons within hadrons. For some processes, those involving "hard scattering" where large momentum is transferred between interacting quarks or gluons, it is adequate to apply perturbation theory to QCD. In this domain, QCD is reasonably well understood and it is here that most of the quantitative confrontations with experiment have been made. For other processes, particularly those involving bound systems, or interactions with too little momentum transfer to reach the perturbative regime, we do not yet know how to obtain definitive answers from QCD. It is in these areas that guidance from experiment is particularly important.

Many exciting possibilities have been suggested by QCD. Glueballs, bound states of gluons — with no quarks, or quark-gluon bound states with exotic quantum numbers, may exist. "Strange matter," stable baryons containing strange quarks, may exist under some conditions. Indeed, it has been suggested that neutron stars, the highly dense remnants of burned out stars, could actually consist of strange matter rather than neutrons. A quark-gluon plasma may be formed in nuclear matter under conditions of extreme temperature and density; searching for this new state of matter is a primary goal of RHIC, the relativistic heavy ion collider now under construction at the Brookhaven. And aside from possible new states of matter, many basic questions of hadron and nuclear structure and dynamics are still to be answered. For example, how much of the spin of nucleons is due to the quarks and how much due to the gluons? Why are nucleons different when they are inside a nucleus? How can we calculate the short and intermediate range part of the proton-proton force?

Experimental progress on these and other important strong interaction questions depends on a wide variety of experiments with a range of probes — from hadrons, including polarized protons, to leptons at a wide range of energies and heavy ions. Such experiments complement those at various high energy physics accelerators around the world, including hadron colliders such as the Tevatron at Fermilab, electron accelerators such as SLAC at Stanford and the hadron-electron collider at HERA in Germany. The two new accelerators for nuclear physics, CEBAF at Newport News, Virginia, and RHIC will probe facets of QCD. The array of phenomena produced by the strong interaction makes this multi-facility approach necessary to determine if QCD is the correct theory of the strong interaction and to determine how to apply it to low energy strong interactions.

### 2.3.1 Short Distance QCD

High energy/high momentum transfer experiments probe the short distances over which the effective strength of the QCD coupling is weak enough for perturbation theory to work. One purpose of such experiments is to directly probe the quark and gluon structure of hadrons. For example, high energy experiments can measure the momentum distributions of quarks as they move rapidly within hadrons. Much has been learned about the internal quark/parton structure of the nucleon from several sources, including deep inelastic scattering (DIS) with high energy electron, muon and neutrino beams. Drell-Yan production of lepton pairs and prompt photon production in both fixed-target and collider reactions have also contributed. However, we know much less about the momentum distribution of gluons and the amount of various antiquarks (sea quarks) within the nucleon. Hadron probes and secondary beams from hadron facilities can selectively examine the glue and the sea. Sea quark distributions, for instance, can best be determined by Drell-Yan or neutrino DIS measurements at high energy. Also, we know very little about parton distributions in mesons. These distribution functions can be obtained through studies of Drell-Yan processes with high energy and high intensity $\pi$ and $K$ beams that will only be available at Fermilab.

The quark and gluon momentum distributions inside nucleons are useful, in turn, when one is interested in how nucleons interact with each other (most often protons with protons, or antiprotons) at very high energies to produce new particles. For instance, an important input to the analysis of top quark production at the Fermilab collider is the QCD cross section for $p\bar{p} \to t\bar{t}$, which depends on our knowledge of quark and gluon distributions. To estimate the production of even the most exotic of particles in high energy collisions, for example in the LHC, it is necessary to have a reasonable knowledge of these distributions.

A fundamental aspect of QCD is that just as positive and negative electrical charges close together tend to neutralize and then interact weakly with matter, quarks of complementary color charge in close proximity will interact weakly with nuclear matter. The clearest way to ensure that the quarks are close together is to perform a reaction at large momentum transfer, which probes short distances. At high energy, such a carefully prepared pair can travel long distances. This technique can map out the quark-antiquark distribution function of mesons. A related application of this concept, sometimes called color transparency, in exclusive reactions is discussed later.

Nuclear effects modify hadronic interactions even at the highest energies that we have studied. One example is the experimental observation from about 20 years ago, still not completely understood today, that the production of particles at large transverse momentum is enhanced with nuclear targets. Another nuclear effect is that momentum distributions

of quarks in the nucleus are significantly different from those in a proton. One important case is the phenomenon of shadowing which indicates that there are a reduced number of low momentum quarks in the nucleus compared to a nucleon. This results from the interactions of quarks in neighboring nucleons. As yet we have little hard information on how the low momentum glue is affected by the nuclear environment. These same interactions can produce coherent increases in cross sections from interference effects between nucleons. Experiments in $p + A$ scattering studying shadowing in this region could be carried out both at Fermilab and at RHIC. They will probably be crucial to understand the dynamics of ultra-relativistic heavy ion scattering at RHIC.

Both the quarks and gluons in QCD carry intrinsic spin angular momentum. The dynamical interactions of the quarks and gluons produce mesons and baryons, including the nucleons, with well defined total angular momentum. Within the past decade, we have seen surprising results from high energy muon and electron scattering experiments which indicate that the basic (valence) quarks may not contribute nearly as much to the spin of the nucleon as was widely expected. To date, all of the information that we have about the spin structure of the nucleon has been derived from deep inelastic scattering from longitudinally polarized electrons and muons (i.e., polarization along the direction of motion). These probes have been used to measure the quark polarization within nucleons. However, gluons inside nucleons may be highly polarized and we need to measure their spin.

There is no information available from lepton scattering about transverse spin effects in the nucleon. In QCD, transverse spin and longitudinal spin effects are equally important and it is crucial to determine both types of spin structure functions to thoroughly test the predictive power of perturbative QCD. The only way to measure effects such as gluon and sea quark polarization and transverse polarization distributions is with high energy polarized hadron beams. At the present time, these beams are not available. However, a US-Japan collaboration has been formed and, with a major commitment from Japan, plans to provide the polarized beam hardware to RHIC are now being finalized. This addition to RHIC would be a major step toward providing the capability to study the spin effects in the nucleon.

### 2.3.2 Long Distance QCD

When the distance scale of a process becomes characteristic of the size of mesons or nucleons, the effective QCD coupling becomes so large that perturbation theory breaks down. A number of models have been constructed to approximate QCD which attempt to understand both the reaction dynamics in this regime and the interactions between quarks and gluons that lead to new forms of matter. There are a wide range of important questions that must be answered, through innovative experiments combined with new theoretical insight, to fully understand the interplay both between perturbative and non-perturbative QCD and between QCD and the baryon-meson models of lower energy nuclear physics.

Symmetries of the QCD interaction play a crucial role in understanding interactions at lower energies. Chiral symmetry, an approximate symmetry of the QCD Lagrangian, and chiral perturbation theory provide a way to interrelate properties of particle decays to dynamical properties of hadronic interactions. Indeed, some of the more interesting electroweak issues in $K$ decays discussed earlier, for example understanding how to interpret measurements of $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0 \mu^+ \mu^-$ branching ratios in terms of CP violation, depend on achieving a better understanding of these properties, and chiral pertur-

bation theory appears to be the best avenue for progress. While the low energy parameters for the mesonic sector have been determined, this is not the case for the $\pi, K$-nucleon sector. This remains as a major challenge which must be addressed by a program of precision measurements. Another fundamental goal must be the extension of chiral techniques to higher energies, which will require the coordinated efforts of theorists and experimentalists. Another feature of chiral symmetry is that polarization effects will disappear in hard quark-quark interactions. Indications from data that is available are that large polarization effects persist even in hadron-hadron collisions at many GeV. Detailed investigations of polarization phenomena throughout the kinematic region from where non-perturbative QCD is applicable to where perturbative QCD can be applied may provide essential information on the transition between these two regimes.

Nuclear, or medium, effects are very prominent in hadron dynamics at lower energies. Color transparency, which was introduced earlier, occurs in a nuclear medium through color screening combined with hard scattering processes. Through investigations of color transparency, we have a unique way to separate different components of reactions, which simplifies the understanding of the dynamics. In particular, color filtering of reactions may allow us to study processes at lower energies with the non-perturbative part of the reaction removed. Some experiments on color transparency at the Brookhaven AGS have already been done but more sophisticated measurements are needed to fully understand the process. Polarization measurements will be quite important to gain a complete understanding of this process since color transparency theory suggests that polarization effects in $NN$ scattering will be suppressed in interactions with nucleons inside nuclei. Polarization experiments that are needed to study both color transparency effects and chiral symmetry require highly polarized beams. At lower energies, they could be carried out at LISS — an accelerator proposed by Indiana University — or at the AGS after it is upgraded to provide highly polarized beams.

### 2.3.3 Exotic Hadrons and Nuclei

QCD inspired models and lattice gauge calculations, which are applicable in the non-perturbative QCD regime, predict a number of exotic physical states that have not been seen: states with no valence quarks, called glueballs; hybrid states such as quark-antiquark-glue or three quark plus glue combinations; multi-quark states which contain several pairs of quarks and antiquarks; combinations of quarks such as the six quark state called the H dibaryon. None of these exotic forms of matter have been conclusively identified by experiment although there are possible candidates for some of them. If these new forms of matter do not exist, we must reexamine QCD since they appear to be a direct manifestation of the theory. To investigate the exotica in light quark spectroscopy requires intense beams of $K$ mesons and antiprotons and better instrumentation to utilize these beams. The best source of $K$ beams in the near future is the Brookhaven AGS. By the turn of the century, the Fermilab Main Injector will be able to produce high intensities of $K$ beams at somewhat higher energies. With the approval of the LHC, the research program at the antiproton source, LEAR, at CERN is not expected to continue. If LEAR closes, the accumulator ring at Fermilab will be the best source of cooled antiprotons available in the world.

These studies in light quark spectroscopy are complementary to those being carried out in heavier quark systems, such as the charm spectroscopy measurements at Fermilab, which rely on the antiproton source. While the basic physics is the same between the two sectors, the underlying assumptions that can be made for theoretical calculations in the two

regimes are quite different. In the heavier quark systems, potential models, much like those used for atomic and nuclear structure physics, can be used to compare experimental results to QCD predictions. In fact, a new symmetry of QCD was found recently that makes the QCD predictions independent of quark mass for heavy quarks. This leads to the remarkable prediction that the spectroscopy of particles containing one charm or one bottom quark will be identical.

A new form of nuclear matter is produced by adding one or more strange quarks to a normal nucleus. The resulting system, a hypernucleus, can be bound by the strong interaction and will typically decay by weak interactions. Hypernuclei provide a unique doorway to understanding the hyperon-nucleon ($YN$) and hyperon-hyperon ($YY$) interactions. Hypernuclear measurements provide our primary constraints on modeling of the underlying baryon-baryon interaction which links $NN$, $YN$ and $YY$ interactions. The availability of new instrumentation and higher intensity $K$ meson beams at the AGS opens up an entirely new class of hypernuclei for study. Studies of $S = -1$ systems will complement measurements that are planned for CEBAF, and $S = -2$ systems, which can be reached through $(K^-, K^+)$ reactions on nuclei, will provide unprecedented information on the baryon-baryon interaction in this sector. Furthermore, these systems will provide opportunities for studying multiply strange hadronic or quark matter which could possibly be formed in high-energy heavy ion collisions at RHIC.

### 2.3.4 Discrete Symmetries

Unveiling the discrete symmetries of nature has played a major role in the development of modern physics. Numerous tests of discrete symmetries, such as CP violation, are discussed in Section 2.2. The strong interaction is assumed to obey the discrete symmetries of parity and time reversal invariance. However, parity violation in $NN$ scattering can occur through the interference of the strong and weak interactions. Low energy studies of these two symmetries have been carried out and confirm this picture. Due to the lack of facilities, very few tests of these symmetries have been performed at higher energies. There exists one unexpectedly large $NN$ parity violation measurement at 6 GeV. If correct, this result is difficult to explain, and needs confirmation. It is important to measure parity violation at several energies with multi-GeV polarized protons in the future. These measurements could be carried out at the AGS, after an appropriate upgrade is completed, or at LISS. They could be extended to higher energies if the Main Injector at Fermilab is upgraded to accelerate polarized protons. A novel approach to studying time reversal invariance will soon be tested at COSY, a proton storage ring in Germany. The experiment will measure the spin-dependence of the stored beam life time in the storage ring. In the future, similar experiments, at much higher energies, could be carried out at LISS.

## 2.4 Summary

Even with all of its successes, many fundamental questions at the very foundations of the Standard Model remain to be answered. Many of these question can be studied most effectively through experiments at multi-GeV hadron beam facilities. Without high intensity and high purity beams of muons, pions, kaons, hyperons and neutrinos, many open questions in the electroweak sector simply cannot be addressed. In the strong interaction sector, testing QCD and understanding how to apply it to the wide range of problems described above requires a broad range of hadron beam energies and particle probes, including

polarized protons. Between the AGS and RHIC at BNL and the Fermilab complex, the primary facilities needed to attack these problems over the next decade are in place or soon will be. Effective utilization of the particle beams at these facilities, along with new instrumentation in some cases, will allow us to make major advances in our understanding of these important problems.

# 3 Facilities

## 3.1 Introduction

Our ability to address the fundamental questions in particle and nuclear physics discussed in the previous section depends on future access to appropriate hadron beams and their by-products. Only a small number of facilities that produce medium to high energy hadron beams now exist in the world. Four synchrotrons are capable of accelerating multi-GeV beams of protons — the AGS at Brookhaven National Laboratory, the Fermilab booster and Tevatron, the SPS at CERN in Geneva, Switzerland and the PS at KEK in Tsukuba, Japan. Five other accelerators, which support programs that overlap with the physics issues in this white paper, produce beams of protons in the energy range from several hundred MeV to 1 GeV, including two proton storage rings (COSY at Julich, Germany and the IUCF ring at Indiana University), three meson factories (LAMPF at Los Alamos National Laboratory, PSI near Zurich, Switzerland, and TRIUMF at Vancouver, British Columbia). With few exceptions, the physics outlined in this white paper requires primary, secondary, tertiary, or polarized beams from multi-GeV hadron beam facilities. Without new accelerator construction projects, we are thus limited to the four operating multi-GeV synchrotrons along with accelerators that are now being built at BNL and Fermilab. However, with the approval of the LHC project at CERN, it is not clear what the schedule for beam time at the CERN SPS will be in the future. The scope of the physics program at the KEK PS is limited by the accelerator in both energy (less than one-half of the AGS at BNL) and intensity (typically about 2% of the AGS). With the completion of the recent upgrades at the AGS, which have substantially increased its beam intensity, and the construction of the Main Injector at Fermilab, which is scheduled for completion in 1998, the United States will have the best facilities in the world to attack the problems in this important field of physics.

The five North American accelerator labs referred to above — BNL, Fermilab, IUCF, LAMPF/LANL and TRIUMF — have had a long history of experimental work in electroweak and strong interaction physics. They jointly have sponsored the three workshops that led to this white paper. Each of the five facilities offers unique capabilities which are described below. Some of the strong interaction physics problems at lower energy could be pursued at the proposed accelerator/storage ring LISS at IUCF. Also experiments that test the electroweak Standard Model by measurements in neutron decay, muon decay and low energy neutrino scattering can be performed at LAMPF and TRIUMF. But it is clear that with the loss of KAON at TRIUMF, the future of this field lies in our access to beams at BNL — both at the AGS and eventually RHIC — and those from the Fermilab complex.

## 3.2 The BNL AGS and RHIC

The Alternating Gradient Synchrotron (AGS) is a synchrotron that accelerates protons (up to 30 GeV), polarized protons (up to 25 GeV) and heavy ions (up to 15 GeV/$A$). Particle beams from the AGS can be delivered simultaneously to up to nine experiments. The completion, in 1992, of the booster ring, a lower energy synchrotron that is used to inject beams into the AGS, was a major step in an intensity upgrade program for the accelerator. The result this year should be a four fold increase in proton beam intensity out of the AGS compared to operation in 1991. The addition of a partial Siberian Snake in the AGS has eliminated problems with depolarization during the acceleration of polarized

proton beams and has increased substantially the proton polarization at extraction.

The current physics program at the AGS is focused on experiments that probe the Standard Model, both through tests of the electroweak sector and QCD. Some of the experiments that are underway include measurements of rare kaon decay processes and searches for kaon decays that are forbidden in the electroweak Standard Model, measurement of very dense nuclear matter produced in heavy ion collisions, searches for glueballs, exotic quark states, and the H dibaryon (stable strange matter), measurements sensitive to color transparency, studies of hypernuclei, and a measurement of the muon anomalous magnetic moment. A long-baseline neutrino oscillation experiment also may be initiated in the near future.

The synchrotron/storage rings for the Relativistic Heavy Ion Collider (RHIC) are now under construction at BNL with funding through the Division of Nuclear Physics (DNP) of DOE. Construction should be completed late in 1998 and the first beams for physics use in RHIC are scheduled for the spring of 1999. The AGS will serve as an injector to RHIC providing heavy ion beams and both polarized and unpolarized protons. At full energy, RHIC will be able to produce circulating proton beams up to 250 GeV and very heavy ion beams up to 100 GeV/$A$. The RHIC polarized proton beams should play a major role in probing important spin dependent aspects of perturbative QCD. The AGS has been operating as a high energy physics facility since 1961. With the completion of RHIC, it will be transferred to DNP at DOE to serve as the RHIC injector. As an injector into RHIC, the AGS will only be needed a small fraction of the time and could be used for a fixed target program the remainder of the time, if funding is available to operate both the accelerator and the experimental areas. Efficient planning for this era requires that plans to provide these funds be formulated soon.

### 3.3 Fermilab

Fermilab is a national laboratory operated by the Division of High Energy Physics (DHEP) of DOE. The accelerator complex consists of the Tevatron collider, which is injected by beams from the booster synchrotron, an accumulator ring which collects antiprotons for reacceleration in the Tevatron where they are used in $p\bar{p}$ colliding beam experiments, and a linac for initial acceleration of the proton beam. In fixed target mode, the Tevatron and the booster produce primary proton beams and secondary and tertiary beams of varying composition, intensity, and energy. Currently beam is delivered either to collider experiments or fixed target experiments in cycles that are typically for two or three years at a time. In fixed target mode, the Tevatron delivers beam to three experimental areas (historically designated Meson, Proton, and Neutrino). This ultimately yields twelve independent experimental stations that can use primary or secondary (or tertiary) beams. During fixed target operation, antiprotons from the 8.9 GeV/c accumulator can be used for low energy experiments. A new synchrotron, the Main Injector (FMI) which is now under construction, will allow fixed target operation with up to 120 GeV proton beams, concurrent with the collider program. The FMI is expected to operate with about one-half of the proton beam intensity and up to four times the energy of the AGS. The FMI is scheduled to be completed in late 1998 and the recommissioning of the Tevatron collider with the FMI is scheduled for early in 1999.

The Tevatron is presently the highest energy accelerator in the world and the physics program at the Tevatron has focused on the high energy frontier since its initial operation as a $p\bar{p}$ collider. Two major detectors, CDF and D0, are now operating at two of the

intersection points around the Tevatron ring and collecting data from $p\bar{p}$ interactions. The Tevatron in fixed target mode supports a program that tests the Standard Model in the electroweak sector through experiments of CP violation in $K$ decays and measurements of neutrino interactions, and in the strong interaction sector through heavy quark spectroscopy and direct tests of perturbative QCD. With the completion of the FMI, the Tevatron likely will be used at least two-thirds of the time in collider mode, substantially reducing the amount of time available for fixed target operation with 800 GeV protons. However with the FMI, protons of up to 120 GeV can be extracted during collider operations providing simultaneous operation of fixed target and collider experiments. Present plans call for a neutrino beam to be used for a new short-baseline neutrino oscillation experiment and possibly for a complementary long-baseline experiment which is under consideration. The FMI will also be used to deliver protons to the existing switchyard which will be used in an upgraded kaon experiment. Other uses of the extracted beam from the FMI will require funds for new detectors. Also funds may be needed to modify existing beam lines in the fixed target area or to construct new ones.

### 3.4 Indiana University Cyclotron Facility

The Indiana University Cyclotron Facility (IUCF), a national facility supported by the NSF, began initial operation in 1975 with two coupled cyclotrons. They provided beams of polarized and unpolarized protons and deuterons together with other light ions for studies of nuclear reactions and nuclear structure. In the 1980's, the laboratory developed the use of electron cooled internal beams and targets with the Cooler ring, which is a synchrotron accelerator/storage ring that is injected by the larger of the two cyclotrons. The Cooler is capable of accelerating protons to energies up to 560 MeV. In addition to its experimental program, the Cooler ring has been used to demonstrate the effectiveness of new technologies applied to the acceleration of polarized beams in a synchrotron, including the effectiveness of Siberian Snakes in overcoming depolarizing resonances during acceleration, a new rf technique for rapidly reversing the spin direction of a stored beam, and the use of windowless buffer cells for increasing the thickness of pure polarized internal targets. A new injector for the storage ring is under construction.

Experience in doing experiments with the present Cooler ring and the technological advances mentioned above have led to the design of the Light Ion Spin Synchrotron (LISS). This machine would provide high quality polarized beams of protons and deuterons with flexible spin orientation within the energy range from 0.4 to approximately 20 GeV. Breakup of polarized deuterons would be used to make a good resolution beam of polarized neutrons. The physics emphasis would be on experiments using internal targets with polarized and unpolarized circulating beams. Electron cooling would be used at energies up to about 4 GeV to improve the stored beam emittance and resolution. The principal goals of the LISS design are to accumulate $10^{12}$ particles (corresponding to a circulating current of about 0.1 A) and to store beam for several hours in the absence of internal targets. The machine is specifically designed from the outset for acceleration of polarized beams with full spin flexibility. A complement of experimental equipment is planned to carry out an initial set of experiments which take advantage of these unique features. The first phase detectors would include high sensitivity beam current monitors which allow the accelerator itself to be used as a detector for spin-dependent total cross section measurements. A magnet chicane also would be inserted into the magnet lattice to allow reaction products to be detected at angles down to 0° using a conventional single arm spectrometer of medium resolution. A

lower resolution dual-arm spectrometer system would be included for the study of processes at large transverse momentum.

## 3.5 LAMPF

LAMPF is a national user facility operated by the DNP at DOE and is part of the Los Alamos National Laboratory. Beam to the experimental areas is provided by an 800 MeV proton linac that accelerates a high-intensity (1 mA) $H^+$ beam, a polarized $H^-$ beam, and an unpolarized $H^-$ beam. The 1 mA beam is used to produce high-quality secondary beams of pions, muons, and neutrinos. Three secondary pion channels provide pion beams from 15 MeV up to over 500 MeV. The SMC (Stopped Muon Channel) is a high-intensity muon channel. A test channel provides a moderate-quality beam of charged particles for development and testing of experimental apparatus. There is a neutrino research area and facilities for isotope production and radiation-damage studies at the beam stop. The unpolarized $H^-$ beam, which can be accelerated simultaneously with the high intensity beam in the linac, is fed into the Proton Storage Ring (PSR), a high-current accumulator and pulse compressor which provides intense pulses of 800 MeV protons. The protons are used for the production of neutrons at targets feeding either the LANSCE or the WNR facilities. The WNR produces a white spectrum of neutrons up to nearly 800 MeV for a wide variety of studies. Moderators are used adjacent to the LANSCE target to reduce the neutron energies to those needed for condensed matter and neutron scattering research.

In the past few years, the research program at LAMPF has focused on studies of pion interactions with nuclei and measurements of electroweak processes in muon, neutron and neutrino interactions. Charged pion spectroscopy, such as measurements of pion double charge exchange, is carried out with EPICS (Energetic Pion Channel and Spectrometer). The NMS (Neutral Meson Spectrometer) is used for measurements with neutral pions in the final state. Large superconducting solenoidal magnets are being used in experiments studying rare muon decays and muonium. In addition, a 200 ton liquid scintillator detector is used for studies of neutrino scattering and neutrino oscillations. Research programs at LANSCE cover a broad range: solid-state physics, chemistry, metallurgy, crystallography, biophysics, materials science, and nuclear physics. In particular, the study of time reversal and parity symmetries using epithermal neutrons has been of great interest to the nuclear physics community. An ultra-cold neutron source is being built at LANSCE for a variety of fundamental physics experiments, including the study of neutron beta decay. Starting in fiscal year 1996, the DOE/Defense Programs will become the "landlord" of the LAMPF facility. Their primary mission is to pursue neutron scattering at LANSCE and WNR. A number of fundamental nuclear and particle physics experiments with neutrons will also be pursued there. In addition, it seems likely that high-intensity beams will also be available; they could be utilized for high-priority nuclear and particle physics experiments with the secondary beams.

## 3.6 TRIUMF

The TRIUMF facility utilizes a separated sector cyclotron to provide both polarized and unpolarized protons from 200 up to 510 MeV. With a maximum current of nearly 200 $\mu$A, the facility produces dc beams of pions and muons as well as extracted beams of protons. A variety of beam lines are available for experiments using either the primary or secondary beams from the cyclotron. During the past decade, TRIUMF worked on the

design of a new accelerator complex, KAON, and proposed its construction to the Canadian government. The proposal was officially rejected by Canada in February 1994. Following this, the laboratory put together a five year plan which has been presented to the Canadian funding agencies. According to the plan, TRIUMF will continue to play a national role in Canada as a user facility and it will become Canada's gateway to international facilities in subatomic physics. A broadly based science program will be supported on the cyclotron, with new science coming on-stream before the end of the five year period from the proposed radioactive beams facility, ISAC-1. In addition, TRIUMF accelerator expertise will be used in conjunction with CERN to make "in-kind" contributions to the LHC on behalf of the Canadian government.

In the past few years, the scientific program has focused on experiments at the recently commissioned spectrometers, SASP using medium-energy protons, and CHAOS using pions. Also experiments to study parity violation in the proton-proton interaction are underway. Active research continues in other areas including condensed matter science, using $\mu$SR techniques, and medical science programs with pions and protons, PET development and radioisotope production. Experiments in the basic research programs noted above would be completed during the period of the five year plan and possible new directions would be developed. Among the experiments being considered are a new test of $e$-$\mu$ universality, new measurements of the Michel parameters in muon decay and a new test of lepton number conservation through a $\mu$-e conversion measurement. A major new thrust for the TRIUMF cyclotron involves the construction of an Isotope Separator and Accelerator Facility (ISAC-1). The scientific program for ISAC-1 spans topics in nuclear astrophysics, nuclear structure, condensed matter research and biomedical research. Also, the low-energy beam from ISAC-1 would feed a neutral atom trap (TRINAT) where fundamental symmetries could be addressed by studying parity violation in atomic transitions, and by making detailed correlation measurements on $\beta$ decays involving superallowed transitions. These experiments, like those involving $\mu$ decay and conversion, are complementary to high-energy tests of the electroweak part of the Standard Model.

# 4 Conclusions and Recommendations

A broad and rich physics program, confronting issues that are central to progress in particle and nuclear physics, has been described in this white paper. In considering the facilities needed to conduct this program over the next five to ten years, a few common themes clearly emerge. These provide the impetus for the following conclusions and recommendations.

- Hadron beam accelerators of medium to high energy, with very high intensity external beams, or beams with special properties, are required to address some of the most fundamental questions in particle and nuclear physics. Stable, long-term support of these facilities must be established if a viable program in this field is to proceed.

- The Brookhaven AGS and the Fermilab complex, augmented by the Main Injector now under construction, provide the best opportunities in the world for conducting much of the research outlined in this white paper. They should be regarded as the primary facilities in the U.S. for conducting this research in the foreseeable future. Exploitation of these opportunities requires sufficient funding for effective utilization of these facilities in the near future, and support for well conceived upgrades in the long-term.

- Special opportunities will exist to address key questions in particle and nuclear physics at other accelerator facilities, such as the polarized beam capability at RHIC. Other opportunities may include polarized beams at the Main Injector/Tevatron, neutrino experiments at LAMPF, or muon experiments at TRIUMF or LAMPF. When deemed cost-effective and consistent with the missions of those facilities, experiments to exploit these opportunities should be allowed to compete for resources on an even footing with experiments at the primary facilities.

- To ensure timely progress and efficient utilization of accelerator facilities, equipment funds and support for university-based and laboratory-based user groups must be given high priority.

Finally, it is important to stress that much of the research discussed in this white paper is of common interest to members of both the high energy physics and nuclear physics communities. Consequently, collaborations on experiments will frequently include members from both communities. While this makes the boundary between these fields harder to locate, it is ultimately a healthy sharing of skills and resources which should be encouraged where a natural overlap of interests occurs. An important corollary of this is that the funding agencies responsible for funding high energy and nuclear physics (DOE and NSF) need to have good communication between their internal divisions which fund research in these two fields.

- Administrative barriers to funding high-energy/nuclear physics collaborative projects should be lowered. The funding agencies should encourage better communication between their advisory committees (such as HEPAP and NSAC), for example by conducting joint meetings on an regular basis.

# A About This Workshop

This white paper is the product of a workshop which took place December 2-3, 1994, at Fermilab. It was the third and final meeting in a series titled "Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities." The previous meetings were at Santa Fe in October, 1992, and Brookhaven in March, 1993. All three meetings were jointly sponsored by Brookhaven, Fermilab, IUCF, LAMPF, and TRIUMF.

Because of the common interest of members of the high energy and nuclear physics communities in multi-GeV hadron beam facilities, the Fermilab workshop was co-organized by one physicist from each community. An organizing committee was assembled from physicists from both communities. Committee members contributed to the overall organization of the meeting and also served as members of one of five working groups: Lepton Physics, Weak Decays, Hadron Dynamics, Hadron and Nuclear Spectroscopy, and Spin Physics. Prior to the meeting in December, each working group put together a preliminary report based primarily on the work presented at the Brookhaven workshop. These were modified, following the discussion at parallel sessions held during the Fermilab meeting, to produce the final reports which are included as the following appendices. The reader should appreciate that each group produced a report which adhered to its own style of presentation and that only minor effort was made to impose stylistic uniformity. The working group reports, along with the proceedings from the two previous workshops and the discussion at the Fermilab meeting, formed the foundation for the production of this white paper.

The program for the workshop at Fermilab was structured to maximize discussion to determine if a consensus on issues could be reached. In fact, a lively and open discussion, ably moderated by Mike Zeller of Yale, ran for almost three hours on the concluding afternoon of the workshop. A significant degree of consensus was achieved, possibly in response to a widespread recognition that the facilities needed in the future to conduct the research highlighted in this document are by no means assured to exist and be adequately funded, and that agreement on the larger issues is more important than disagreement on the smaller ones. The list of registered participants, many of whom played an active role in the discussion, follows as Appendix G.

The co-chairs of the organizing committee acted as editors of this white paper. One member of each working group acted as a coordinator for that group and was instrumental in putting together their working group report. The membership of the organizing committee is listed on the following page. The agenda for the workshop also is included below.

The success of the workshop is due in no small measure to the skillful organizational and logistical support provided by Ms. Cynthia Sazama of Fermilab and other members of the Fermilab staff under her direction.

## Organizing Committee

| | | |
|---|---|---|
| Co-chairmen: | J.L. Ritchie (HEP) | University of Texas at Austin |
| | R.E. Tribble (NP) | Texas A&M University |
| Lepton Physics: | A. Bodek | University of Rochester |
| | D.W. Hertzog | University of Illinois |
| | W.J. Marciano | Brookhaven |
| | N.W. Reay | Kansas State University |
| | B.L. Roberts | Boston University |
| | D.H. White, Coordinator | LANL |
| Weak Decays: | G.J. Bock | Fermilab |
| | D. Bryman | TRIUMF |
| | B.R. Holstein | University of Massachusetts |
| | K. McFarlane | Norfolk State/CEBAF |
| | R.E. Mischke | LANL |
| | T. Numao, Coordinator | TRIUMF |
| Hadron Dynamics: | C.N. Brown | Fermilab |
| | M.D. Corcoran | Rice University |
| | T.H. Fields | Argonne |
| | D.F. Geesaman | Argonne |
| | J.T. Londergan, Coordinator | Indiana University |
| | J.G. Morfin | Fermilab |
| Hadron and Nuclear Spectroscopy: | C. B. Dover | Brookhaven |
| | A.R. Dzierba, Coordinator | Indiana University |
| | B.F. Gibson | LANL |
| | N. Isgur | CEBAF |
| | R.P. Redwine | MIT |
| Spin Physics: | K.J. Heller | University of Minnesota |
| | R.L. Jaffe | MIT |
| | J.B. McClelland, Coordinator | LANL |
| | G.F. Sterman | SUNY – Stony Brook |
| | W.T.H. van Oers | TRIUMF/University of Manitoba |
| | S.E. Vigdor | IUCF |

## Workshop Agenda

Friday, Dec 2

| | |
|---|---|
| | Chair — G.T. Garvey, LANL/OSTP |
| 9:00 | Welcome (K. Stanfield, Fermilab) |
| | Opening Comments (R. Tribble, Texas A&M) |
| 9:15 | The Electroweak Standard Model and Beyond (W. Marciano, BNL) |
| 10:05 | Strong Interactions I (A. Mueller, Columbia) |
| 10:40 | Coffee Break |
| 10:55 | Strong Interactions II (N. Isgur, CEBAF) |
| 11:30 | Plan for White Paper and<br>Strawman Physics/Facilities Recommendations (J. Ritchie, Texas-Austin) |
| 12:00 | Lunch |
| | Chair — W.T.H. van Oers, TRIUMF/Manitoba |
| 1:15 | View from the Labs<br>BNL (T. Kirk)<br>Fermilab (J. Peoples)<br>IUCF (J. Cameron)<br>LAMPF (C. Hoffman)<br>TRIUMF (J.-M. Poutissou) |
| 3:45 | Coffee Break |
| 4:00 | Parallel Working Group Sessions |
| 6:00 | Reception |

Saturday, Dec 3

| | |
|---|---|
| 8:30 | Parallel Working Group Sessions |
| 10:30 | Coffee Break |
| | Chair — M. Strikman, Penn State |
| 10:45 | Plenary Session — Working Group Reports<br>Lepton Physics (H. White, LANL)<br>Weak Decays (T. Numao, TRIMUF)<br>Hadron Dynamics (T. Londergan, Indiana University)<br>Hadron and Nuclear Spectroscopy (A. Dzierba, Indiana/C. Dover, BNL)<br>Spin Physics (J. McClelland, LANL) |
| 12:30 | Lunch |
| | Chair and Moderator — M. Zeller, Yale |
| 1:30 | Plenary Session — Open Discussion |
| 3:00 | Coffee Break |
| 3:15 | Plenary Session — Open Discussion |
| 5:00 | Adjourn |

# B Lepton Physics

## B.1 Introduction

The charge to this group is to summarize the ongoing and near future projects in physics with leptons excluding that part which is specifically focused on hadrons. We have included deep-inelastic scattering (DIS) using neutrinos but have omitted the subfield of deep inelastic scattering with muons. The work of this group is then divided into four sections. They are:

- Fundamental properties of muons, particularly $g-2$.
- Deep inelastic scattering with neutrinos.
- Tests of the Standard Model with neutrinos.
- Neutrino oscillations.

## B.2 Muon $g-2$

The muon $(g-2)$ value obtained at the CERN PS has provided a testing ground for both the Standard Model, as well as for new theories[1]. In addition to having a definite value in the Standard Model, new physics such as muon substructure, an anomalous $g$ value of the $W$ boson and supersymmetry, can produce a measurable contribution to the muon anomaly.

Our current limits on muon substructure and the $W$ moment come from the CERN III experiment[1], which obtained an error on $a_\mu = (g-2)/2$ of 7.3 parts per million (ppm). That experiment did not have sufficient sensitivity to observe the contribution from the $W$, $Z$ gauge bosons, which is predicted (through second order) to be $1.31 \pm 0.04$ ppm. A new Brookhaven experiment (E821) aims for an improvement of 20 or more over the CERN experiment, and could possibly reach a sensitivity of $\pm 0.2$ ppm by the end of the running in $\sim$1999. Below we discuss the limitations on the interpretation of the results of the $(g-2)$ experiment, and speculate on improvements that might be possible to reach greater precision than the current goals for the Brookhaven experiment.

A review of the theory of the muon $(g-2)$ value is given by Kinoshita and Marciano[2]. In the table below, we list the sensitivity to new physics when E821 reaches the precision of 0.35 ppm error.

In the Standard Model, the muon $g$ value consists of a QED, a hadronic, and a weak gauge boson piece. In addition, any as yet unobserved field that couples to the muon can also contribute.

The dominant calculational error on the Standard Model value of $a_\mu$ comes from the evaluation of the contribution of hadronic vacuum polarization. This contribution can be calculated using dispersion theory from the cross section for $e^+e^- \to$ hadrons, and is found to be $\sim 60.3$ ppm. The uncertainty is currently dominated by the experimental errors on the low-energy cross section measurements, which give an uncertainty of $\sim \pm 0.75$ ppm on $a_\mu^{\text{hadronic}}$. The precision electroweak tests from LEP and SLC also need more precise data on hadronic weak corrections. However, because of a factor of $s^{-2}$ in the dispersion integral for $a_\mu^{\text{hadronic}}$, the data from threshold up to the $J/\psi$ dominate this contribution, although improvements are expected.

| New Physics | E821 Sensitivity | Comments |
|---|---|---|
| $\mu$ substructure[a] | $\Lambda \geq 5$ TeV$^\dagger$ | LHC domain |
| $\mu$ Form factors $(1 - k^2/\Lambda^2)$ | $(W^\pm)$ $\Lambda > 450$ GeV<br>$(Z)$ $\Lambda > 64$ GeV<br>$(\gamma)$ $\Lambda > 180$ GeV | $\Lambda_{LEP\ I} > 300$ GeV |
| excited muon | $m_{\mu^*} \geq 400$ GeV | LEPII comparable |
| $W^\pm$ substructure[b] | $\Lambda \geq 400$ GeV$^\dagger$ | LEPII $\sim$ 100–200 GeV |
| $(g_W - 2)/2 \neq 0$ | $\geq 0.02^*$ | LEPII $\sim$ 0.05, LHC $\sim$ 0.2 |
| Heavy Higgs | $\leq 500$ GeV | $O(g)$ coupling |
| Supersymmetry[c]<br>$W_R^\pm$<br>$Z'(E6)$ | $\leq 130$ GeV$^\dagger$<br>$\leq 250$ GeV$^\dagger$<br>$\leq 100$ GeV | Fermilab $\bar{p}p$ collider<br>Fermilab $\bar{p}p$ collider<br>Fermilab $\bar{p}p$ collider |

[a]For substructure $\Delta a_\mu \sim m_\mu^2/\Lambda^2$.
[b]Goes to 0 if $M_W \to 0$ to get proper coupling to conserved current.
[c]Signature for SUSY in the 100–200 GeV region is a value of $a_\mu$ below the SM value, although some authors take exception to this statement.

Table 1: Sensitivity to new physics of the new muon $(g-2)$ experiment. The experimental error is assumed to be 0.35 ppm, and the error from theory is assumed to be negligible compared to 0.35 ppm. Limits that scale linearly with error are marked with an $*$ and those that scale as the square root are labeled by $\dagger$. (This table is taken primarily from Ref. [2].)

The ultimate theoretical limit comes from the light-on-light hadronic radiative correction, which cannot be evaluated from experimental data. The contribution is estimated to be 0.42 ppm with an error of perhaps 10%, but we can assume reasonably that this uncertainty will be eventually reduced to $\leq 0.04$ ppm, setting the scale for the useful accuracy of a next-generation experiment.

In the final CERN experiment and in E821, a storage ring is constructed from a uniform dipole magnetic field with electrostatic quadrupoles to provide the vertical focusing. For muons with the magic $\gamma = 29.3$, the electric field does not contribute to the spin precession. Since there is a finite range of momenta in the storage ring, a correction must be made for those muons with momenta different from the central momentum. To eliminate this correction, and the need to know the electric field an order of magnitude better, one could restrict the momentum acceptance of the ring with collimation, or apply RF and rotate the bunch in phase space to narrow the momentum spread.

In examining the systematic errors, it is clear that it will be difficult to achieve a systematic error of better than about 0.03 to 0.02 ppm, without substantial improvements over the technologies now available. This systematic limit represents an improvement of 5 to 10 over the errors that might be reached in E821, and is consistent with the theoretical uncertainty likely to be obtained in the evaluation of the hadronic light-on-light contribution.

Since rate-dependent effects are serious to the measurement, it is not possible to just turn up the rate in a single fill of the muon storage ring even though higher-intensity injectors can be foreseen. To significantly increase the statistics, one needs to note the duty

cycle of the current project. The BNL experiment will have $3.5 \times 10^{12}$ protons per bunch incident on the pion production target. There are 12 fills per AGS cycle, with the extracted bunches separated by 33 ms. The total cycle time is about 2 s. Therefore, with a muon fill lasting somewhat less than 1 ms, the overall experiment runs at less than $6 \times 10^{-3}$ duty factor. If one could increase the repetition rate by a factor of 10 to 100 while maintaining the present levels of muons per fill, a significant gain in stored muons per hour could be achieved without an increase in singles rates in the decay-electron detectors.

The ideal situation would be to decrease the storage ring aperture from the E821 value of $r_0 = 45$ mm, which would decrease the sensitivity to the electric field corrections, as well as field inhomogeneities. Since the number of stored muons scales as $r_0^5$, one could decrease the instantaneous singles rates in the detectors from 5 MHz to about 1 MHz, and up the number of fills substantially from the 12 per 2 seconds to several hundred per second. This increase in cycle time is not possible with the existing BNL-AGS-Booster complex, nor with the existing Fermilab booster, but its attractive nature ought to spawn discussion among the experts as to a possible path to realize such flexibility. An accumulator ring in the AGS might present a substantial improvement, especially if it is possible to greatly increase the number of bunches in the machine. The practical limit to the number of bunches is determined by how quickly the fast kicker can turn on and off after kicking a proton bunch out to the pion production target. In addition to the described benefit to a next-generation muon $(g-2)$ experiment, rapid shots may well benefit other pulsed experiments being considered.

In conclusion, we have described the near-future BNL $(g-2)$ experiment briefly and have remarked on how to extend the utility of the current storage ring in a next-generation effort at an unnamed facility. The complex analysis of the effectiveness of pushing well below the 0.35 ppm will be for some time mired in debates on the uncertainties in the measured and calculated hadronic contributions to the $(g-2)$. Nevertheless, if rigor can be obtained in this contribution to the theory, higher-order weak corrections to the Standard Model would be exploited by such an endeavor. In addition to the Standard Model tests, a new window through which to look for new physics will be opened. We particularly remark on the sensitive tests of muon and $W$ boson substructure and on limits on particle detection in various versions of supersymmetry, particularly those with high values for $\tan(\beta)$.

## B.3 Deep Inelastic Scattering with Neutrinos

In neutrino deep inelastic scattering experiments, an incoming neutrino scatters from one of the quarks in the protons and neutrons that comprise the target. The probability for this to occur is related to the structure functions, which parameterize the quark content of the target. Hence, deep inelastic neutrino scattering is an ideal laboratory for measuring these structure functions.

Structure function studies are important for three reasons: as fundamental measurements, as tests of QCD, and as constraints on the quark and gluon distributions that are used as input for calculations of other interactions. Fermilab is unique in its ability to provide the very high-energy neutrino beams and high statistics needed to extend these fundamental measurements into unexplored kinematic regions. The neutrino beam studies provide complementary results to the electron beam studies at HERA (DESY), and provide measurements of much better accuracy. New precision measurements of structure functions provide an opportunity to reduce by over a factor of four the error on the fundamental QCD

parameter $\Lambda$ (or, alternatively, $\alpha_S$), which sets the strength of the strong interaction. This is important because, although in principle deep inelastic scattering and LEP experiments should measure the same value for this parameter, systematically the measurements have differed by 2–3 sigma, possibly hinting at new physics. If a high statistics study confirmed this discrepancy, the result would be very exciting. Precise measurements of the energy dependence of the strengths of the strong, weak, and electromagnetic forces provide important tests of grand unification theories, since those theories predict that these forces will eventually become equal at extremely high energies.

Finally, the structure functions are directly related to the quark and gluon content of the proton. These quark and gluon distributions are used as input to all calculations involving proton interactions, including particle production at the collider. In particular, the neutrino experiments can provide better measurements of the antiquark and strange quark distributions. The next generation of neutrino deep inelastic experiments will provide unique tests of our understanding of theory as well as important measurements of fundamental parameters.

At present, much of the information on nucleon structure comes from high-energy deep inelastic neutrino data. The experience of the CCFR neutrino collaboration (Fermilab experiments E770 and E744) and the current neutrino experiment at Fermilab (E815, scheduled to run in the 1996–97 fixed-target run) can be used to estimate reliably the improvements that can be accomplished with higher intensity and higher energy beams.

The measurements that can be greatly improved with increased statistics and energy include: (1) increased precision in the measurement of $\sin^2\theta_W$, (2) a number of QCD tests including determinations of $\Lambda_{\rm QCD}$ and $\alpha_S$, and (3) improved parton distributions and, in particular, the antiquark distributions and the strange sea. Either improvement, in statistical power or neutrino energy, would improve these measurements.

The combination of an increase in intensity with an increase in energy can increase the neutrino sample by nearly two orders of magnitude. The LINAC upgrade has improved the fixed-target intensity by a factor of two, and the Main Injector will further improve it by a factor of three. Finally, longer fixed-target runs will allow a run for two years instead of one. Therefore, the total increase from currently planned machine improvements in proton intensity is a factor of twelve over the existing old CCFR data. Finally, one can undergo a detector improvement program to increase the target mass by 75%, which increases the fiducial volume by a factor of two. Therefore, one can expect a factor of 24 increase in statistics over the present data, provided the present intensity improvement programs in the LINAC and the main injector are successful, and there is a detector upgrade.

An energy upgrade from the present 0.8 TeV to 1.6 to 2 TeV can further increase the rate by about a factor of 3.5. This comes because the raw particle production rate will double with a doubling of energy, and the resultant neutrinos will have a higher energy and hence about twice the cross section. However, the longer lifetimes mean that with a fixed decay pipe length, fewer higher-energy particles will decay. Therefore, one expects about a factor of 3.5 increase in rate due to the higher energy rather than a factor of 4. The total improvement from the energy upgrade is then a factor of 7, and the product of intensity and energy is 84.

A hundred-fold increase in statistics over the present data also would result in a measurement of $\Lambda_{\rm QCD}$ to $\pm 15$ MeV, a significant improvement over the present error of 65 MeV. This statistical power, coupled with an increase in neutrino energy by a factor of two, would further check the evolution of the strong coupling constant with $Q^2$ within a single experi-

ment. Although the increased precision in the strong coupling constant comes mostly from the increased statistics, an energy upgrade would allow a determination of the strong coupling constants at several values of $Q^2$ within the same experiment. At present, the values of the strong coupling constant at LEP and measured through DIS disagree by about 2–3 standard deviations, with the DIS values being consistently lower. This disagreement is not presently understood and could be indicative of new physics. Precise measurements of the strengths of the strong, weak, and electromagnetic couplings and their $Q^2$ dependence provide important tests of grand unification theories. Grand unification theories predict that these forces will eventually become equal at the extremely high $Q^2$ of the grand unification scale. At present, the precision of the measurements of the three coupling constants implies that they do not become equal at these scales, unless supersymmetry is introduced into the evolution equations. This provides indirect evidence for the existence of new interactions at the TeV scale. Therefore, more precise determinations of the strong coupling constant can provide further constraints on the existence of new interactions beyond the Standard Model.

The existence of HERA does not detract from the need for improved DIS experiments. It is not expected that a precision measurement of $\Lambda_{\rm QCD}$ can be done at HERA. Similarly, since most of the statistics at HERA is at small $x$, the HERA data are mostly sensitive to the gluon distributions. The quark and antiquark distributions, which are fundamental properties of the proton, are used as input to all calculations involving proton interactions, including particle production at hadron colliders. In particular, the neutrino experiments can provide much improved measurements of the antiquark and strange quark distributions. Therefore, fixed-target DIS neutrino experiments can provide more precise determinations of $\Lambda_{\rm QCD}$, $\alpha_S$, and precise determinations of the quark distributions. Here, neutrino scattering experiments at high energy are better suited than muon experiments because of higher statistics at high $Q^2$.

In summary, neutrino physics at high energy can benefit most from a large intensity upgrade of the existing Tevatron, and a detector upgrade. Current planned upgrades coupled with a detector upgrade can yield a factor of 24 over the present data (which consist of about 1 M charged current neutrino interactions). Higher proton intensities would be even more beneficial. An energy upgrade to 1.6 to 2.0 TeV would result in another factor of 3.5 to 4 in neutrino intensity. The higher energy and increased statistics would result in a reduction of systematic errors in all measurements, and also yield a measurement of the evolution of the strong coupling constant with $Q^2$ within a single experiment.

## B.4 Precision Electroweak Tests with Neutrino-nucleon Scattering

Accurate measurements of the weak mixing angle in neutrino-nucleon scattering have been a key input to tests of the Standard Model, including the most precise predictions of the masses for the $W$ boson and top quark. Also, since neutrino scattering is uniquely sensitive to certain effects of new heavy particles, a comparison of the neutrino measurements with the electroweak results from other processes may give the first evidence for new physics beyond the Standard Model. Current measurements of the weak mixing angle from the neutrino sector are comparable in accuracy to those obtained at electron and hadron colliders. These results, when combined with the accurate measurement of the $Z$ boson mass from LEP, show a spectacular agreement with the predictions of the Standard Model for a top quark mass of around 180 GeV. The upcoming neutrino measurement by the NuTeV collaboration at Fermilab should reduce the uncertainty on the mixing angle by about a factor of 2.5

corresponding to an equivalent $W$ boson mass uncertainty of $\pm 100$ MeV/$c^2$. The NuTeV result will be an important component, through the end of the decade, of the precision tests of the Standard Model when combined with the electroweak measurements at SLC, LEP II, and the Tevatron, and may give us the best window to hints of new physics. For future measurements at Fermilab, in the post Main Injector era, neutrino event samples nearly 2 orders of magnitude larger should be available. This will allow the measurements to be improved at least another factor of 2, leading to a mixing-angle determination with an uncertainty of less than 0.001, equivalent to a $W$ boson mass measurement with a $\pm 50$ MeV/$c^2$ error. At this level, the neutrino measurements will give one of the most important probes for new physics beyond the Standard Model and, therefore, should remain an important component of the investigations in our field.

## B.5 Neutrino Oscillations

Neutrino oscillation experiments provide the most sensitive way to determine if neutrinos have mass and to probe for indications of Cabibbo-like mixing in the lepton sector of the Standard Model. Three types of neutrinos are known to exist, $\nu_e$, $\nu_\mu$, and $\nu_\tau$. At present, only two of them can be made into beams, $\nu_e$ and $\nu_\mu$. There are two types of oscillation experiments, appearance and disappearance; the former has reduced systematics and is generally more sensitive. Disappearance experiments depend to a greater extent on understanding of the beam and detectors, so are chosen when for some reason the appearance method will not work. For example, a search for sterile neutrinos can only be done by disappearance. The search for neutrino oscillations has been lengthy and at present there is one reasonably well-established indication, namely the solar neutrino deficit. Neutrino events observed in Kamioka and IMB from interactions in the upper atmosphere show a statistically significant departure for the ratio of electron to muon events that may be due to oscillations. An experiment at Los Alamos has indications that may also be interpreted in this general framework. In the immediate future, it is expected that SuperKamioka in Japan will provide significantly more data on the atmospheric neutrino problem, and the Los Alamos experiment will also have a much greater data sample. Experiments that are starting to take data at CERN are CHORUS and NOMAD, both of which will search for $\nu_\tau$ in a dominantly $\nu_\mu$ beam capable of sufficient energy to produce real tau quasi-elastic events. In France there is under construction an experiment to search for $\nu_e$ disappearance from a reactor source of $\nu_e$, and in the U.S. a second experiment of this type is also proposed. Approved, but not yet under construction, is an experiment at Fermilab using neutrinos from the Main Injector, which is under construction. The solar neutrino problem will receive finer definition from the SuperKamioka experiment and will provide even more precise insight when neutral current processes as well as charged current rates are available from SNO in Canada.

The question raised for this group to consider is the need for other facilities or detectors to capitalize on these existing data or to continue the search for this phenomenon in regions not yet accessed. The Fermilab Main Injector is clearly a unique source in that it is capable of producing real tau interactions and has high flux, so that a sensitive search for transitions to $\nu_\tau$ can be made. Although the current approved experiment is planned for an upstream position, other locations are feasible depending on the results from the CERN experiments and all of the other work in progress. There is much activity considering very long baseline experiments devoted to $\nu_\tau$ searches at high distance over energy, and we assume they will use the same beam. There are two complementary initiatives, one is an approved experiment

at BNL for $\nu_\mu$ disappearance measuring the ratio of charged and neutral currents and an initiative at Fermilab for a beam from the Booster for $\nu_\mu \rightarrow \nu_e$ transitions. The Fermilab proposal has also a part devoted to neutrino-proton elastic scattering, which is not strictly part of this group's considerations but should probably be mentioned here. One experiment that has not yet been proposed but that seems to us to have merit is a repetition of the atmospheric neutrino work in an accelerator beam. If the mass difference squared that has been discussed in interpreting these experiments is in fact correct, then these experiments are hard, but if it is somewhat higher than has been discussed, then an experiment extending the BNL or the Booster work may acquire a lot of support.

## B.6 Summary

The programs and facilities that are seen to be desirable over the next decade are:

- The muon $g-2$ program brought to limits of precision.
- A continuation of the Tevatron neutrino program with an intensity upgrade.
- A Main Injector neutrino beam capable of $\nu_\tau$ searches from close in to potentially long baseline neutrino detectors.
- Beams at BNL and the Booster for neutrino experiments at a number of distances from the source, from close in to distances that are sufficiently extended to impact the atmospheric neutrino problem.

Along with these beams, the following detectors must be considered:

- An upgrade to the existing Tevatron detector.
- A direct search for $\nu_\tau$ through the observation of quasi-elastic tau events, both close in and at a significant distance.
- A $\nu_\mu \rightarrow \nu_e$ transition search at intermediate distance from either BNL or the Booster and a consideration of a disappearance $\nu_\mu$ measurement.
- A repetition of the atmospheric neutrino experiment at an accelerator, presumably using either the BNL or Booster beam.

In summary, we have identified two laboratories that have proton accelerators that are deemed important to the progress of the lepton physics, which has been our charge to discuss. The $g-2$ experiment should be brought to a conclusion, exhausting the potential for precision, this requires the BNL AGS to provide muons for the storage ring. The high-energy fixed-target neutrino program at Fermilab has significant potential for precision, and this program should continue until this precision potential is exhausted. The neutrino oscillation field is presently wide open. Three indications, Solar Atmospheric and the Los Alamos work all give positive results and these questions must be resolved. To carry through a meaningful program, it is desirable to complement the CERN work on an appearance with the detector approved for the Main Injector at Fermilab. The three initiatives that are under evaluation, namely long baseline at the Main Injector, long baseline at BNL, and the shorter baseline at the Booster all have merit, and after proper evaluation, the program should become clear. In our view, each of these initiatives has merit in the current state of understanding of neutrino oscillations.

# References


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# C Weak Decays

## C.1 Introduction

The electroweak Standard Model (SM) has been very successful in explaining observed phenomena in particle physics. The inclusion of three generations provides a possible solution for the CP violation problem. However, there are many unanswered questions in the SM, *e.g.* why is there repetition of generations, and what is the structure of the Higgs sector. Because there are many unspecified parameters, it is widely believed that the SM is a low-energy approximation of an ultimate theory although no confirmed experimental data point in an obvious direction beyond the SM. Two effective approaches to proceed are putting the SM predictions under intensive scrutiny with precision experiments and searching for forbidden decays that provide access to extremely high mass scales through virtual processes.

To examine the SM predictions precisely, the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix as well as the top quark mass need to be determined. There could be a unitarity problem in the first generation CKM matrix; presently $\mid V_{ud} \mid^2 + \mid V_{us} \mid^2 + \mid V_{ub} \mid^2 = 0.9957 \pm 0.0017$ [1]. A discrepancy from unity may suggest the existence of a fourth generation quark, or some other problems in the SM. There are still several poorly determined parameters, such as $V_{to}$. Following Wolfenstein [2], the CKM matrix can phenomenologically be written using four parameters; $A$, $\lambda$ (Cabibbo angle), $\rho$ (a mixing parameter between the first and third generations) and $\eta$ (imaginary part, which is responsible to CP violation). From existing data $A$ and $\lambda$ are reasonably determined to be $0.85 \pm 0.09$ and 0.22, respectively. There are very loose bounds on the $\rho$ and $\eta$ parameters. The branching ratios of the decay $K^+ \rightarrow \pi^+ \nu\overline{\nu}$ and the CP-violating decay $K_L^0 \rightarrow \pi^0 \nu\overline{\nu}$ can be unambiguously predicted in the SM for a set of these parameters, or conversely these branching ratios can be used to determine them unambiguously. The constraints imposed by unitarity give rise to a useful relation, $V_{ub}^* - \lambda V_{cb}^* + V_{to} \sim 0$, which represents a unitary triangle in the ($\rho$,$\eta$) plane. CP violation in $B$ meson decays are sensitive to the angles of the triangle, providing complementary information on these parameters obtained from $K$ decays. Therefore, many aspects of the SM can be rigorously tested by combining the information gleaned from decays of $\mu$'s, $\pi$'s, $K$'s and $B$'s.

Lepton Flavor Violating (LFV) decays are forbidden in the SM. Observation of a LFV process is a clear indication of new physics [3]. Many theories beyond the SM predict the existence of LFV processes through new hypothetical particles, such as massive neutrinos in the left-right symmetric model [4], extra Higgs particles [5], leptoquarks [6] and supersymmetry partners [7]. Some predictions are very close to the present upper limits of such processes. Even if no LFV decays are seen, their upper limits will set very tight bounds on the masses of hypothetical particles.

## C.2 Tests of the Standard Model

The universal coupling scheme of leptons has naturally been built into the three-generation SM, and is now studied with $\pi$, $\tau$ and $W$ leptonic decays. The best tests of electron-muon universality $g_e/g_\mu = 0.9985 \pm 0.0016$ come from the branching ratio of the decays $\pi^+ \rightarrow e^+\nu$ and $\pi^+ \rightarrow \mu^+\nu$ [8]. This level of precision senses the mass scale up to 200 TeV/c$^2$ for hypothetical particles that induce pseudoscalar couplings such as leptoquarks. The new SM calculation for this branching ratio[1], $R_{\pi\rightarrow e\nu} = (1.2350 \pm 0.0005) \times 10^{-4}$,

leaves room for improvement of the experiment almost by an order of magnitude. New experiments [9] aiming at a precision $\leq 0.1\%$ are compellingly required to put the SM to an unprecedented level of scrutiny.

The V–A nature of the Standard Model is tested by precise measurements of the Michel parameters ($\rho$, $\delta$, $\eta$ and $\xi$) in muon decays and the muon polarization from pion and kaon decays. Much effort has recently been invested in this area, providing a mass bound of the right handed gauge boson, $M_{W_R} > 0.4$ TeV/c$^2$. A new measurement of the $\rho$ parameter is being carried out at LAMPF and a new generation experiment is planned at TRIUMF for a better accuracy by almost an order of magnitude in $\rho$, $\delta$ and $\xi$ parameters.

Ambiguities in unitarity tests of the CKM matrix are dominated by those in the diagonal elements. The CKM matrix element $V_{ud}$ has been derived from superallowed $0^+ \rightarrow 0^+$ nuclear $\beta$ decays, but theoretical ambiguities in nuclear wave functions and radiative corrections limit the accuracy of the matrix element determination to a level of 0.2%. On the other hand, theoretical calculations for pion $\beta$ decay $\pi^+ \rightarrow \pi^0 e^+ \nu$ do not involve nuclear wave function effects and are more reliable. Although the branching ratio is very small ($(1.025 \pm 0.034) \times 10^{-8}$), it is potentially a very good candidate to determine $V_{ud}$. There is an experiment being prepared for running at PSI [10] with the goal of a 0.5% measurement using a stopped pion beam. The ultimate goal for the future experiments should be at a precision level of 0.1%. A possible improvement in $V_{ud}$ determination could come from accurate measurements of the neutron lifetime, combined with measurements of neutron $\beta$ decay asymmetry that determines the ratio $G_A/G_V$.

The Glashow-Iliopoulos-Maiani (GIM) mechanism, which prohibits first-order flavor-changing neutral currents and suppresses second order effects, makes decay rates very small and for certain cases almost unobservable at presently existing machines. Because the Feynman diagrams for the short-distance second-order decay modes such as the decays $K^+ \rightarrow \pi^+ \nu \overline{\nu}$, $K_L^0 \rightarrow \mu^+ \mu^-$ and $K_L^0 \rightarrow \pi^0 \nu \overline{\nu}$ involve a virtual top quark and related CKM matrix elements $V_{to}$ and $V_{ts}$, these decay modes are very sensitive to those poorly determined parameters. The decay $K_L^0 \rightarrow \mu^+ \mu^-$ has played an important role in the understanding of flavor changing neutral currents in the context of the development of the SM. The short-distance contribution through second-order weak diagrams is expected to be small compared to long-distance effects, which proceed through two virtual photons. Based on the observed branching ratio for the decay $K_L^0 \rightarrow \gamma\gamma$, the long-distance contribution arising from the intermediate states with two on-shell photons gives the "unitarity bound" $6.8 \times 10^{-9}$ for the branching ratio of the decay $K_L^0 \rightarrow \mu^+ \mu^-$. Other long-distance effects including the off-shell photon contribution are estimated from other radiative decays of $K_L^0$ but uncertainties are still large. Nevertheless, the branching ratio of the decay $K_L^0 \rightarrow \mu^+ \mu^-$ ($(6.86 \pm 0.37) \times 10^{-9}$[11] and $(7.9 \pm 0.7) \times 10^{-9}$[12]) has provided constraints on the undetermined SM parameters. To extract information on detailed short distance effects, it is necessary to know the contribution from dispersive effects of two intermediate state off-shell photons , which is difficult to obtain theoretically. It has been suggested that precise measurements of $K_L^0 \rightarrow ee\gamma$ (100 times more events) and form factors in $K_L^0 \rightarrow eeee$ might allow extraction of the dispersive contribution [14]. Also, the presence of the dominant long distance contribution requires that this mode be measured at about the 1% level. A new experiment (BNL E871) for a higher precision of $K_L^0 \rightarrow \mu^+ \mu^-$ measurements, as well as the search for the decay $K_L^0 \rightarrow \mu^\pm e^\mp$, has started at BNL and will be described in section C.4.

In the decay $K^+ \rightarrow \pi^+ \nu \overline{\nu}$, the contributions from long distance effects are negligible and QCD corrections are of the order of 10% of the short range contribution. The SM prediction

for the branching ratio of the decay $K^+ \to \pi^+\nu\overline{\nu}$ is somewhere in the 1–4 $\times 10^{-10}$ [13] range depending on the undetermined parameters, particularly on $V_{to}$ (or the $\rho$ parameter). Once the CKM matrix elements have been determined, this decay mode is, perhaps, the only precisely calculable second order weak interaction that is accessible to measurements. In the BNL (E787) experiment for the search of the decay $K^+ \to \pi^+\nu\overline{\nu}$ and other rare decay modes [15], a $K^+$ beam is stopped in an active target, which is surrounded by a tracking device and photon vetoing counters. The E787 group has upgraded the detector system and the beam line for higher sensitivity using a more intense kaon beam with less pion contamination to meet the goal of the first observation of this decay mode at a sensitivity of $10^{-10}$. The decay mode $K^+ \to \pi^+\nu\overline{\nu}$ must be measured at a precision of 10% in order to complete our description of the SM and a new high-intensity experiment will be required to reach the required level of precision. A conceptual design of a future detector at a multi-GeV high intensity facility is similar to the existing E787 detector although it should have better resolutions, finer detector segmentation, and a better photon vetoing capability. New ideas have also been discussed for a possible alternative experiment using $K^+$ decays in flight [16].

Other rare kaon processes that are presently being investigated include decays $K^+ \to \pi^+\ell^+\ell^-$, $K^0_{L,S} \to \gamma\gamma$, $K^0_{L,S} \to \pi^+\pi^-\gamma$, $K \to \pi\gamma\gamma$, and other radiative kaon decays. Long distance effects generally dominate such processes but recent successes using chiral perturbation theory to parameterize the strong interaction dynamics encourage further experimental work in this area [17]. Careful studies of these modes are expected to eventually reduce the ambiguities in the extraction of $\rho$ and $\eta$ parameters. Although they are suppressed or prohibited in first order, the $\eta$ meson predominantly decays through strong or electromagnetic interactions. Because of this and the similarity in the mass, $\eta$ meson decays such as $\eta \to \mu^\pm\mu^\mp$ provide important information to sort out the strong interaction contributions to kaon decays. If a sensitivity of $10^{-11}$ can be reached, the decay $\eta \to \pi\ell\nu$ could probe the presence of second class currents.

## C.3 CP and T Violation

In neutral kaon decays, a mixture of a CP even state $K^0_1$ ($\epsilon \simeq 0.2\%$) in the mass eigenstate $K^0_L$ induces CP violating decays (indirect component). In addition, while bare superweak models predict zero, the SM predicts a non-zero direct CP violating contribution ($\epsilon'$) arising from "penguin" diagrams ($\Delta S = 1$) in the range $\epsilon'/\epsilon = 10^{-4} - 10^{-3}$ depending on the $\eta$ parameter. Because the direct CP violating contribution appears in the double ratio

$$\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 = \frac{\left[\frac{\Gamma(K^0_L \to \pi^+\pi^-)}{\Gamma(K^0_S \to \pi^+\pi^-)}\right]}{\left[\frac{\Gamma(K^0_L \to \pi^0\pi^0)}{\Gamma(K^0_S \to \pi^0\pi^0)}\right]} \simeq 1 + 6(\epsilon'/\epsilon),$$

a precise measurement of a deviation from unity is sensitive to the direct CP violating contribution. Taking a double ratio also allows minimizing experimental uncertainties arising from acceptance differences and other systematic effects. Another requirement of the experiment is to achieve a very low background environment, because the two $\pi$ decay mode of $K^0_L$ is CP-suppressed and background could be a serious source of systematic errors. Higher $K^0_L$ momenta have been used to take advantage of better mass resolution and to reduce backgrounds because the measurement includes photon detection. A CERN experiment NA31 [18] reported consistency with the SM picture of CP violation, finding a non-zero value for the ratio $\epsilon'/\epsilon = (23 \pm 3.4(\text{stat}) \pm 6.5(\text{sys})) \times 10^{-4}$, while Fermilab experiment E731

[19] found $\epsilon'/\epsilon = (7.4 \pm 5.2(\text{stat}) \pm 2.9(\text{sys})) \times 10^{-4}$ consistent with zero. Higher precision experiments with perhaps $10^7$ $K_L^0 \rightarrow \pi^0\pi^0$ events are now required to make progress on the measurement of $\epsilon'/\epsilon$. Knowledge of systematic uncertainties must also be improved commensurately and the long learning process that has accompanied this effort has led to new experiments by the groups at CERN (NA48) and Fermilab (E832), which have aims of reaching total uncertainties on $\epsilon'/\epsilon$ of 1 to $2 \times 10^{-4}$. New higher intensity beams and enhanced detectors with higher rate capabilities are being employed. Both new efforts use a two-beam approach and precision calorimetry to reduce systematic uncertainties from energy scales, calibrations, acceptance variations and accidental backgrounds for the four decay modes being studied. A similar sensitivity will be pursued at DAΦNE, a $\phi$ factory based on an $e^+e^-$ collider [20]. Precise measurements of the phase angle differences of $\eta_{00}$, $\eta_{+-}$ and $\phi_\epsilon \equiv tan^{-1}(\frac{2\Delta m_{S,L}}{\Gamma_S - \Gamma_L})$ will also provide a sensitive test of CPT invariance. The groups studying $\epsilon'/\epsilon$ have been working simultaneously on this subject [21].

The decay $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ is an exceptionally interesting reaction (referred to as "the Golden reaction" by Wolfenstein [2]), the observation of which could unambiguously establish the SM origin of CP violation. The branching ratio is expected to lie in the range $0.3\text{–}20 \times 10^{-11}$ where the uncertainties arise almost entirely from presently unknown CKM parameters and $m_t$ [2, 22]. Because the charm contribution is negligible for the CP violating mode, this mode is essentially free from theoretical uncertainties. When $m_t$ is known precisely, measurements of both the charged and neutral channels of $K \rightarrow \pi\nu\overline{\nu}$ to accuracy of 10 to 20% would provide the best possible route to determining $V_{to}$ and its phase (or equivalently $\rho$ and $\eta$ in the Wolfenstein representation). The contribution from indirect CP violation is of the order of $BR(K^+ \rightarrow \pi^+\nu\overline{\nu}) \times \epsilon^2 = 10^{-15}$ [23] and the CP conserving part is negligible, too. The signature of this decay mode is two photons from the decay $\pi^0 \rightarrow \gamma\gamma$ without any other activity in the detector system. Observing this reaction presents a challenge as all particles are neutral and there is no definite kinematic constraint. The present limit from the Fermilab experiment E799 is $B(K_L^0 \rightarrow \pi^0\nu\overline{\nu}) < 5.8 \times 10^{-5}$ [24]. A study done for the Main Injector at Fermilab, found a sensitivity of $3 \times 10^{-12}$ might be achievable in the presence of background [25] and there is a proposal at KEK to lower the sensitivity to a $10^{-11}$ level [26]. At lower energies, "momentum analyzed" $K_L^0$ beams could provide the additional handle needed to reject backgrounds (coming primarily from $K_L^0 \rightarrow \pi^0\pi^0$ events). In conjunction with sub-nanosecond primary beam micro-structure, some possibilities under consideration include using time-of-flight in secondary (e.g. broad band neutral beams) and tertiary beams (neutral kaon production via $(\pi, K)$ reactions) to enable the momentum of individual neutral kaons to be obtained [27]. The detector should have the capabilities of high efficiency for neutral particle detection ($10^{-3}$ inefficiency for low energy photons) including both position and angular measurements and good time resolution ($<$ 1 ns). Due to the low decay rate and difficult experimental signature, $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ is only accessible for background-free study with an intense kaon source.

The decay $K_L^0 \rightarrow \pi^0 e^+e^-$ can have a branching ratio of the order of $10^{-11}\text{–}10^{-12}$ due to direct CP violation from one-photon "penguin" diagrams. There is also an indirect CP violating component due to CP state mixing. This contribution was estimated by chiral perturbation theories to be $10^{-11}$ using the observed spectrum of the process $K^+ \rightarrow \pi^+e^+e^-$, but it still remains very uncertain. The CP conserving contribution coming from two-photon diagrams was estimated to be $\leq 10^{-11}$ using the branching ratio and the spectrum of the decay $K_L^0 \rightarrow \pi^0\gamma\gamma$. Experimentally, there are two approaches; one is to have a high kaon-beam momentum and a good angular resolution so that a good $\pi^0$ mass resolution and a

large acceptance can be achieved. This type of experiment has been described above; the experiment at Fermilab (E731/799) is in the first stage of the search. The experiments at KEK (E162) and BNL (E845) used a lower momentum beam with a large-solid-angle good-resolution detector. The E799 group obtained an upper limit of $4.3 \times 10^{-9}$ [28] for this decay mode but the E845 group [29] observed a potential background coming from the decay $K_L^0 \to \gamma\gamma e^+e^-$, which has the same event topology except that the calculated mass from two photons is variable ($m_{\gamma\gamma} = m_{\pi^0}$ for the decay $K_L^0 \to \pi^0 e^+e^-$). With the most stringent cuts (a single point in the phase space) the background level was estimated to be $10^{-11}$, comparable to the signal level [30]. Because this physics background is unavoidable, the observation of the decay mode $K_L^0 \to \pi^0 e^+e^-$ would depend on background subtraction with good statistics. The ultimate feasibility of using $K_L^0 \to \pi^0 e^+e^-$ to reveal direct CP violation may become clear once the reactions $K_L^0 \to \pi^0\gamma\gamma$ and $K_S^0 \to \pi^0 e^+e^-$ are well studied. The decay $K_L^0 \to \pi^0\mu^+\mu^-$ (presently $< 5.1 \times 10^{-9}$) [28] is expected to occur at a rate of $\sim$1/4 of $K_L^0 \to \pi^0 e^+e^-$ but this mode suffers slightly less from the same pollution.

Measurements of decay asymmetry and polarization of kaon decay products also provide tests of CP violation. Transverse muon polarization in the decays $K_L^0 \to \pi^-\mu^+\nu$ and $K^+ \to \pi^0\mu^+\nu$, which violate T invariance, is expected to be zero in the SM because the decay processes are induced by first order charged currents. Some alternate models, *e.g.* those with extra Higgs doublets, however, predict non-zero polarization as high as $10^{-2}$. The latest value $0.0031 \pm 0.0053$ in transverse muon polarization came from the decay $K^+ \to \pi^0\mu^+\nu$ [31]. A group at KEK [32] is working to lower the sensitivity to muon polarization from the same decay mode to a $9 \times 10^{-4}$ level. The detector is designed to maintain a symmetry in order to cancel systematic effects. Using a toroidal spectrometer, a muon is momentum-analyzed and stopped in a polarimeter where the muon precesses due to the magnetic field. Longitudinal polarization of muons from the decay $K_L^0 \to \mu^+\mu^-$ is expected to be of the order of $10^{-3}$ in the SM [33]. Polarization as high as 7% could occur in some models [34]. Spin-spin correlation of muons from the decay $K^+ \to \pi^+\mu^+\mu^-$ is an other possible indication of direct CP violation [35]. Using the detector system of E787 with a slight modification in the range measurement device, it might be possible to measure transverse muon polarization from the decay $K^+ \to \pi^+\mu^+\mu^-$ at a level of 1% [36]. The difference in the slope parameters measured in $K^\pm \to \pi^\pm\pi^+\pi^-$ is also sensitive to direct CP violation and could be improved by two orders of magnitude using a similar setup to the search of $K^+ \to \pi^+\mu^\pm e^\mp$.

Outside the $K\overline{K}$ system (other than $D$ and $B$ mesons), non-leptonic decays of hyperons such as $\Xi$ and $\Lambda$ could sense direct CP violation in the charge asymmetry of the angular distribution parameter $\alpha$. The world average experimental limit is $-0.03 \pm 0.06$ in $\Lambda$ ($\overline{\Lambda}$) decays. A possible sensitivity of experiments could be as good as $10^{-4}$ (Fermilab E871) [37], around the level of the theoretical predictions by the SM and other models. T violation can be studied using the resonance neutron capture process with the polarized neutron and target. In parity violation experiments where a small admixture of $s1/2$ states in $p1/2$ states is detected, there is enhancement of $10^2$–$10^6$ arising from a small energy denominator and a large ratio of neutron decay amplitudes between two mixing states. A similar enhancement also applies to T violation experiments. Although the SM predicts small polarization, the effect of an additional neutral Higgs particle could be as high as 0.1–10%. Experiments at a high intensity neutron facility have a potential to reach a sensitivity of $10^{-4}$ [39].

| Modes | Present ($10^{-11}$) | In progress ($10^{-11}$) | Future |
|---|---|---|---|
| $\mu \to e\gamma$ | 4.9 | 0.01 | 0.001 |
| $\mu^- A \to e^- A$ | 0.4 | 0.001 | 0.00001 |
| $K_L^0 \to \mu^\pm e^\mp$ | 3.3 | 0.1 | 0.01 |
| $K \to \pi\mu^\pm e^\mp$ | 21.0 | 1.0 | |

Table 2: Status of LFV experiments.

## C.4 Lepton Flavor Violation

According to many theoretical calculations, coherent neutrinoless $\mu$-$e$ conversion ($\mu^- A \to e^- A$), in which the nucleus remains in the ground state, may be enhanced because of coherence of many nucleons in the nucleus; on the other hand, incoherent reactions leading to nuclear excited states are suppressed by the Pauli-blocking effect. The signature of the reaction $\mu^- A \to e^- A$ is a peak at the energy approximately $E_e \sim m_\mu c^2 - B$, where $m_\mu$ and B are the muon mass and the binding energy of the muonic atom, respectively. The present upper limit $\sim 4 \times 10^{-12}$ was obtained by the TRIUMF and PSI groups [40], which provided tight constraints on the masses of leptoquarks and other particles (1–300 TeV/c$^2$). A new experiment at PSI (SINDRUM II) is aiming at a sensitivity of $10^{-14}$. The sensitivity could be improved by orders of magnitude using a high-intensity multi-GeV accelerator and a beamline-detector system proposed by Lobashev and Djilkibaev [41]; at the ultra-high rates needed to reach a sensitivity of $10^{-16}$, $\mu$-e conversion becomes more attractive because of a "single" track signature, immune from accidental background.

A certain class of supersymmetry and left-right symmetry models favors the $\mu \to e\gamma$ decay [3]. The present limit is $4.9 \times 10^{-11}$ [42]. A new search for the decay $\mu \to e\gamma$ is currently going on at LAMPF for the sensitivity of $10^{-13}$ using the MEGA detector consisting of seven cylindrical wire chambers and surrounding photon detectors, which give good angular resolution between the positron and the $\gamma$-ray [43].

The LFV decay $K_L^0 \to \mu^\pm e^\mp$ involving both quarks and leptons has a large available phase space and occurs at a favorable rate in many models. The major background source for the studies of the processes $K_L^0 \to \mu^\pm e^\mp$ and $K_L^0 \to \mu^+\mu^-$ comes from the semi-leptonic decays $K_L^0 \to \pi^\pm \mu^\mp \nu$ and $K_L^0 \to \pi^\pm e^\mp \nu$ with the decay-product pion subsequently decaying in flight to a muon and an unobservable neutrino. This would be a serious background especially when pions decay in an analyzing magnet and a wrong momentum is measured. To suppress this background, the detector system measures the momentum twice. The present upper limit is $3.3 \times 10^{-11}$ [44]. The characteristics of the background to these processes (due to particle misidentification and reconstruction mistakes in the semi-leptonic decays mentioned above) have been estimated to the level of $10^{-12}$ from the experiments [44, 45]. In the new BNL experiment (E871) aiming at a sensitivity of $10^{-12}$, the tracking device has more redundancy in order to suppress pathological track fits, one of the major sources of the background. The high counting rate problem is reduced by an elaborate beam plug in the middle of the detector. In future experiments, extraction of the $K_L^0$ beam at a large angle could reduce the fraction of photons and neutrons in the beam to almost a comparable level to the $K_L^0$'s and allow the detector system to take a significantly higher-intensity $K_L^0$ beam.

Even if $K_L^0 \to \mu^\pm e^\mp$ is absent, $K^+ \to \pi^+\mu^\pm e^\mp$ could occur, generated by vector or scalar currents. Experimentally, the three-body charged particle final state makes vertex reconstruction reliable and allows energy and momentum constraints to be imposed. The main potential background is due to $K^+ \to \pi^+\pi^+\pi^-$ decay in which two pions are misidentified as a muon and an electron. The recent result from BNL E777[46] was $B(K^+ \to \pi^+\mu^+e^-) < 2.1 \times 10^{-10}$ based on no observed candidate events and assuming a uniform phase space distribution. A new experiment is presently taking test data at BNL (E865), which incorporates a new intense 6 GeV $K^+$ beam (7 times the previous beam intensity) and new apparatus including larger magnets, improved muon detection and finer granularity detectors. The longer larger-gap analyzing magnet allows a 3 times larger solid angle. The aim is a sensitivity of $3 \times 10^{-12}$ for $K^+ \to \pi^+\mu^\pm e^\mp$. A similar mode $K^0 \to \pi^0\mu^\pm e^\mp$ has been studied at Fermilab and will be probed at a sensitivity of $10^{-11}$ in KTEV experiments. The decay $\pi^0 \to \mu^\pm e^\mp$ can be sought in these experiments. Other LFV processes such as $\mu^+e^- \to \mu^-e^+$ conversion and $\eta \to \pi^0\mu^\pm e^\mp$ have a unique sensitivity to some models [47].

## C.5 Beam Requirements for the Next Generation Experiments

A beam with $10^6 - 10^7$ stopped $K^+$ with a $K : \pi$ ratio of $\sim 3 : 1$ has been realized at the Brookhaven AGS for the search of the decay $K^+ \to \pi^+\nu\overline{\nu}$. A pure higher-intensity lower-momentum $K^+$ beam is necessary for the determination of $\mid V_{to} \mid$ at the level of 10–20% from the decay $K^+ \to \pi^+\nu\overline{\nu}$. A 100% duty-cycle beam would be essential to reduce the acceptance loss due to chance coincidence. The same beam characteristic is required by other stopped $K^+$ beam experiments such as muon polarization measurements in the decays $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^0\mu^+\nu$. Experiments using in-flight decays (e.g. $K^+ \to \pi^+\mu^\pm e^\mp$ and $K^+ \to \pi^+e^+e^-$) need a high-intensity pure $K^+$ beam with no beam halo.

For the detection of photons and electrons, a higher momentum beam allows a higher calorimeter threshold and a better reconstructed mass, resulting in cleaner signals. Measurements of $\epsilon'/\epsilon$ and searches and the decay $K_L^0 \to \pi^0e^+e^-$ have benefited from the high energy accelerators. This argument may not be applicable to the experiments that require photon vetoing (due to the cost) and the detection of charged particles (*e.g.* $K_L^0 \to \mu^\pm e^\mp$ and $K_L^0 \to \mu^+\mu^-$), and these experiments have been carried out at lower energy beam lines so far. To maximize important physics results, a few high-intensity $K^0$ beams are necessary. The beam purity, which helps significantly reducing the background, could be improved by large angle extraction; this requires even higher intensity of the primary beam. In the low-momentum experimental search of the decay $K_L^0 \to \pi^0\nu\overline{\nu}$, a micro beam structure will provide kinematic constraints.

When a 1 GeV $\pi^-$ beam hits a hydrogen target, it produces a monochromatic $K^0$ beam, which provides additional kinematic constraints in the search of the decay $K_L^0 \to \pi^0\nu\overline{\nu}$. This type of beam lines is expected to have less contamination. The required beam intensity for ultra-rare decay experiments is $\sim 10^{11}$ $\pi^-$/s. A similar type of beam line could be used for $\eta$ particle production.

A few orders of magnitude higher intensities in both $\mu^+$ and $\mu^-$ beams are required in the search of LFV decays, $\mu^-A \to e^-A$ and $\mu \to e\gamma$. A beam line with a super-conducting solenoid at the production target may provide a very high intensity $\mu^-$ beam. The pion contamination has to be $\leq 10^{-10}$ in the $\mu^-$ beam.

| | P GeV/c | Intensity (present) part/s | Intensity (future) part/s | Typical Modes | Physics |
|---|---|---|---|---|---|
| $\mu^+$ | $\leq 0.1$ | $10^5$ | [a]$10^5$ | $\mu$ pol., $\mu^+ \to e^+\nu\overline{\nu}$ | V–A |
| | | $10^7$ | $10^9$ | $\mu \to e\gamma$ | LFV |
| $\mu^-$ | $\leq 0.1$ | $10^7$ | $10^{10}$ | $\mu^- A \to e^- A$ | LFV |
| $\pi^+$ | $\leq 0.1$ | $10^6$ | [a]$10^8$ | $\pi^+ \to e^+\nu$, $\pi^+ \to \pi^0 e^+\nu$ | $g_e/g_\mu$, $V_{ud}$ |
| $\pi^\pm$ | $\sim 1$ | $10^9$ | $10^{11}$ | $K_L^0 \to \pi^0\nu\overline{\nu}$<br>$\eta$ decays | $Im(V_{to})$<br>$\chi$PT |
| $K^+$ | $\leq 0.8$ | $10^6$ | $10^7$ | $K^+ \to \pi^+\nu\overline{\nu}$,$K^+ \to \pi^0\mu^+\nu$ | $\mid V_{to} \mid$, T-viol. |
| | $\sim 6$ | $10^8$ | $10^9$ | $K^+ \to \pi^+\mu^\pm e^\mp$<br>$K^+ \to \pi^+ e^+ e^-$<br>$K^+ \to \pi^+\mu^+\mu^-$ | LFV<br>$\chi$PT<br>$\chi$PT/CP |
| $K^0$ | $1 \sim 50$ | $10^8$ | $10^9$ | $\epsilon'/\epsilon$, $\phi_{+-} - \phi_{00}$<br>$K_L^0 \to \pi^0\ell^+\ell^-$, $K_L^0 \to \pi^0\nu\overline{\nu}$<br>$K_L^0 \to \ell^+\ell^-$, $K_S^0$ decays<br>$K_L^0 \to \mu^\pm e^\mp$ | CP, CPT<br>$Im(V_{to})$<br>CP/$\chi$PT<br>LFV |
| $n$ | $\leq$1 keV | $10^7$ | $10^9$ | $n$ decay, $n$ capture | $V_{ud}$, T-viol. |
| $\Xi^\pm$, $\Lambda$ | $\sim 150$ | $10^5$ | $10^5$ | $\Xi \to \Lambda\pi$, $\Lambda(\overline{\Lambda}) \to p(\overline{p})\pi$ | CP |
| [a]Improvements in the beam quality. | | | | | |

Table 3: A summary of required secondary beams.

## C.6 Summary

Searches for new processes and precise measurements of rare decays have provided key experiments in the advance of particle physics, and the expected physics results from future high-precision and rare-decay experiments will be extremely fruitful. The basic ingredients of the SM, universality and the V–A structure of weak interactions, will be rigorously tested by pion and muon decays. Rare kaon decays like $K^+ \to \pi^+\nu\overline{\nu}$ could uniquely determine CKM parameters such as $V_{to}$ when the top quark mass is known. Evidence of direct CP violation can be probed by precise measurement of the ratio $\epsilon'/\epsilon$ in $K_{S,L}^0 \to \pi\pi$ decays; the new experiments with a precision of $10^{-4}$ proposed at Fermilab and CERN may confirm the existence of direct CP violating component for the first time. However, theoretical uncertainties may hinder a quantitative interpretation. The CP violating decay $K_L^0 \to \pi^0\nu\overline{\nu}$ provides a clean unambiguous signal of direct CP violation and will determine the imaginary part of $V_{to}$, and initial attempts have just started. Polarization measurements of muons from the decays $K \to \pi\mu^+\nu$ and $K_L^0 \to \mu^+\mu^-$ may provide complementary information on additional CP violation sources. Physics beyond the SM could be best tested in the searches of lepton flavor violating decays such as $\mu \to e\gamma$, $\mu^- A \to e^- A$, $K \to \pi\mu^\pm e^\mp$ and $K_L^0 \to \mu^\pm e^\mp$. The mass scales in the TeV/c$^2$ region are probed for hypothetical particles introduced by many extensions of the SM. As described in the previous sections, coherent studies of other decay modes, such as $K \to (\pi)\gamma\gamma$ and $K \to (\pi)\ell\ell$, will also provide the same quantities mentioned above, and are equally important for testing the SM—there is the possibility of surprises as various decay modes are studied in ever greater detail.

These important experiments can only be done at high intensity hadron facilities and it

is essential to have strong initiatives in this direction to carry them out. Progress in this field is very much dependent on beams of ever increasing intensity and quality, and continues to require new and upgraded detectors and various accelerators that produce secondary beams from low energy muons to high energy hyperons. At the present time and for the foreseeable future, the Brookhaven AGS and the Fermilab fixed-target program, as supplemented by the Main Injector now under construction, provide the main opportunities for the experiments using kaons and hyperons. Because of the difference in the energy domains, each machine has its own uniqueness and strength as discussed in the previous sections. Consequently, the programs which can be pursued at the AGS, Fermilab and meson factories appear to be extremely complementary, and each machine deserves necessary upgrades to complete a variety of important programs.

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# D Hadron Dynamics

## D.1 Introduction

Hadron Dynamics is the study of strong hadron interactions amongst themselves and with gauge fields under a wide range of kinematic conditions. We have extensive experimental evidence that QCD is a correct theory of the strong interactions. At extremely high momentum transfers (very short distances) on free nucleons, we have a successful picture of relatively free partonic processes, where perturbative QCD is valid. At low energy the interaction between hadrons is described by the traditional approach with 'elementary' baryons exchanging light mesons. As the momentum transfer to a hadron increases toward a GeV the mesonic picture becomes both unwieldy and suspect of being fundamentally flawed, because of the potential role of parton degrees of freedom at short distances. These problems are reflected in the uncertainties that surround the equation of state of hadronic matter at high temperature and density. The challenge is to use QCD to develop a robust widely applicable dynamics which successfully treats the regime $Q^2 > 1$ GeV$^2$. In the non-perturbative region we presently rely on models or approximations (constituent quark, bag, flux tube,...) which incorporate some aspects of QCD.

Only in experiments in the perturbative regime can we directly measure the fundamental quark distribution functions of hadrons. One aspect of high energy hadron dynamics involves directly measuring these quark or gluon distributions at large energy and momentum transfer via the Drell-Yan process or direct photon production. When there is overlap with similar information from electroweak interactions the agreement is excellent. In addition to providing the partonic distribution for a free nucleon, it is possible to measure the modifications of these distributions within nuclei. Such modifications have been observed since the early 80's and have proved perplexing as they occur where they are unexpected (valence distributions) and do not occur where expected (sea distribution). These reactions allow one to examine unusual states of strongly interacting matter. For example hadrons selected in point like configurations by virtue of surviving a hard collision, as well as colored quarks, can be made to propagate through nuclei, and QCD gives rather firm predictions for the expected behavior.

In these notes, we review a set of important physics questions which can be addressed at hadron facilities. We then discuss the facilities (machines, detectors, etc) necessary to carry out these investigations. Finally, we provide a prioritized list of facilities to carry out this physics. A comprehensive program of hadron dynamics requires experimental facilities capable of spanning the region from the onset of short-distance phenomena to the regime of perturbative QCD.

## D.2 Questions in Hadron Dynamics

### D.2.1 Baryon-Baryon Reactions

Our understanding of the free baryon-baryon interaction is a crucial ingredient in building the laws of hadron dynamics. At lower energies, for the past fifty years we have understood nucleon-nucleon scattering in terms of a meson-nucleon description of this interaction. One of the great successes of this work was a simultaneous understanding of the free N-N interaction, and the effective interaction of nucleons within a nucleus. The meson-nucleon model can give a satisfactory description of data up to 1 GeV, and in fact the mesonic

theory of nuclear forces has been a great success in our understanding of dynamics. However, several open questions still remain, and hadron dynamics experiments can help answer them.

First, the **Nucleon-Nucleon Interaction** is still not understood quantitatively at the quark/gluon level. Although quark/gluon models of baryon resonances have been quite successful, descriptions of scattering do not provide detailed agreement with experiment. Several models have been proposed, but can describe existing data only qualitatively. A crucial step will be to develop models which can be successfully extrapolated from the regime of very high energy and momentum transfer, where perturbative QCD should become valid, down to low momentum transfers and energies, where the meson/baryon picture currently dominates.

At energies above 1 GeV, where the mesonic picture breaks down, spin information is particularly crucial in understanding the free N-N interaction. It is clear that naive QCD arguments, which suggested that spin effects should vanish, were not borne out. Existing polarization and asymmetry data clearly show surprisingly large spin effects, which persist to rather high energies, although such data now exist at only a few energies and angles. Systematic data on N-N spin effects could be obtained at the AGS, with the Siberian Snake, or at LISS.

Better knowledge of the **Hyperon-Nucleon Interaction** can give much insight into the baryon-baryon force. Two important questions in this regard are: whether the hyperon-baryon interaction can be satisfactorily described by a meson/baryon picture; and what is the SU(3) structure of the baryon-baryon interaction. Historically, much information on the hyperon-baryon interaction has been obtained by studying the spectroscopy of hypernuclei (see Appendix E), but such studies give us the effective hyperon-nucleon interaction in nuclei. More complete information requires hyperon-baryon scattering studies. Low-energy hyperon formation is most easily accomplished with intense pion or kaon beams. At low energies this can be done at the AGS, or KEK. Higher energy intense kaon beams would be possible with the Fermilab Main Injector (FMI), if a kaon beam line were installed. Another possibility would be to examine the production and decay of excited hyperons, through the reaction $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$, which would require suitable antiproton beams.

### D.2.2 Meson-Baryon Reactions

Meson production and propagation in nuclei has given us much information relating the nuclear force (mediated by meson exchange) to the production and scattering of mesons. At present, mesons containing significant strange or charmed quark content can give us interesting information on the flavor dependence of light quark processes. For example, with $\eta$ mesons, by studying $\eta$-nucleus interactions we could deduce the nuclear dynamics of the $N^*(1535)$ resonance. Since the $\eta$-N S-wave interaction is strongly attractive, this may produce $\eta$-nuclear 'bound states,' which could be seen in low-energy $\eta$ production. Another interesting question is the dynamical origin of the OZI rule, which predicts substantially suppressed amplitudes for processes which include disconnected quark lines. Comparison of nuclear production of $\phi$ and $\omega$ mesons can give information on the OZI rule. Some experiments suggest 'evasion' of the OZI rule, and systematic energy-dependent measurements could answer this question. Similarly, one can extend these investigations to $c\bar{c}$ states in $J/\psi$ production, also to mesons with overall strangeness or charm. Such investigations can be done at the AGS.

The nonlinearity of QCD makes it difficult to apply to low energy hadron dynamics. However, **Chiral Perturbation Theory**, which treats the pion as the Goldstone boson of spontaneously broken chiral symmetry, leads to a variety of low-energy theorems which allow precision tests of key features of QCD in pionic and kaonic interactions. Of particular importance in this regard is $\pi\pi$ scattering at low energies, since the $\pi\pi$ scattering amplitude at threshold is completely determined by the chiral symmetry breaking interaction. Precision measurement of $\pi\pi$ low energy scattering, at the few percent level, is important to extract certain terms in the chiral perturbation theory Lagrangian. The scattering lengths can be extracted from the process $\pi N \rightarrow \pi\pi N$; this has been measured at TRIUMF and LAMPF. One could also try to produce a $\pi^+ - \pi^-$ bound state ("pionium"); an experiment is planned for IUCF. Such a measurement would help separate the $I = 0$ and $I = 2$ $\pi - \pi$ scattering lengths. In addition, precise comparisons of weak decays of $K$ and $\eta$ can also pin down parameters in chiral perturbation theory ($\chi PT$).

### D.2.3 Hadron Weak Form Factors

Hadron facilities are the only means available for producing neutrino beams. Surprisingly these beams are extremely important for the investigation of crucial aspects of hadronic physics. Charge changing elastic scattering from nucleons depends on their isovector axial current as characterized by the nucleon's axial vector form factor $G_A(Q^2)$. There is an ongoing controversy regarding severe quenching of $G_A(0)$ in the nuclear medium. A measurement of quasielastic charge changing neutrino scattering in nuclei appears to be the only way to solve this long standing dispute. The neutral current coupling of neutrinos to nucleons provides a unique opportunity to measure $G_s(Q^2)$, the nucleon's strangeness axial vector form factor. ($G_A(Q^2)$ is directly related to the $NN\pi$ axial coupling, and $G_s(Q^2)$ measures the strange quark content of the proton.) Directly complementary to work proposed at CEBAF, the strangeness vector form factors, $F_1(Q^2)$ and $F_2(Q^2)$, can also be determined. Experiments are presently being carried out at LAMPF. Significant new research in this area can be carried out at the AGS or the Fermilab Booster.

### D.2.4 Parton Distributions

In determining the partonic structure of the nucleon we have accumulated detailed information on structure functions from several sources. In addition to DIS data obtained from $e$, $\mu$ and $\nu$ beams, and lepton charge asymmetry from $W$ production, hadronic interactions provide crucial input from Drell-Yan (DY) and prompt photon data, in both fixed target and collider reactions. We briefly review our current state of knowledge of nucleon parton distributions, focusing particularly on the role of hadron facilities.

**Nucleon sea and valence distributions:** In general, for $x > 0.1$ we have considerable data on spin independent nucleon sea and valence distributions (at least for non-strange quarks). The consistency of the data over a wide energy range demonstrates how well QCD works. However the data while consistent are not very precise, nor is the flavor dependence sufficiently well determined. This is particularly true for gluon distributions and the flavor dependence of the sea. Recent experiments indicate that the sea is very flavor asymmetric at $x \sim 0.1$, a result in disagreement with perturbative QCD predictions. Recent progress has been made on extracting SU(2) flavor asymmetry (i.e., $\bar{d}^p - \bar{u}^p$) through DIS structure functions on proton, deuterium and nuclear targets, lepton-pair production, and the recent $A_W$ measurement. Crucial additional data on this quantity should be forthcoming from

the fixed target experiment Fermilab E866. Future experiments might search for charge symmetry breaking at the partonic level (e.g., $d^p(x)-u^n(x)$). The strange quark distribution is not well measured. Neutrino dimuon data shows that the strange quark distribution is roughly half the non-strange sea distribution, but inclusive $F_2$ data from muons and neutrinos at small $x$ seems inconsistent with this hypothesis; this discrepancy needs to be understood.

**The gluon distribution:** Presently our best information on the gluon distribution comes from the $Q$-dependence of the DIS structure functions, direct photon production and heavy quark pair production. Global analyses currently assume that the small $x$ behavior of gluon distributions is the same as that of the sea quarks (rather well determined by the new HERA data). This assumption needs to be checked. For moderately large $x$, direct photon data should determine $G(x,Q)$. New collider data is becoming available and better fixed-target measurements are anticipated from the on-going analysis of experiment E706. A wealth of data on jet-production at colliders is becoming available: this is extremely sensitive to $G(x,Q)$, and is being obtained from the CDF and D0 experiments at the Fermilab collider. This promises to be an active area of investigation, and will complement data obtained at HERA.

**Nuclear parton distributions:** The EMC Effect showed that the structure function $F_2$ measured from a heavy nuclear target differed from that measured off a free nucleon. This could be interpreted as an indication that parton distributions within an isolated nucleon are different from parton distributions of nucleons within a nucleus. It has been proposed that comparing the ratio of leading positive and negative hadrons from a nuclear target and a nucleon target would determine the ratio of valence quarks in a nucleus to those in a nucleon at small $x$. Drell-yan and direct photon experiments will allow for the study of nuclear effects for gluons and antiquark distributions in a wide range of $x$ to determine if effects, similar to the EMC effect, are present for those distributions. The high fluxes and lepton beams available with the Fermilab fixed target program are well suited for such experiments.

**Meson parton distributions:** Measurement of parton distributions for mesons will demonstrate how their momentum is shared between valence quarks, sea quarks and gluons. At present, we know relatively little about parton distributions in mesons. Only the pion valence distribution has been studied and is still rather poorly determined, while the pion sea distribution is essentially unknown. The pion sea should be especially interesting because the pion is viewed as a Goldstone boson whose collective nature should be manifested via a particular sea distribution. In all measurements to date the pion appears as a conventional $q\bar{q}$ system. Comparison of the partonic structure of the pion and kaon would demonstrate the extent of $SU(3)$ breaking. We have very little knowledge of $K$ parton distributions. Meson-induced DY processes could make an important contribution here. These experiments would require the high intensity from the FMI both directly, and through the resulting increased intensity for Tevatron fixed target beams. The $x$ regime that can be studied is roughly $x_h > (30\ \mathrm{GeV/c})/P_h$.

### D.2.5 Coherent Processes

As the fractional momentum, $x$, of the quarks in a hadron decreases, the longitudinal distances over which interference phenomena can become important increases as $1/(2M_n x)$. This results in new physics even when the transverse scale, the inverse of the momentum

transfer $Q$, is small. At the highest energies one can reach a new QCD domain where the coupling constant $\alpha_S(Q^2)$ is small but the quark density, $q(x, Q^2)$, is very large.

The clearest experimental signal of such coherent phenomena is the detection of **diffractive events**. In "normal" hard scattering, a color field connects the quarks experiencing the hard interaction, the struck quarks, and the remnant of the target or projectile hadrons. As this color field hadronizes there is a continuous distribution of particles between the struck quark and the remnant. In a diffractive event, the interaction results from the exchange of a colorless object and there is no color field connecting the remnants, leading to gaps, so-called "rapidity gaps" between the jets of hadrons.

In the past two years, evidence for diffractive events in deep-inelastic lepton-nucleus scattering has emerged at HERA and Fermilab. This is associated with the exchange of a colorless object, the pomeron, which can be thought of as two-gluon exchange between hadronic fluctuations of the virtual photon and the target. This phenomenon provides a new technique to study the gluon distribution of the nucleon. At higher momentum transfer, the pomeron structure is intimately tied to the evolution structure of parton distributions. Of course, hadronic interactions at high energy also exhibit rapidity gaps and diffractive structure, and are also used to study this physics.

Considering deep-inelastic scattering in a laboratory frame picture as the interaction of hadronic configurations of the virtual photon with the target emphasizes the importance of the QCD prediction that these configurations will interact weakly at small transverse scales, a concept known as **color transparency** (CT). This transparency is a consequence of QCD which is essential to preserve the success of the parton model. High energy is important to freeze the transverse separation of the hadronic configurations throughout the scattering process.

A nuclear target provides a natural longitudinal length scale to compare with the large longitudinal distances probed in these reactions. The resulting interference phenomena are measured by the reduction of nuclear cross sections or shadowing observed in deep inelastic scattering from nuclear targets at very low $x$. Fermilab results indicate that a significant fraction (10–20%) of the deep inelastic scattering cross section on heavy nuclei at low $x$ is due to diffractive events. By concentrating on diffractive phenomena in exclusive processes, evidence of color transparency has apparently been seen at Fermilab in exclusive $\rho$ production. As the momentum transfer increases, the relative cross section increases, approaching $A$ times the nucleon cross section at higher momentum transfer. CT is not observed in comparable momentum transfer experiments in quasifree $(e, e'p)$ at SLAC. Exclusive $(p, 2p)$ experiments at the AGS, at similar momentum transfer, saw a large unexpected energy dependence in the transparency. Experiments such as EVA at AGS are likely to be important in resolving these CT issues.

It has been suggested that polarization phenomena seen at several GeV, but not allowed in perturbative QCD, may be suppressed in interactions with nucleons inside nuclei, by a color filtering process. This could be studied at AGS with Siberian Snakes, or at LISS.

Studies of coherent diffraction of hadrons off nuclei can be used to map the structure of transverse color fluctuation of hadrons. One technique for this is diffractive electroproduction of various final states such as the $\phi$, $\rho'$, $\psi$ and $\psi'$. In some cases the interference is predicted to be destructive leading to shadowing or absorption. In other cases the interference should be constructive. A complementary technique is the coherent inelastic production of jets with a hadron beam. Here the transverse momentum of the jets provides a natural measure to control the "hardness" of the interaction. In each case, the reaction

is quite sensitive to the structure of the quark-antiquark Fock states of the hadron wave function.

### D.2.6 Jet Physics

At high energies ($\sqrt{s} \sim 20$ GeV), a parton description of hard scattering processes is essential. The interacting particles are quarks, gluons, and possibly photons, and the outgoing partons hadronize into jets. Uncertainty principle arguments show that at these energies, hadronization takes place on a distance scale of a few tens of fermis or more. The only available "laboratory" to probe such distances is a nucleus. Jet processes allow us to study hard scattering in a nuclear medium to learn about the hadronization process and the behavior of partons in nuclear matter. Previous work on jet physics has given us valuable information on nuclear gluon distributions, and on the value of $\alpha_S$.

There is some evidence that many-body effects such as gluon shadowing and jet quenching would be significant in $p+A$ reactions, but might completely dominate $A+A$ processes. This jet physics could be studied at RHIC.

The "anomalous nuclear enhancement" of high $p_t$ production of single pions and other particles (the "Cronin effect") has been known for 20 years, but is not completely understood. If one characterizes the $A$-dependence of the cross section as $\sigma(pA) = A^\alpha \sigma(pp)$, one finds that $\alpha > 1$. This effect is generally attributed to multiple scattering of the hard-scattered partons after the interaction but before they exit the nucleus. Hadronization itself is a long-distance effect compared to the size of the nucleus, so this effect must be at the parton level, before hadronization takes place.

Anomalous nuclear enhancements have also been seen in dihadron production and dijet production. Such experiments can directly measure the large multiple nuclear scattering of the final state partons. Although we have some accurate data on these poorly understood phenomena, their behavior as a function of $p_t$ and $\sqrt{s}$ is not well mapped out. A beam energy of 120 GeV is most likely not high enough to study hard scattering processes which would greatly increase our understanding of parton propagation in nuclei. Progress in this area will require fixed target running at the full Fermilab Tevatron energy.

An area of jet physics which would benefit greatly from systematic study is the spectator system (i.e., the forward- or backward-going remnant of a hadron after a hard scatter). It produces a forward or backward jet and is responsible for the "underlying event" in a hard scattering interaction. Very few measurements of the spectator system exist, as small-angle particles are difficult to detect in collider experiments. Monte Carlo models which describe the hard-scattered system well generally do a poor job of describing the spectator system, which could be studied at the Fermilab Tevatron fixed-target program.

## D.3 Hadron Facilities

In this section, we provide a prioritized list of a few hadron facilities. We briefly review the important hadron dynamics which could be investigated at each facility. At existing facilities, we discuss upgrades or additions which could enhance the opportunity for hadron dynamics studies; for proposed facilities we cite the types of physics which could in principle be investigated, and we attempt to outline the conditions which would be necessary for such studies.

1. **Fermilab**. Fermilab offers unique opportunities for continuing a series of high energy hadron dynamics experiments. One can investigate Drell-Yan processes, direct photon production, heavy quark production and jet physics. The 800 GeV fixed target program is essential for the studies of $A$ dependence at high energies. The Fermilab Main Injector (FMI) will provide high intensity beams in the 10-100 GeV range, even during Tevatron Collider operation. Polarized beam in the main injector could open a entire new range of study of spin carried by partons, chirally odd spin structure functions, and directional correlations in exclusive channels. The FMI could produce 10-20 GeV charged kaons with intensities an order of magnitude greater than presently available. The practicality of such new capabilities with the FMI should be carefully studied.

2. **RHIC**. Parton and jet physics can only be done in the US at Fermilab or RHIC. At RHIC, very high energies will also be reached for $p + A$ processes, making possible Drell-Yan measurements, and studies of high energy medium effects. The RHIC Spin project will allow the investigation of $\vec{p} + \vec{p}$ reactions. There are plans to study nucleon spin structure functions, polarized Drell-Yan $p + p$ processes, $W^+$ production in such reactions, and gluon distributions through direct photon or jet production. At present RIKEN has entered into agreements with BNL which should provide funds for the roughly \$20 M for Siberian Snake and detector modification for this project. RHIC Spin would require about 20% of RHIC beam time for $\vec{p} + \vec{p}$ reactions.

3. **AGS Fixed Target Operations**. AGS is presently continuing programs on exclusive reactions, color transparency (with the EVA detector), hypernuclear physics, and kaon beams and $\eta$ physics. It would be possible to produce an rf-separated kaon beam at AGS, which would give increased $K$ intensity. Kaon beams are also available at KEK, but with lower intensity than AGS. The addition of a partial Siberian Snake at AGS should maintain proton polarization up to proton energies of 25 GeV.

4. **LISS**. A proposed 10-20 GeV light ion synchrotron at IUCF. The high luminosities for polarized beams and polarized internal targets would allow a study of physics in the nonperturbative transition regime, complementing efforts at the facilities listed above. LISS could investigate $\vec{p} + \vec{p}$, $p + A$ medium effects up to 20 GeV (including polarized CT), baryon-baryon interactions, meson production.

# E Hadron and Nuclear Spectroscopy

## E.1 Introduction

This report summarizes activities in two areas, hadron spectroscopy and strangeness physics. The former addresses the issue of non-perturbative QCD and the makeup of mesons and baryons. The latter attempts to achieve an understanding of the properties of hypernuclei and the underlying hyperon-nucleon and hyperon-hyperon interactions.

With regard to future hadron facilities, physicists working in these two areas have a common interest in seeing existing facilities, especially beams at the Brookhaven AGS, fully utilized in the coming years. Both groups could also benefit from the construction of LISS at Indiana. In the future, CEBAF will play an increasingly important role in the study of hadron spectroscopy. Hypernuclear studies are also planned at CEBAF.

In Section E.2 we will review the physics issues in hadron spectroscopy. New high intensity hadron beams, accompanied by state-of-the-art detectors, are needed to explore non-perturbative QCD in the light quark sector up to the charmed quark sector with the strange quark sector providing the important bridge between the two. The need for these beams and detectors is crucial because of the gaps left by the demise of the KAON project, the imminent close-out of LEAR and the decision to not build SUPERLEAR. Highest priority should be given to the construction of:

1. a high intensity r.f.-separated $K$ beam at Brookhaven or at Fermilab.
2. external antiproton beams at Brookhaven and in the range from 0.02 to 5.2 GeV and at the new Fermilab Main Injector in the range from 9 to 150 GeV.
3. a first-rate detector facility to exploit these beams. The detector facility should provide hermetic coverage for charged particles and photons, particle identification, high-rate capability and the flexibility for selective triggers.

The case for these priorities is presented in Section E.2. Progress in hadron spectroscopy has depended on and will continue to depend upon results from complementary processes. There are proposals for or plans under discussion to study the Primakoff production of hybrids at Fermilab, baryon spectroscopy with hyperons at Fermilab, double-pomeron production of mesons at RHIC and central production of mesons at LISS. Although not a hadron facility, photon beams at CEBAF are expected to be high in $s\bar{s}$ content and will thus be important for both meson spectroscopy and baryon spectroscopy studies.

There is an active community pursuing hypernuclear studies at Brookhaven and KEK. This program is summarized in Section E.3. The beams for continued studies are in place at Brookhaven. The continuation of this program depends on the continued operation of the AGS beams into the RHIC era. The continued program of spectroscopy studies, which include the construction of an r.f.-separated $K$ beam, also crucially depends on continued operation of AGS beams. The need for higher resolution spectroscopy experiments at Brookhaven could be met by moving the Neutral Meson Spectrometer from Los Alamos to Brookhaven. There are also contributions to hypernuclear studies which could to done at the proposed LISS at Indiana.

## E.2 Hadron Spectroscopy

### E.2.1 Introduction

It is remarkable that we find ourselves with a theory (QCD) which has been with us now for twenty years (and which is almost certainly correct) and yet it is not clear what are the physical states of the theory. QCD inspired models (flux tube and bag models) predict states with no valence quark content. Lattice gauge calculations are generating predictions for these glueballs. In addition to pure glue, hybrid states and multi- quark states are predicted. There is a rich spectrum of such new states predicted in the mass region from 1 to 2.5 GeV. The list of tantalizing candidates for these unconventional mesons uncovered by recent experiments is growing as new technology is being brought to bear on re-examining old territory with unprecedented sensitivity. There is not yet a clear smoking gun candidate for a glueball or exotic state but what is clear is that the standard picture of mesons simply as $q\bar{q}$ systems is clearly inadequate — there are more states than can be accommodated and these excess states have peculiar decay modes or peculiar patterns of production.

The search for and the understanding of these QCD states addresses a fundamental issue in the Standard Model, every bit as important as the detailed and systematic electroweak tests being performed at the highest energies now available. The pattern of the recent decades has been to cluster immense experimental effort up against the highest energy frontier leaving behind unanswered fundamental questions at lower energies. These essential studies need to be done, at lower energies, using existing accelerator facilities with appropriate upgrades.

### E.2.2 Experimental Issues

What has become evident from experimental findings thus far is the need for a wide variety of complementary production processes. Much has been learned from $J/\psi$ radiative decays, which are expected to be glue-rich. Photon-photon collisions provide constraints on produced states since gluons do not couple directly to photons and spin-one states cannot be produced from the collision of two real photons. Peripheral and central collisions using pion and proton beams at the AGS, CERN, IHEP and KEK have uncovered a number of states with peculiar properties. At LEAR, the $\bar{p}p$ initial state has well-defined quantum numbers and selection rules severely constrain the number of partial waves contributing to the final state. Indeed their recent analysis has unveiled a rich spectrum of scalar states, far too many for the naive quark model. What we have at present are a number of meson states in scalar sector, the pseudoscalar sector, the axial-vector sector, the tensor sector and manifestly exotic sector, all of which need closer scrutiny since they are clearly not simple $q\bar{q}$ systems.

### E.2.3 Future Beams and Detectors at Brookhaven and/or Fermilab

**Kaon Beams** With the demise of KAON and its anticipated $K$ beams of $10^7$ particles per spill, there is strong motivation for an r.f.-separated $K$ beam to address the physics issues which had been planned there. Crucial experiments can be done with charged $K$ beams in the momentum range of 10 to 20 GeV/c and with intensities of order $10^6$ Hz. These include exotic, hybrid and glueball spectroscopy.

$K$ beams provide spectroscopic physics not available in $\pi$ initiated reactions. Peripheral processes in $K^-p$ reactions, for example, produce forward $s\bar{s}$ systems and forward $q\bar{s}$ sys-

tems, allowing for searches for exotics and hybrids containing $q\bar{s}$ and $s\bar{s}$. From the meson exchange view, $K^-$ beams provide a mechanism for the peripheral production of mesons which couple to $K\overline{K}$. This $K$ beam physics is complementary to the existing $\pi$ beam program at the AGS. With the r.f.-separated $K^-$ beam comes a high intensity $\bar{p}$ beam at comparable momenta.

The recent upgrade of the AGS to $6 \times 10^{13}$ protons per spill leads to the potential of r.f.-separated $K^-$ beams in the 10–20 GeV/c momentum region with intensities of order $10^6$ $K$/pulse. On a 30 cm hydrogen target this gives a luminosity of order 1000 events/nb for a 1000 hour run, two orders of magnitude greater than present experiments at SLAC and CERN. At SLAC, for example, a thorough study of $K^-$p physics at 11 GeV/c was done in the LASS spectrometer, at the 4 events/nb level. At CERN an r.f.-separated beam in the 10–40 GeV/c range was utilized for several experiments in the OMEGA spectrometer, where luminosities in the 1 to 12 events/nb were achieved.

The Fermilab Main Injector (FMI) with $5 \times 10^{13}$ protons at 120 GeV/c is in a position to produce secondary beams of considerably higher intensity than the $6 \times 10^{13}$ protons at 30 GeV/c available at the AGS. Typically beams with $K^-$ intensities in the $10^8$ range will be achievable, adding two orders of magnitude to the potential luminosity, and to the level of exploration of the physics. As a longer range option, an r.f.-separated beam at Fermilab looks promising.

AGS energies (20 GeV incident energies) are ideal for peripheral meson spectroscopy studies in the 1–3 GeV mass regime. Lower energies result in problems with acceptance. Higher energies make analyses more complicated as exclusive reactions of interest fall off with energy and the opening up of new channels introduces backgrounds.

**$\bar{p}$ Beams** Antiproton induced reactions have unparalleled versatility. Their reach extends across the frontiers of QED and QCD to the most fundamental symmetries of particle physics, and their past triumphs include the discovery of W, Z, and the top quark. The recent precision work on charmonium at Fermilab (E760) has further highlighted the remarkable capabilities of antiproton beams to do high resolution spectroscopy of heavy quark systems, to measure nucleon form factors in the time-like region, and to shed light on the nucleon-antinucleon scattering and its relation to nucleon-nucleon scattering.

The identification of several candidates for exotic QCD constructs, hybrids and glueballs, at the CERN Crystal Barrel facility and the Fermilab E760 experiment illustrates the unique ability of $p\bar{p}$ annihilation in producing light quark exotics. With higher antiproton energies these successes can no doubt be extended to charmed hybrids, which are expected to be easier to identify unambiguously. At the lowest energies antihydrogen can be produced and used for fundamental symmetry tests of unmatched sensitivity. Experiments with nuclear targets can lead to definitive results on charmonium-nucleon cross sections whose knowledge is crucial for the identification of quark-gluon plasma.

Despite these clear-cut advantages of antiproton reactions, only two facilities exist today in the world to do antiproton physics. Of these two, LEAR at CERN is scheduled to close in 1997. At Fermilab the only place at which non-Tevatron antiproton physics can be done is the Antiproton Accumulator, which accommodates only one experiment (E760/E835) in less than ideal conditions (non-magnetic detector, scheduling once in six years).

We believe that the advent of the Booster ring at BNL and the new Main Injector at Fermilab provides an unique opportunity to make a quantum difference in the worldwide access to pure antiproton beams. The BNL Booster can provide external antiproton beams

in the range from 0.02 to 5.2 GeV, and open doors to experiments on antihydrogen (unique tool for study of fundamental symmetries like TCP) and light quark structures in the mass range inaccessible to either LEAR or E760. The new Fermilab Main Injector will allow extraction of external antiproton beams in the range from 9 to 150 GeV, and will accommodate experiments with internal targets. Its ability to do so during the Tevatron collider operation will make an order of magnitude difference in the exploitation of the richness of antiproton physics.

**Detectors** The advent of new detectors with sophisticated triggering techniques now makes possible the collection of highly enriched data samples with unprecedented statistics. This, coupled with the explosion in computer technology has made possible the analyses of these large data sets including the subtle issues of acceptances so crucial to the partial wave analyses needed to extract information about these states. Such studies were not possible in the past and as a result the low statistics and limitations of detectors led to doubtful measurements and controversial results.

At Brookhaven, there has been a recent upgrade to the Multiparticle Spectrometer (MPS) to utilize the 18 GeV pion beam. The recent installation of a 3000 element lead glass detector adds powerful neutral particle detection. The comparison of identical intermediate meson systems with eventual different final states (e.g., the $\eta$ can decay into $2\gamma$, $3\pi^0$, or $\pi^+\pi^-\pi^0$) provides powerful information to the understanding of the systematics of acceptance and its relation to spin analyses. In addition to the lead glass detector, the target region instrumentation has been upgraded to include a CsI detector and a charged-particle tracker around the target and soft-photon detection downstream of the target. The capabilities of the triggering system have been also been greatly expanded.

However significant these improvements are, they fall short in satisfying the need for hermetic coverage which would provide unambiguous identification of an exclusive final state and allow one to capitalize on the interference information from the overlap of the production at the beam vertex with the production at the target vertex. This requires a complete redesign of a detector with careful attention to having a tracking and magnet system optimized for hermeticity, high rates, particle identification and with a flexible triggering system.

### E.2.4 Other Future Opportunities

There are plans to study the Primakoff production of exotic hybrids at Fermilab. This requires a higher energies than available at Brookhaven.

CEBAF may not at first glance be thought off as a hadron facility but this facility can (and will) produce high energy photon beams. The basic production mechanism is through vector dominance. Because the photons have relatively large $s\bar{s}$ content they are a good source of strangeonium states. Strangeonium spectroscopy bridges the heavy quark and light quark sectors. The spin 1 structure of the photon also makes it an excellent source for exotic hybrids.

Central production of mesons, that is doubly-diffractive processes, is expected to be rich in glue content and has already been used as a tool in fixed target experiments and ISR experiments to understand the nature of non-$q\bar{q}$ candidates. One could probe this kinematic sector by using the very high energies at RHIC or exploiting the good beam characteristics and high luminosity (therefore a very restrictive trigger) at LISS.

The recent development of stored, polarized beams and pure internal polarized targets

at IUCF allow an entirely new class of experiments to be considered using multi-GeV hadron beams. At LISS, polarization measurements may be used to enhance signal-to-background ratios in investigations of nucleon resonances or more exotic hadron structures. The use of the spin- and isospin-selectively available with polarized light-ion beams can provide a selective filter for N* resonances of specific quantum numbers. In addition, efficient searches for dibaryon resonances that couple to the pp system could be made at LISS by measuring the spin-dependent total cross sections as a function of beam energy in the storage ring.

## E.3 Strangeness Physics

The ultimate aim of this field is to achieve an understanding of the strong, weak and electromagnetic properties of hypernuclei and the underlying hyperon-nucleon and hyperon-hyperon interactions. We emphasize that the study of hypernuclear physics extends and enriches conventional nuclear structure physics. Strangeness represents a degree of freedom with many novel aspects, among them new dynamical symmetries in hypernuclear spectra, non-mesonic weak decays, and the interplay of the quark-exchange and boson-exchange aspects of strong baryon-baryon forces. A knowledge of $S = -1$ and $S = -2$ systems represents a steppingstone towards multi-strange hadronic matter, which may be accessible in high energy collisions of heavy ions.

To produce hypernuclei, intense pion and kaon beams in the 1 GeV/c region are required. The most intense and pure low-energy separated beams are available at the Brookhaven AGS and they are attracting collaborative proposals from around the world. Several proposals involve moving existing detector systems to Brookhaven and others involve the construction of new and innovative detectors.

The goal of measuring the level spectra and decay properties of $S = -1$ and $S = -2$ hypernuclei is to test the energies and wave functions from microscopic structure models. The experimentally determined properties of hypernuclei can then be used to put constraints on baryon-baryon interaction models which link $NN$, $YN$ and $YY$ interactions. These interactions are not well determined by the sparse data on free two-body interactions outside the $NN$ sector, and such information is crucial. Some experiments, for instance at the proposed LISS facility, will improve the data on $YN$ interactions. The weak two-body interaction involving hyperons, which provides the predominant non-mesonic, weak-decay mode of most hypernuclei, can only be studied in the environment of a hypernucleus. This represents a unique test of the $\Delta I = 1/2$ rule for weak decays, and provides a link to fundamental issues in particle physics.

### E.3.1 Hypernuclear Physics

The priorities for future hypernuclear physics research are focussed on higher resolution spectroscopy and coincidence experiments. The neutral meson spectrometer (NMS) from LAMPF could form the backbone of high precision $\Lambda$ hypernuclear studies via the $(K^-, \pi^0)$ reaction and $\pi^0$ weak decays. The energy resolution of less than 1 MeV for this device would enable significant advances in the measurement of level splittings in $\Lambda$ hypernuclei. Note that a whole new class of $\Lambda$ hypernuclei will be accessible via this reaction which converts a proton into a $\Lambda$. Much new, and more precise, information would be obtained by $\gamma$ or weak decay measurements, in coincidence with the production of $S = -1$ hypernuclei via the $(K^-, \pi^0)$, $(K^-, \pi^-)$ or $(\pi^+, K^+)$ reactions. The principal goal is to extract the spin dependence of the $\Lambda N$ interaction and to establish the form of the three-body $\Lambda NN$

interaction.

For $S = -2$ systems, the current $K^-$ beam intensities on an AGS beamline at 1–2 GeV/c built for $H$ dibaryon searches are sufficient to make a qualitative advance in our knowledge of $\Xi$ and $\Lambda\Lambda$ hypernuclei, which at present consists of a handful of emulsion events. There are approved experiments, new proposals, and letters of intent to establish the existence of $\Lambda\Lambda$ and $\Xi$ hypernuclei. A key question is whether discrete $\Xi$ quasiparticle states exist in nuclei. Except for the A=4 case, recent investigations at the AGS have not indicated a corresponding series of narrow states for the $\Sigma$. However, the $\Xi$ case is much more favorable, since the phase space available for the strong decay $\Xi N \rightarrow \Lambda\Lambda$ is much smaller than for $\Sigma N \rightarrow \Lambda N$. The binding energies of $\Xi$ hypernuclear states would fix the strength of the $\Xi N$ interaction, the widths of the $\Xi$ states the strength of the $\Xi N \rightarrow \Lambda\Lambda$ interaction, and the binding energies of $\Lambda\Lambda$ hypernuclei the strength of the $\Lambda\Lambda$ interaction. This basic information would provide an excellent test of quark exchange aspects of the strong force, since long range $\pi$ exchange is essentially absent in the $S = -2$ sector. This line of research also provides a gateway to the study of multiply strange hadronic or quark matter. This is of crucial importance for studies of the role of strangeness in the equation of state at high-density, as probed in the cores of neutron stars and high-energy heavy ion collisions at RHIC, for instance.

Novel experimental approaches are being used to study $\Lambda\Lambda$ hypernuclei produced either directly or via the capture of $\Xi^-$'s from atomic states. These include the use of segmented scintillating fiber arrays, cylindrical solenoidal detector systems for observing sequential $\Lambda$ decays, and large neutron detector arrays. Many proposals include coincidence studies made possible by the high fluxes and improved instrumentation. A large acceptance spectrometer with high resolution is essential for the study of $\Xi$ hypernuclear states (see Section D.3.3).

### E.3.2 Hadron Spectroscopy and Dynamics

The search for a stable six quark dibaryon, the $H$, which has important implications for the Bag Model of QCD, will continue with high priority at BNL, exploiting the increased $K^-$ beam intensity available with the AGS Booster and new beamlines. There are also a number of proposals to look for the $H$ with heavy ion beams at the AGS.

The 2 GeV/c separated kaon line (D6) at the AGS was developed for two ongoing searches for the doubly-strange $H$ particle, in the reactions $\Xi^-_{stopped} + d \rightarrow H + n$ and $K^- + {}^3\mathrm{He} \rightarrow K^+ + H + n$. The new work being initiated on the properties of $S = -2$ nuclear systems also bears directly on the existence of the $H$ particle, since $\Lambda\Lambda$ hypernuclear ground states would be expected to decay to $H$ plus a nuclear core if $M_H < 2M_\Lambda - B_{\Lambda\Lambda}$.

With intense $\pi$ and $K$ beams at the AGS, one of the central goals in the realm of spectroscopy and dynamics is the investigation of how strange and non-strange baryon resonances propagate in the nuclear medium. The modifications of the mass and width of these objects tells us about the interaction of unstable particles with nucleons via the resonance-nucleus optical potential. The $\Lambda(1520)$ and $\Lambda(1670)$ are prime candidates for such studies, since their free-space decay widths are of the order $\Gamma \sim 15$ and 35 MeV, respectively, much less than the width of the $\Delta(1232)$ in the non-strange sector. There is also the attractive possibility of studying baryon resonances which couple strongly to the $\eta$ channel, in particular the $N(1535)$ and $\Lambda(1670)$, with the goal of better determining the $\eta$ decay branching ratio and providing a challenging constraint for quark modelers. Along this line, an interesting example of medium effects, representing an ongoing theoretical

challenge, has appeared in the $K^+$ total cross section and quasi-free scattering data taken on a range of nuclei at the AGS.

### E.3.3 Facilities and Detectors: Present and Future

It is crucial to the maintenance of a well-balanced national program of research that support for a versatile secondary-beam program at the AGS continue now and into the RHIC era. As it moves toward its role as an injector for RHIC, the AGS has been endowed with a booster injection ring and more powerful radiofrequency cavities, which will allow it eventually to achieve accelerated proton currents of about 10 $\mu A$, *a substantial fraction of the requirement envisioned in the 1989 Long Range Plan.*

The AGS currently provides essential support for High Energy, Medium Energy and Heavy Ion Physics programs. Several international collaborative efforts are underway to either move existing detector systems to the AGS or to construct new and innovative detectors. Examples of the devices being suggested for installation at AGS facilities include the LANL neutral meson spectrometer (NMS), the solenoidal CDS detector, and the S2S spectrometer for $S = -2$ hypernuclei.

The low-energy separated beams at the AGS provide the world's most intense beams of kaons below 1.0 GeV/c. The LESB-2 line has two branches, selectable by a rotating dipole assembly. In the C-6 position, the momentum dispersed beam is focused on the pivot point of the Moby-Dick spectrometer, which is used for hypernuclear studies. Moby-Dick features an effective resolution of 3.0 MeV and a solid angle acceptance of 18 msr, with a momentum bandwidth of about 12% in $\delta$p/p. The C8 branch, providing a momentum recombined beam, is useful for investigation of the $(K^-, \pi^0)$ reaction for hypernuclear studies. For this purpose, the recently-developed NMS spectrometer at Los Alamos is ideal. It features a pair of cesium iodide calorimeters, bismuth germanate converters, and tracking chambers for conversion vertex determination. The NMS offers a $\pi^0$ resolution of less than 1.0 Mev coupled with a solid angle acceptance in the range of 10 to 20 msr. The device can be used for direct production of reaction $\pi^0$'s or those produced in decay of hypernuclear fragments. In either case, its capabilities lead to a major improvement over the performance of existing spectrometers at BNL and KEK, and the opportunity to explore systems which are mirrors of those already produced via the $(K^-, \pi^-)$ and $(\pi^+, K^+)$ reactions. Truly high-precision hypernuclear spectroscopy requires a large $4\pi$ $\gamma$ detector array for coincidence studies with any of these reactions.

The 2 GeV/c beam line at the AGS (D-6) is capable of delivering intense and relatively pure beams of kaons, antiprotons and pions. It provides about $2 \times 10^6$ negative kaons at 1.8 GeV/c for every $10^{13}$ protons at 24 GeV, with a beam purity in excess of 50% $K^-$'s at 1.8 GeV/c. This $K^-$ flux is about 100 times that available at KEK. The cylindrical detector system (CDS) is a general purpose out-of-beam detector for D-6 being designed and constructed in Japan. It has a large acceptance of ~65% of $4\pi$, good particle identification, and a good momentum resolution of 3 MeV/c (FWHM) at 100 MeV/c. It will be used in the identification of doubly-strange systems by the detection of sequential decay pions.

A new, high-resolution, high-acceptance spectrometer for $(K^-, K^+)$ reactions is urgently needed for exploitation of this beam line for cascade and $\Lambda\Lambda$ hypernuclei. One such spectrometer, dubbed the Strangeness $-2$ Spectrometer (S2S), is under study. The design goals are a solid angle of about 100 msr and a resolution of 1 MeV. This spectrometer will open up exciting opportunities in double strangeness physics at the AGS D-6 Line.

# F Spin Physics

## F.1 Introduction

Spin permeates almost all areas of physics discussed in this white paper. Spin plays a prominent role in QCD, the theory of strong interactions between spin-1/2 quarks and spin-1 gluons. Historically, there have been many examples of how polarization measurements have forced us to change the way in which we view physical processes. It was obvious from the workshops leading up to this white paper that there remain many important open questions in nuclear and particle physics that require further polarization measurements in the hadronic sector. Although the majority of the experiments involve lepton-hadron and hadron-hadron reactions, it should be emphasized that the nucleus further provides a powerful laboratory in which to test the understanding of QCD in a strongly interacting medium.

Attention is focused on issues in which the spin degree of freedom plays the central role, primarily in areas where unexpected polarization effects have been observed at energies above a few GeV. These issues fall naturally into three physics topics; the spin structure of hadrons, polarization tests of symmetry principles, and spin-dependence of hadronic interactions.

The intent is to consider the most important physics issues that need to be addressed and to define the role of hadron facilities in accomplishing those goals. We believe that the physics agenda put forth in this particular area cuts to the very heart of the understanding of the strong interaction and its implications for the quark structure of hadrons. The time is also right for the technology of polarized beams and targets. Recent developments made in the past few years in the acceleration of polarized beams using Siberian Snakes, in polarized ion sources, and in polarized targets, perhaps represent the most outstanding advances in the techniques of nuclear and particle physics. These advances make the field ripe for new discoveries. The keen physics interest in polarization as a tool for the understanding of QCD is also reflected in theoretical developments needed to interpret the results of polarization experiments.

Polarized beams at existing (or soon to exist) hadron facilities such as the Relativistic Heavy Ion Collider (RHIC) at BNL operating in a $\vec{p}+\vec{p}$ or $\vec{p}+A$ configuration, the AGS, the Main Ring Injector and/or Tevatron at Fermilab, and new facilities such as the Light Ion Spin Synchrotron (LISS) at IUCF could provide the necessary beams to carry out the essential experiments.

## F.2 Hadron Spin Structure

The spin structure of nucleons has become a rich and active area of research. Just a few years ago it was thought that the issues and likely answers were clear: that the spin of the proton is carried mostly by its valence quarks, and that the transverse spin structure is uninteresting. Data from the Yale/SLAC experiment scattering polarized electrons from polarized protons seemed to confirm this: certainly at large $x$, the $u$ quark in a polarized proton carries most of the proton spin. However, when the EMC experiment measured the same spin structure functions at low $x$, they observed much less quark polarization than expected. This was the "spin crisis" and it spawned several experiments and theoretical initiatives. Most of all, it made clear how little is known about very fundamental issues – including the proton spin, gluon polarization inside the proton, sea quark polarization, and

transverse spin.

*While our knowledge of the spin structure of the nucleon has been derived primarily from deep-inelastic lepton scattering, most of the questions that remain will require polarized hadron beams.* Longitudinally polarized electrons and muons scattering from polarized nucleon targets measure the quark polarization in the nucleons. It has been recognized that the gluons inside nucleons may be highly polarized, that the sea might have important polarization, and that there is additional fundamental information that can be learned from transverse spin structure functions. The possibility that a large gluon polarization could exist has stimulated discussion of experiments to measure $\Delta G(x, Q^2)$ with hadron probes. Particularly sensitive experiments to measure the gluon helicity distribution can be done utilizing inclusive direct photon production, $J/\Psi$ production, $\chi$ decay, and jet production in polarized $\vec{p} + \vec{p}$ collisions at high energies.

Another explanation of the EMC data is that the sea quarks are polarized. While the prevailing view has been that the most natural state for the $q\bar{q}$ sea in the nucleon is unpolarized, it has been shown that a polarized sea is possible and could explain the data. Here too, this additional information is accessible at hadron facilities. Sea polarization can be probed using Drell-Yan production and $W^{\pm}$ and $Z$ production, also measured in polarized $\vec{p} + \vec{p}$ high-energy collisions. In addition, low-energy neutrino-proton elastic scattering measures the polarized strange quark content of the proton directly.

Since transverse spin effects and longitudinal spin effects are on a completely equivalent footing in perturbative QCD, measurement of $h_1$, the twist-2 chiral-odd transverse spin structure function, is therefore essential to the understanding of the nucleon spin-structure. Deep inelastic lepton scattering in QCD proceeds via only *chirally-even* quark distributions because the quark coupling to the photon and gluon preserve chirality. Therefore, up to corrections of order $m_q/Q$, $h_1(x, Q^2)$ decouples from lepton scattering. There is no analogous suppression of $h_1(x, Q^2)$ in deep inelastic processes such as Drell-Yan with hadronic initial states. Indeed, $h_1(x, Q^2)$ determines the transverse-target, transverse-beam asymmetries in Drell-Yan. The structure functions $h_1, g_1$, and their twist-3 counterparts can all be measured in Drell-Yan experiments with appropriately polarized beams and targets at polarized hadron facilities.

### F.2.1 Hadron Spin Structure: Future Directions

The Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory is planning a polarized proton beam capability that would provide polarized $\vec{p} + \vec{p}$ collisions from center of mass energies from 50–500 GeV with the same luminosity for polarized proton collisions as for unpolarized protons — $\mathcal{L} = 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ at $\sqrt{s} = 500$ GeV. It is planned to install the spin hardware during RHIC construction, so that the spin program will follow closely the first heavy ion run in 1999. The RHIC Spin Collaboration (RSC) proposal has outlined a robust program of spin physics measurements utilizing the STAR and PHENIX detectors at RHIC. The approved physics program includes direct photon, photon + jet, jets, $W$ and $Z$, Drell-Yan, $J/\Psi$, and $\chi$ probes, and both longitudinal and transverse polarization. Polarized beams at RHIC and upgraded detectors will therefore provide the ideal facilities for the polarized structure function program described here.

Acceleration and extraction of 120 GeV polarized protons from the Fermilab Main Injector (FMI) into external experimental areas has been considered in detail by the SPIN collaboration at Fermilab. A solenoidal partial Siberian snake is required in the Booster

along with two pulsed RF quadrupoles. The FMI requires two Siberian snakes, for which the required space has been provided in the construction project. Total cost of the polarized external 120 GeV beam capability is estimated at about $8 M.

Polarized beam operation of the FMI is compatible with its primary task of providing antiprotons for the antiproton accumulator. In this operational mode, one high-intensity Booster batch is fast extracted for pbar production, while five Booster batches of polarized beam would be slow extracted with a 0.5–1.0 second flattop to external beam transport. Other uses of the FMI beam, e.g., neutrino or kaon production, would not be compatible with simultaneous operation for polarized beam.

The violation of the Ellis-Jaffe Sum Rule observed by the EMC has raised significant issues on the role of strange quarks in the nucleon. The neutral weak axial vector form factor, $G_1^s(0)$, of the nucleon is directly sensitive to strange quark contributions to the nucleon spin. This form factor is measurable in neutrino-nucleon elastic scattering. It has the added advantage that it does not require the use of $SU(3)$ symmetry to extract the isosinglet contribution nor is any extrapolation to $x = 0$ required. The LSND experiment at LAMPF will measure $G_1^s(0)$. Future direction in this area include a new neutrino detector at Fermilab or BNL to accurately map out the $Q^2$ dependence.

## F.3 Discrete Symmetries

### F.3.1 Parity Violation

Measurements of parity-violating longitudinal asymmetries in $\vec{p}$-induced reactions provide a unique window on the interplay between the weak and strong interactions between and within hadrons. They are complementary to studies of parity-violating $\vec{e}$-$p$ asymmetries, the next generation of which focus on constraining the contributions of strange sea quarks to proton form factors.

It is very important to measure parity-violation in hadronic processes induced by multi-GeV polarized protons at a minimum of three distinct energies. First, a new measurement near 6 GeV/$c$ should be initiated to verify the unexpectedly large result ($A_L^{\rm tot} \simeq$ few $\times\ 10^{-6}$) obtained in the one previous $\vec{p}$-$p$ measurement above 1 GeV (Lockyer et al. at the ZGS). It should be noted that no clear weaknesses have been identified in the ZGS experiment. The one viable theoretical explanation offered to date for an effect much stronger than $10^{-7}$ attributes an important role to weak interactions within a vector diquark from one proton as it interacts with a quark from the second proton. Although the applicability of this model at the small $p_\perp$ sampled by the experiment remains controversial, the calculation suggests how parity violation results may offer powerful constraints on models of the strong interaction in this non-perturbative QCD regime.

Secondly, although the model described above cannot predict the absolute value of $A_L^{\rm tot}$, it does predict a very strong dependence on bombarding energy. A test is needed of this prediction, via a measurement well above 6 GeV/$c$. The parity violation test is an important part of the proposed program for LISS, and may also be studied at KEK, the AGS, MRI, and RHIC.

At collider energies, the opportunity exists to observe very large parity-violating one- or two-spin asymmetries in electroweak processes — $W^\pm$, $Z$, or Drell-Yan dilepton production — in $\vec{p}$-$p$ or $\vec{p}$-$\overline{p}$ collisions at facilities such as RHIC and the Tevatron. These asymmetries should be firmly predictable based on the Standard Model and $q, \overline{q}$ spin structure functions available from other experiments. An experimental test of these predictions, requiring $\vec{p}$

capability at a collider, is extremely important.

At energies $\sqrt{s} \geq 0.5$ TeV, parity violation in inclusive hadron or jet production in $p$-$p$ or $p$-$\bar{p}$ collisions offers a way to reveal effects of possible quark substructure. Such measurements might provide uniquely sensitive limits on distance scales of any such substructure.

Finally, several new $\vec{p}$-$p$ parity violation experiments are being prepared for the immediate future at TRIUMF and COSY, at energies near or below 1.5 GeV. These should be pursued with high priority, as they will add needed new constraints on the set of six effective weak meson-nucleon coupling constants used to characterize the weak interaction between hadrons at relatively low energies.

All of the hadronic parity-violation experiments require extremely high precision, and will place unparalleled demands on the stability and control of accelerator performance with polarized beams. It is therefore essential that their demands be taken into account in accelerator design considerations, and that frequent access to polarized beam operation be available during the debugging stages of the experiment. Siberian Snakes will be a central component in accelerating polarized beams of adequate quality. For the fixed-target experiments, the use of a Snake in conjunction with a stored beam and pure internal $H_2$ target, offers a novel environment for parity measurements, with exciting possibilities for the cancellation of systematic errors.

### F.3.2 Time Reversal Invariance

Another interesting symmetry test accessible by precise measurements of the spin-dependence of stored beam life times in a storage ring is a search for parity-even, time-reversal-odd interactions. The best current experimental limits on such interactions are $\sim 10^{-4}$ of strong interaction amplitudes. A true null test for such interactions can be performed by determining the spin-flip sensitivity of the total cross section for polarized protons incident on a tensor-polarized deuterium target (e.g., when the beam polarization is sideways and the deuteron spin alignment axis is midway between vertical and longitudinal). For such an experiment, the use of pure, gaseous polarized deuterium, stored in a windowless cell, offers significant advantages over cryogenic alternatives based on deuteride compounds. It seems feasible to improve existing limits on P-even, T-odd interactions by 1–2 orders of magnitude. Such a time reversal invariance test is currently being prepared at COSY.

### F.3.3 Discrete Symmetries: Future Directions

Measurements of parity-violation in $\vec{p}$-$p$ scattering with longitudinally polarized beams could be made in the energy region of tens of GeV at facilities as LISS, the AGS, and the Main Ring Injector. At collider energies very large parity-violating one- and two-spin asymmetries in electroweak processes in $\vec{p}$-$p$ or $\vec{p}$-$\bar{p}$ collisions could be studied at facilities as RHIC and the Tevatron.

The study of time reversal invariance could be made through measurements of the spin-flip sensitivity of the total cross section for polarized protons incident on a tensor-polarized deuterium target in a storage ring facility as LISS.

The study of CP non-conservation in other systems that the kaon system can be made through comparison of decay asymmetries in hyperon non-leptonic decays. Such measurements can be made at a SuperLEAR facility and at Fermilab.

## F.4 Spin-dependence of Hadronic Interactions

Quantum Chromodynamics (QCD) has the proper symmetries and general features to be the correct underlying theory of the strong interaction. Unfortunately, we do not yet know how to make reliable calculations within QCD for any but the very highest momentum transfers, where a perturbative approach can be successfully applied. Understanding how this theory is realized in the non-perturbative regime is one of the great challenges facing nuclear and particle physics in the coming decades. Existing experimental results suggest that the spin-dependence of hadronic interactions carry essential clues about this realization. For example, the chiral symmetry of QCD leads to the expectation that single-spin asymmetries will vanish asymptotically in hard quark-quark collisions. In marked contrast to this expectation, sizable polarization effects have been commonly found in hadron-hadron collisions, including both inclusive and exclusive processes, at the highest energies and momentum transfers yet probed. Although these polarization experiments are typically neither large, costly, nor long running, their data are scattered because of the lack of appropriate hadron beam time at existing accelerators. Many experiments using spin to probe the strong interaction simply need good quality, general purpose, high intensity hadron beams. In some cases they require neither polarized beams nor polarized targets. In addition, recent advances in the technology of accelerating polarized beams, polarized sources, and polarized targets now make systematic studies of the spin dependence feasible in those cases where polarized facilities are needed.

Because the goal is to understand the non-perturbative region in which the common manifestations of the strong interaction reside, experiments must span the kinematic region between non-perturbative and perturbative QCD. Important measurements of hadronic spin-dependence include a broad range of energies and momentum transfers. We illustrate this by two examples.

The results of low- and intermediate-energy nuclear physics experiments suggest that meson exchange is a successful approximation for the effective interaction characterizing the strong interaction in this kinematic region. It is not clear, however, that meson exchange models are generally useful in the entire non-perturbative regime of QCD. In particular, the viability of meson exchange as a low-energy realization of QCD for hadrons with *strange* or *charmed* valence quarks remains an open question. There exist few measurements of the scattering of heavy baryons from nucleons, and *absolutely no polarization measurements.* Spin-dependent features of hyperon-nucleon scattering, including the $^3S_1$ versus $^1S_0$ $\Lambda N$ and $\Sigma N$ scattering lengths, can be inferred by studying final-state interactions in exclusive hyperon production reactions induced by polarized nucleon beams on a polarized hydrogen target. Such measurements would also test charge symmetry in the strange sector by comparing $\vec{\Lambda}\vec{n}$ to $\vec{\Lambda}\vec{p}$ scattering.

At much higher momentum transfers, it is important to determine the kinematic behavior of polarization effects in inclusive and exclusive hadron scattering, both in free space and inside nuclear matter. For example, do the large asymmetries observed to date in $pp$ elastic scattering and in inclusive hyperon production persist at higher momentum transfers, or does one begin to see an approach toward the asymptotic perturbative QCD expectations? Predictions of "color transparency" suggest that the effective onset of the perturbative QCD regime may occur at lower energies *inside* than outside nuclei because the nucleus preferentially transmits scattered hadrons that have undergone a hard collision.

### F.4.1 Spin-dependence of Hadronic Interactions: Future Directions

Understanding the origin of spin effects in the strong interaction will require a systematic study in both inclusive and exclusive reactions, and at both intermediate and high energies. At the lower end of the energy scale, 1–30 GeV polarized nucleon beams at facilities such as the AGS, the Fermilab booster, or the proposed LISS accelerator could provide access to the short-range baryon-baryon force in a regime where meson-exchange models may no longer provide an effective basis for their description. In this kinematic region, strangeness- and charm-production channels are opening.

Investigation of spin effects at higher transverse momentum transfer requires both unpolarized and polarized high-intensity hadron beams from the Tevatron, the Fermilab Main Injector, and in the RHIC collider. The higher luminosities accessible in fixed-target experiments at the FMI would be needed for polarized beam and target exclusive reaction measurements, while collider energies at RHIC could allow the first polarization studies of hard collisions signaled by inclusive jet production.

## F.5 Recommendations/Conclusions

1. Polarized beams at RHIC would make possible an essential part of the proposed investigations of spin in hadronic interactions in the perturbative QCD regime.

2. Polarized beams at the new Main Injector and Tevatron at Fermilab, and the continued operation of fixed-target, polarized beams at the AGS would provide further opportunities for the exploration of the spin-dependence of hadronic interactions in the non-perturbative QCD regime. The construction of a polarized beam storage ring (LISS) to be used with internal targets at IUCF offers the possibility of a dedicated facility for precision spin studies.

3. Further neutrino-proton elastic scattering measurements may be needed to better define the strange quark contribution to the nucleon spin. These might be done at LAMPF, Fermilab, or BNL, depending on the future of the neutrino programs at those laboratories.

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