HADRON PHYSICS
in the 21st CENTURY

A Planning and Physics Opportunity Study

for Near-Term Experiments in Hadron Physics

Report of the Special Workshop

held at the

George Washington University Research Campus

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Foreword

On March 27-29, the Special Workshop entitled "Hadron Physics in the 21st Century" was held on the Research Campus of George Washington University near Washington, D.C. It was decided that a White Paper which focussed on a near-term opportunity would be produced. To have sufficient consideration in the budget preparation exercises of funding agencies, the Paper would have to be produced expeditiously with a deadline of July 1. For coherence and in order to serve a common objective, the individual contributions of the various subgroups have been edited into an overall document.

The following people contributed to the preparation and/or review of the materials in this White Paper. They are listed with their institution along with the areas of their principal interest.

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Executive Summary

With the recognition that 1998 might be the last year for experiments in the area of medium energy physics at the AGS, the Special Workshop "Hadron Physics in the 21st Century" was organized to consider future options. With about two months notice, over 70 people from around the world gathered on the Research Campus of George Washington University near Washington, D.C. on March 27-29 to discuss the future of a crucially important field: *Hadron Physics*.

The hadron physics program in the United States with electron and photon beams is well provided for in the near term by the experimental programs being carried out at DOE's Jefferson and Bates Laboratories. Exploring the realm of quarks and gluons with heavy ions will be provided by RHIC. A corresponding program with hadron beams is also required to provide a proper scientific balance. Although an appropriate facility would be the AGS, it is scheduled to become the injector to RHIC in 1999. This recommissioning makes the future of non-perturbative QCD physics with hadron beams in the U.S. very uncertain. The only new hadron-beam research center in the field, the Japanese Hadron Facility (JHF), is still in the planning stage and will not become available until well into the next decade.

The Special Workshop highlighted the vital role that hadron physics has in developing the understanding of QCD in the strongly interacting regime, in the determination of many of the input parameters of the Standard Model and QCD, and in performing crucial precision tests of these theories. Non-perturbative QCD physics is concerned with the quantitative understanding of the strong interaction and hence underpins much of the research in other areas of nuclear and particle physics. Important issues and continued research in this energy domain, primarily at the AGS, were the focus of the meeting. They are also the subjects of this paper. Although many other important subjects in hadron physics were not covered, discussion was given to follow-up initiatives, where they could be addressed.

The fundamental particles and interactions in nature are currently described by the Standard Model. The sector of strong interactions is described by QCD. Many important and fundamental issues in non-perturbative QCD remain to be understood and resolved. Among them are the following interrelated issues.

- *What is the connection between QCD and the strong force as manifested in nature?*
- *What is the mechanism of confinement?*
- *What is the role of strangeness in hadronic matter?*

A consensus emerged at the Workshop that both a short-term and a long-term strategy were needed for the continuation of a world-class program with hadron beams in the U.S. It was recognized that the main short-term emphasis should be to preserve and strengthen the hadron physics program at the Brookhaven AGS by supporting a small series of high-profile experiments, partly with existing detectors. The long-term program would be developed later. It could include upgrades of existing detectors to provide new capabilities, construction of a few new devices with an eye on their possible use at the JHF, and opportunities at other hadron-beam facilities such as Fermi Lab. This paper is devoted to the short-term program, partly in terms of the experiments already approved at the AGS and partly in terms of new initiatives there. These experiments will address:

- *Searches for new types of baryonic matter.*
  Highlights of a program in baryon spectroscopy include measurements of (1) the radiative decays of the $\Lambda(1405)$ hyperon because it is a unique candidate for a meson-nucleon bound state; and (2) all neutral decays of the $\Sigma(1750)$ for a similar reason.

- *Searches for new types of mesonic matter.*
  Recent evidence for the existence of exotic mesons compels searches for additional candidates and elucidation of the implications for QCD. New techniques with $\overline{p}$ beams and existing apparatus at the AGS can be exploited advantageously.

- *Studies of hyperon interactions and decays, and strange nuclei, by using the s quark to delineate the role of quark flavor in hadronic matter.* Ground-breaking experiments that are already approved and which have the potential to open up new fields of research should be completed. A unique opportunity is available only at the high-intensity AGS D6 line for studies in the $S = -2$ sector. Light hypernuclear non-mesonic decay experiments can test the ΔI $= 1/2$ rule.

- *Precision measurements of important, rare, and forbidden kaon and eta-meson decays.*
  The $K^+ \to \pi^0 e^+ \nu$ decay can be used to determine V_{us}, the second element of the CKM matrix. Together with V_{ud}, this term allows a novel test of the Standard Model that is sensitive to the possible existence of supersymmetric particles. The $\eta \to \pi^0\gamma\gamma$ rate and spectrum will test χPT to order p^6. Several C- and CP-violating decay modes of the η can be studied.

Elements of this experimental program have important bearing on other fundamental quantities in physics, primarily through the "hadronic corrections" that must be made to experimental results. They are also an essential complement to the success of the research programs at RHIC and JLab. An estimate of costs at the AGS, as additional contributions to the expected support for fixed-target operation from DOE-HEP, is a few million dollars per year.

A hadron physics facility which could produce more intense beams of secondary particles and utilize new technologies has been discussed and promoted for many years. With construction and installation activities at JLab and RHIC almost finished, greater attention can be given to enhance hadron physics facilities. It now appears that the High Energy program office of DOE will maintain a base level of support for fixed-target AGS operations, in order to carry out some highly important experiments. Under these circumstances, a modest increment of funding from the Nuclear Physics program office for other key experiments at an existing facility is thus a highly leveraged and cost-effective investment.

I. Introduction

The structures that can be formed from the interaction of elementary quarks and gluons are, at this time, the most fundamental and represent the frontier of challenges to the human understanding of nature. Research in the patterns of hadrons led to the hypothesis of quarks, later demonstrated in experiment, and also to the discovery of the "color" degree of freedom in their interactions. The corresponding theory of quantum chromo-dynamics (QCD) has accounted well for many known features of the "strong" or "hadronic" nuclear interaction.

Except at the highest energies, which for the most part are not naturally available, strongly interacting matter has an intrinsic feature that sets it apart from other interactions, which is the diverging strength of the unshielded strong force at large distances. The highly non-linear (and non-Abelian) character of the strong interaction precludes traditional perturbative methods which are so fruitful in many other fields of science. This non-perturbative QCD domain poses a new frontier of intellectual challenges. Progress will likely be achieved by carefully elucidating patterns, testing and honing theoretical techniques or developing entirely new ones, and great inspiration.

II. Basic Issues in non-Perturbative QCD

The fundamental particles and interactions in nature are currently described by the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ Standard Model (SM). This model has many input parameters, the 17 most important of which are: the masses of the three charged leptons, the six quarks, and the Higgs boson, four parameters which characterize the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, and three couplings (one for each symmetry group). The neutrino masses are assumed to be zero, where now recent evidence would suggest additional parameters.

The up (u) and down (d) quarks are special because of their abundance; except for the possible masses of neutrinos, these quarks and their dynamical interactions contribute over 99% of the observed mass of the universe. Surprisingly little is known about these quarks. Whereas, for example, the masses and magnetic dipole moments of the e and μ leptons have been measured accurately and their electroweak interactions can be calculated with precision, the masses of the u and d quarks are uncertain by a factor of two or more. In addition to being fundamental parameters for QCD, the light quark masses play an important role in isospin and $SU(3)$ symmetry breaking as well as in the effects of pseudoscalar meson mixing, and therefore need to be determined more precisely. In spite of a presumed intrinsic quark/antiquark symmetry, quark systems in the universe exceed antiquark systems by at least ten orders of magnitude.

Many important and fundamental issues in non-perturbative QCD remain to be understood and resolved. Among these issues are the following interrelated questions:

- *What is the connection between QCD and the strong force as manifested in nature?* The u and d current-quark masses of a few MeV in the QCD Lagrangian differ substantially from their constituent masses in hadrons. As another example, a significant fraction of the spin of the proton arises from components other than the constituent quarks. The gluons must have a large role in hadrons. What is the process of hadronization and how much do the gluons contribute to the physical properties of hadronic structures?

- *What is the mechanism of confinement?* With two possible exceptions in the meson domain, the quark combinations $q\overline{q}$ and q^3 are (to date) the only ones known in nature. But other color singlet configurations (glueballs, hybrids, $q^2\overline{q}^2$ mesons, dibaryons, pentaquarks, strangelets, etc.), are also possible. Where are they? If such states are not seen at a sensitive level, what are the implications for the modeling of confinement?

- *What is the role of strangeness in hadronic matter?* Because the current mass of the strange quark is about 25 times that of the u or d quark, its role in the nucleon is anticipated to be small. Nevertheless, there are indications of the possibility of up to ($\sim$20%) contributions of the strange quark to the proton's spin. There are significant implications regarding the nucleon within an extended nuclear medium. In addition, understanding strangeness in hyperons as well as in hypernuclei is helpful for unraveling the dynamics of quarks and gluons in matter as we know it.

These issues are commonly addressed through the use of models and effective Lagrangians. What symmetry principles should be utilized? What are the effective degrees of freedom? What features will provide the best description and foundation for further insight? Some of the implications of QCD are being explored directly through lattice gauge calculations. In addition, two main phenomenologies have emerged in the treatment of hadrons. One is the quark model which has wide appeal because of its similarity to other quantum mechanical structures (nuclei, atoms, etc.). It also has had much success in describing many known features of hadrons. The other treatment involves Chiral Perturbation Theory (χPT), which is a low-energy effective field theory for momenta of the order 100 MeV.

Chiral Perturbation Theory in Nuclear and Particle Physics

The evaluations of many of the key parameters or "constants" of other areas of physics require that hadronic corrections be applied to the experimental results. Examples include the electromagnetic fine-structure constant α_e, the strong coupling constant α_s in the perturbative large-Q^2 domain, and the muon g-2 factor. Chiral perturbation theory is emerging as the theory of choice for such hadronic corrections due to three of its features. *i*) It includes *all* interactions with the observed symmetry pattern while making minimal assumptions about the strong interaction dynamics. A certain combination of the parameters corresponds to the Standard Model, and other combinations to extensions of the SM. *ii*) It is a theory for all of hadronic physics. *iii*) It makes use of a systematic expansion in momenta. At any given order, predictions with plausible error estimates can be made.

χPT is a unique tool for extraction of certain SM parameters. For example, model-independent ratios of light quark masses can be found precisely with experimental input. Currently the largest input uncertainty is the decay rate $\eta \rightarrow 3\pi$. Because electromagnetic corrections to this decay are strongly suppressed, this process is also the best place to pin down the ratio $(m_u - m_d)/(m_u + m_d)$, which is important in the hadronic corrections to the measured K_{e3} decay rate.

In order to obtain electroweak parameters, one needs as input those parameters of the chiral Lagrangian that correspond to strong interactions. The latter carry information about the structure of QCD, and can in principle be determined from lattice calculations. Their determination will also provide clues about QCD dynamics. Some examples include:

1. The strangeness content of the nucleon, accessible through the πN sigma term and other low-energy parameters after corrections for isospin symmetry breaking.

2. The magnitude of $SU(3)$ breaking, which is related to the KN sigma term, the kaon potential in nuclear matter, the equation of state in neutron matter, and the proton-spin problem.

A variety of experiments are possible for testing the reliability of χPT. Examples include:

1. $\pi\pi$ scattering near threshold through peripheral $\pi N \to \pi\pi N$ scattering, K_{e4} decay, and pionium.

2. Convergence in $\overline{K}N$ scattering is affected by the presence of the $\Lambda(1405)$, depending on whether the latter is introduced as an elementary field or reproduced as a bound state; $\overline{K}N$ scattering and radiative decays of the $\Lambda(1405)$ can help to decide the issue.

3. Some nucleon parameters in the chiral Lagrangian can only be obtained by using nuclear targets — for example, the deuteron as a neutron target — so one needs a consistent treatment of one- and few-nucleon effects. Empirical information on the pion-exchange of the NN potential, some πN parameters, and a $3N$ potential can fruitfully be compared with χPT. Extensions to hyperon systems are also possible.

Tests of this paradigm require a vigorous, dedicated experimental and theoretical program. In the meson sector the theory is mature, but more accurate experiments are crucial. In the baryon sector, theory is developing to meson standards, but advance is hampered by lack of threshold data. In the many-nucleon sector, more quantitative calculations are needed to match the rich database and upcoming hypernuclear data.

III. Baryons

- *Searches for new types of baryonic matter.*
  Highlights of a program in baryon spectroscopy include measurements of (1) the radiative decays of the $\Lambda(1405)$ hyperon because it is a unique candidate for a meson-nucleon bound state; and (2) all neutral decays of the $\Sigma(1750)$ for a similar reason.

Quark confinement is a most perplexing phenomenon. Lattice gauge calculations and effective Lagrangian models are being used in many efforts to understand it. Specific quark models generally use a spin-dependent quark-quark interaction that is patterned after the effects of gluon exchange in QCD. The masses of the constituent quarks in these models are quite different from those of the current quarks of QCD; *e.g.*, $m_u(\text{constituent}) \approx 335$ MeV$/c^2$, while $m_u(\text{current}) \approx 5$ MeV$/c^2$. Several specific problems dominate the phenomenology of quark confinement including the non-observation of diversity in quark systems and the issue of "missing resonances."

"Diversity" of the Quark Systems

In addition to the simple three-quark states, confinement of color singlets in QCD allows for the possibility of "diversity" in the form of other types of baryonic matter, for instance pentaquarks, meson-nucleon bound states, hybrids containing gluons, and dibaryons, although it is not yet known whether the dynamics of QCD actually can lead to a realization of this possibility. One can expect both quarks and gluons to be constituents of these states. Yet no direct evidence for a role of gluons in baryonic matter has been reported. The recent evidence of an exotic meson as a candidate for a hybrid meson is certainly encouraging.

An important tool for elucidating the confinement phenomenon is the search for exotic hadrons. Some baryon resonances of interest in this regard are possible hybrid baryon candidates such as the $P_{11}(1440)$ Roper resonance and (perhaps) the $P_{11}(1710)$ and $P_{13}(1720)$; the $\Lambda(1405)$ hyperon, which is a candidate for a meson-nucleon bound state; and the $\Sigma(1750)$ resonance, for a similar reason. Recent flux-tube calculations instead predict the lightest hybrid baryons to be near 2 GeV. The properties of these states need to be clarified by experiment in order to resolve some of the issues.

Baryon Families

All models of baryon structure predict the existence of many more states than are known experimentally. In particular, there are far fewer strange hyperons compared to non-strange baryons. Part of the problem may result from the previous limitations of probes, such as kaon beams with inadequate fluxes. In addition, the likelihood that many of the N^* and Δ resonances could be very broad and might overlap each other substantially makes distinct identification difficult. More subtle causes, based on features of the underlying physics, are the following.

1. Because some resonances do not couple sufficiently strongly to standard production channels, they may not have been detected in past experiments. Searches for N^* and Δ resonances that couple more strongly to the photon channel are being pursued at Jefferson Lab (JLab).

2. There may be symmetries, either not yet discovered or not yet fully implemented, that exclude the existence of particular states. Some possible examples are chiral symmetry, diquark symmetry, and various dynamical symmetries. A good way to discover such symmetries is to search for "new" regularities in the hadron spectra. Activities along these lines are underway at the AGS.

3. It seems plausible that, in addition to the conventional q^3 baryons, there are hybrid baryons or multiquark systems such as meson-baryon molecules. A rich spectrum of baryon exotica might be found in high-statistics experiments.

An Intriguing Baryon State

The well-established $J^P = \frac{1}{2}^-$ $\Lambda(1405)$ hyperon vies for the distinction of being one of the most interesting resonances. To some it must be a $\overline{K}N$ bound state; to others it is the first allowed $SU(3)$-singlet q^3 state with a depressed mass. Each explanation suffers from some serious problems.

If the $\Lambda(1405)$ is a strongly bound $\overline{K}N$ state, there must exist a hitherto undetected "other" $J^P = \frac{1}{2}^-$ Λ resonance with a mass around 1520 MeV/c^2 as the required $SU(3)$-singlet q^3 state. If, instead, the $\Lambda(1405)$ is the $SU(3)$-singlet uds state, it nevertheless is strongly coupled to the S-wave $\overline{K}N$ channel. It must also be paired with the $J^P = \frac{3}{2}^-$ $\Lambda(1520)$ state and be mass-degenerate with it. The quark models must then have a large spin-orbit coupling to push the mass of the $\frac{1}{2}^-$ state down, a feature not seen elsewhere. Other $J^P = \frac{1}{2}^-$ baryons that would make up the octet which must go with the $\Lambda(1405)$ singlet include the $N^*(1535)$. However, the $\Lambda(1405)$ is 130 MeV/c^2 lighter than the $N^*(1535)$ even though it contains an s quark which is 100–150 MeV/c^2 heavier than the d quark.

Even if the $\Lambda(1405)$ is a bound $\overline{K}N$ state with a binding energy of $Q = -30$ MeV, it is not a stable particle because $\Sigma\pi$, $\Sigma\gamma$, and $\Lambda\gamma$ decays are allowed. Its nature can be better understood through studies of its radiative decays, specifically the ratio $\Gamma\{\Lambda(1405) \to \Lambda\gamma\}/\Gamma\{\Lambda(1405) \to \Sigma^0\gamma\}$ as a function of the Q value in the range -30 MeV $< Q < +30$ MeV. A thorough search for the alternative new $J^P = \frac{1}{2}^-$ Λ state with a mass near 1520 MeV/c^2 is also important. Careful measurements of the angular distributions of the various neutral final states, specifically of $\Lambda\,2\pi^0$ and $\Sigma^0\pi^0$ as produced in K^-p interactions, can be made with the Crystal Ball spectrometer at the AGS.

It is a remarkable fact that the ηN and $\eta\Lambda$ s-wave scattering lengths are large and attractive. This result has led to speculations about the existence of other meson-nucleon bound states. It has been proposed that the $\eta\Sigma$ scattering length is large and attractive as well, and that it is connected to the properties of the $\Sigma(1750)$ resonance. This speculation can be tested through measurements of the neutral final-state decays of the $\Sigma(1750)$.

IV. Mesons

- *Searches for new types of mesonic matter.*
  Recent evidence of the existence of a gluonic hybrid compels searches for additional candidates and elucidation of the implications for QCD. New techniques with $\overline{p}$ beams and existing apparatus at the AGS can be exploited advantageously.

A meson is nominally a bound state of a quark (q) and an antiquark ($\overline{q}$). But QCD also allows for more complicated color-singlet states, in which a meson may consist of a multiquark state (two or more pairs of $q\overline{q}$), or a gluonic hybrid ($q\overline{q}$ + gluon). Although it now appears that light multiquark states most likely exist only as weakly bound or unbound combinations of simple $q\overline{q}$ and q^3 systems rather than as single hadronic resonances, other exotic mesons remain possible. In certain cases, they can be identified by "exotic" quantum numbers that are not allowed for $q\overline{q}$ systems.

Glueballs and Hybrids

Theoretically allowed color-singlet states can be formed from gluons, either as pure glue states called "glueballs" or in combination with quarks, such as $q\overline{q}g$ "hybrid mesons" and q^3g "hybrid baryons." The physical states will of course be mixtures of these idealized basis states, including quark-model basis states when these have identical quantum numbers.

Lattice gauge calculations predict a scalar (J^{PC}=0^{++}) pure glue state at about 1.6–1.7 GeV. Next in mass are a 0^{-+} and a 2^{++} state at about 2.2–2.3 GeV. No glueballs with exotic quantum numbers are predicted below about 3 GeV. Thus, glueball searches may encounter significant mixing with $q\overline{q}$ meson states, especially the broad I=0 $n\overline{n}$ ($n = u$ or d) and $s\overline{s}$ states in the 1.3–1.5 GeV region. A candidate scalar glueball, the $f_0(1500)$, was reported by several LEAR experiments at CERN (ca. 1994). This state is surprisingly narrow for a 1.5-GeV 0^{++} hadron, which may be consistent with its being a glueball. Because glueballs are the most unusual hadrons predicted by QCD and are the most important for comparison with theoretical calculations, establishing the spectrum and properties of these states is of the highest priority. In addition, the "background" of conventional $q\overline{q}$ mesons must be well understood.

The mass of the lowest $J^{PC} = 1^{-+}$ gluonic hybrid is predicted in various theoretical models to be between 1.4–2.1 GeV, with lattice-gauge and the flux-tube model preferring the higher masses. Although very recent results from the AGS suggest that J^{PC} exotics occur in nature, the observed masses and decay modes differ significantly from most theoretical expectations. The exotic hybrid mesons are expected to couple most strongly to decay channels of the type $(\overline{q}q)_S + (\overline{q}q)_P$, such as $f_1\pi$ and $b_1\pi$, which lead through sequential decays into rather complicated final states and therefore have received only recent attention. The channels in which the exotics are actually reported, $\eta\pi$ and $\rho\pi$, are something of a surprise, as are also the light exotic masses. Of course these $(\overline{q}q)_S + (\overline{q}q)_P$ modes are also expected, albeit with reduced couplings. It is clear that the search for exotic mesons and gluonic excitations is at an early stage, and we are already faced with surprising results that do not accord well with theory. High-statistics studies of the various open decay channels for hybrid candidates, with careful subsequent partial wave analyses, should be very useful for clarifying the puzzling results in this field.

Meson Spectroscopy

The spectrum of ordinary mesons is far from complete, and it must be well understood if exotic states are to be found in its midst. Only about half of the $q\overline{q}$ states expected below 2.1 GeV are known. We should also note that a very fundamental aspect of QCD, the mechanism of strong decays, is also not well established. Current decay calculations of $q\overline{q}$ mesons and q^3 baryons assume $q\overline{q}$ pair production with S=1, L=1, J=0 (vacuum) quantum numbers, the "$^3P_0$ model." Why this model works, and what it has to do with QCD, is unknown. Further clues regarding the QCD decay mechanism should come from studies of the decays of mesons into channels with several amplitudes, which are very sensitive to the quantum numbers of the produced pair. It is surprising that this very fundamental problem, the mechanism of strong decays, has not received more attention.

Novel Search for Exotic Mesons

The direct s-channel formation of mesons via $\overline{p}p$ reactions can limit the identification of exotic mesons. However, u-channel formation is also possible. Consider, for example, a baryon-exchange reaction

$$\overline{p} + p \to X^0 + \eta, \quad X^0 \to \pi^{\pm}\rho^{\mp}, \quad \rho^{\mp} \to \pi^{\mp} + \pi^0 \tag{1}$$

in which the X^0 meson is formed by virtual p or $N^*(1535)$ exchange from the proton to the antiproton, leaving an eta meson. It is clear that the meson-formation vertex corresponds to

$$\begin{aligned} \overline{p} + p(\text{virtual}) &\rightarrow X^0 \rightarrow \pi^\pm\rho^\mp \\ \overline{p} + N^*(1535)(\text{virtual}) &\rightarrow X^0 \rightarrow \pi^\pm\rho^\mp. \end{aligned} \tag{2}$$

It is not known which of the two virtual particles in (2) dominates the X^0 production, but the $N^*(1535)$ exchange is expected to be substantial because the branching ratio for $N^*(1535) \rightarrow p + \eta$ is in the 30–55% range.

From Regge phenomenology, the quantum numbers allowed for the X^0 vertex can be determined in the limit in which the virtual particle becomes an on-shell physical state. In this limit, the initial state $\overline{p}p$ is the same as a $\overline{q}q$, and so the J^{PC}-exotic states should be absent in the s-channel. However, the $\overline{p} + N^*(1535)$ initial state is *not* an eigenstate of C, so that J^{PC}-exotic states are now allowed. For example, assume that $\overline{p}$ ($J^P = \frac{1}{2}^-$) and $N^*(1535)$ ($J^P = \frac{1}{2}^-$) are in a relative P-wave and that the total intrinsic spin is zero, i.e. $S = 0$. Then, the state X^0 produced in the s-channel can be both $J^{PC} = 1^{--}$ and $J^{PC} = 1^{-+}$. Of course, the latter cannot be a $\overline{q}q$ state. Studies of such processes can be made by combining the charged-particle detection capability of the Multi-Particle Spectrometer with the neutral-particle capability of the Crystal Ball spectrometer at the AGS.

V. Strangeness in Nuclear Physics

- *Studies of hyperon interactions and decays, and strange nuclei, by using the s quark to delineate the role of quark flavor in hadronic matter.* Ground-breaking experiments that are already approved and which have the potential to open up new fields of research should be completed. A unique opportunity is available only at the high-intensity AGS D6 line for studies in the $S = -2$ sector. Light hypernuclear non-mesonic decay experiments can test the $\Delta I = 1/2$ rule.

Strangeness nuclear physics includes studies of baryon-baryon interactions and hadronic structures. The baryon-baryon force is responsible for an essential part of the structure of matter in the universe, both ordinary nuclear matter and the hypothetical strange matter (strange hadronic or strange quark matter). Hadronic beams provide opportunities for studies of hypernuclei, and also for strong two-body interactions through free hyperon-nucleon (YN) and hyperon-hyperon (YY) scattering as well as hyperon-antihyperon production.

This physics is important and relevant to current research in subatomic physics for several reasons. Strangeness as a new degree of freedom represents an extension and enrichment of conventional nuclear physics. Relaxing the constraints of the Pauli principle for the hyperon as a distinguishable (from the nucleon) particle allows for new dynamical symmetries. Many interesting questions in non-perturbative QCD and also in weak interactions can be examined in this field. Among them are $SU(3)$ symmetry breaking of the baryon-baryon interaction, ΛN-ΣN and $\Lambda\Lambda$-ΞN mixing, quark-gluon vs. boson-exchange pictures, non-traditional hadrons such as the H dibaryon, charge symmetry breaking, spin-dependent effects that are quite different from those of the nucleon, novel weak non-leptonic baryon-baryon interactions, and parity-violating asymmetries in weak hypernuclear decays. The role of the Λ in nuclear structure has been established, and very recently isospin has been shown to be a good quantum number in low-mass Σ-hypernuclei. Very little is known about $S = -2$ systems, but new experimental opportunities now exist.

$S = -1$ Systems

The short lifetime of the hyperons and the resulting lack of lower-energy hyperon beams has resulted in a very poor database for hyperon-nucleon scattering. At the same time hypernuclei have now been exploited for several decades as the premier laboratory for studies of the effective hyperon-nucleon interaction. Gross features and systematic trends of the Λ bound to nuclei have been established. Recent Λ-hypernuclear investigations have focused on higher resolution spectroscopy. Improvements in energy resolution can be achieved by the use of better spectrometers and/or beamlines for (K^-, π^-), (π^+, K^+), or (K^-, π^0) reactions. The current state of the art is the SKS spectrometer at KEK with an excitation energy resolution of about 2 MeV (FWHM).

High resolution is indispensable for elucidating the spin-dependent components of the effective ΛN interaction, *i.e.*, the spin-orbit, spin-spin, and tensor parts. In sharp contrast to the case for nucleons, the Λ spin-orbit interaction is known to be small but the exact value remains to be determined. A major leap forward in resolution (into the keV region) can only be achieved via the detection of de-excitation gamma rays between particle-stable hypernuclear levels in $(K^-, \pi^-\gamma)$ or $(\pi^+, K^+\gamma)$ coincidence experiments. The feasibility of this technique has recently been demonstrated with NaI detectors at BNL. A new detector, the recently completed Japanese Ge-Ball, is expected to provide dramatic improvements. The first use of the Ge-Ball is planned for BNL (E930) in late 1998, while a full understanding will require additional targets.

One highlight of hypernuclear research is the study of their unique weak decays. While theoretical interest has been strong, the experimental data have been woefully insufficient. Weak decays of Λ-hypernuclei appear in two forms: mesonic decays $\Lambda \to p\pi^-/n\pi^0$ like the free Λ, and the non-mesonic decays $\Lambda p \to np$ and $\Lambda n \to nn$. Because of the low nucleon kinetic energy (~ 5 MeV) the mesonic decays are strongly Pauli-suppressed in all but the lightest hypernuclei. On the other hand, the non-mesonic decays provide a unique laboratory for the study of the weak baryon-baryon interaction. In addition, the poorly-understood $\Delta I = 1/2$ rule, of fame in non-leptonic kaon and hyperon decays, can be tested here, as will be pursued in BNL experiment E931. The coincidence nature of such experiments and the importance of the neutron-stimulated branch $\Lambda n \to nn$ require high beam intensity, such as that available at BNL.

$S = -2$ Systems

Because most multiquark clusters appear to spontaneously dissociate into conventional quark-model hadrons, and so probably do not exist as resonances, an important exception occurs for states that lie below all of their two-hadron thresholds, in which case they are stable to the strong interaction. Thus it is important to search for the lowest-lying multiquark states predicted by theoretical models. Early bag-model calculations of multiquarks in the q^6 sector indicated that the flavor-singlet $u^2d^2s^2$ 0^{++} state, called the H, was the most deeply bound "dibaryon" and was below the $\Lambda\Lambda$ threshold by about 80 MeV. If this H dibaryon does exist, we would not expect to find strongly-stable $\Lambda\Lambda$ hypernuclei, because the $\Lambda\Lambda$ pair in a hypernucleus would coalesce into an H and depart from the nucleus with the kinetic energy recovered from $\Lambda\Lambda \to H$ binding. Thus, a simple search for $\Lambda\Lambda$ nuclei can have profound implications for our understanding of the nature of multiquark systems.

The exploration of this new frontier of flavor physics has only just begun. Two candidates for $\Lambda\Lambda$-hypernuclei were claimed in emulsion experiments in the 1960s. In 1998, the count stands at only three. The quest for the discovery of the H dibaryon has now existed for over 20 years. A basic understanding of $S = -2$ nuclei, of the $\Lambda\Lambda$ system, and of their interrelations with a possible H dibaryon remains the key for an understanding of multi-quark strange matter. Such matter in various forms has received significant attention in relativistic heavy ion physics as well as astrophysics (composition of neutron stars).

In recent years the availability of a high-flux and high-purity kaon beam, the D6 line at the AGS, has led to an intensification of $S = -2$ experimental efforts. Of key interest is the possible existence of relatively narrow Ξ^--hypernuclear states. The issue is whether the 28-MeV energy release in the strong process $\Xi^- p \to \Lambda\Lambda$ prevents narrow Ξ^--levels or not. In the absence of an H, $\Lambda\Lambda$-hypernuclei should be the ground state of $S = -2$ systems, and they can presumably be produced through different decay modes of Ξ-hypernuclei. As was the case for Λ-hypernuclei, electromagnetic as well as new types of weak decays ($\Lambda\Lambda \to \Lambda N/\Sigma N$) are interesting novel processes.

Strangeness $S = -2$ hypernuclei can be produced by several methods. The one-step reaction $K^- p \to K^+ \Xi^-$ may be used to produce Ξ^--hypernuclear states, whereas two-step processes are required for $\Lambda\Lambda$-hypernuclei: $K^- N \to \pi\Lambda$, followed by $\pi N \to K\Lambda$, or $K^- N \to K\Xi$, followed by $\Xi N \to \Lambda\Lambda$. BNL experiment E906 will seek to identify $\Lambda\Lambda$-hypernuclei through the observation of their characteristic sequential π-mesonic decays. The Cylindrical Detector System, designed and built at KEK, is being prepared for production data in late 1998. The search for $S = -2$ hypernuclei represents only the initial ground-breaking phase, and will open up a new field for more detailed studies. In addition, the most fundamental $S = -2$ system, the $\Lambda\Lambda$, needs to be investigated.

Although the experiments at the AGS D6 line benefit from the very good K^- fluxes available, they are hampered by the limited resolution of the existing K^+ spectrometer (~ 10 MeV FWHM in missing mass). The most important future extension for this physics program would combine the flux and purity of the AGS D6 line with a magnetic spectrometer similar to the SKS at KEK ($\Delta E \sim 2$ MeV, $\Delta\Omega \sim 100$ msr, scaled up to $p_{max} \sim 2$ GeV/c). Such a facility would produce as much as 1000 counts per Ξ-state in a 500 hour run, which would even make the detection of decay products feasible. It is conceivable that joint funding with Japan could be established for such a spectrometer, with an eye to relocating it at the JHF later.

The possibility of bound states in multiquark structures is actually a special case of the more general question of determining scattering amplitudes of hadrons. This topic is extremely important for issues such as the origin of NN forces, and, surprisingly, is poorly understood. The NN interaction is well known experimentally, but the traditional attribution to short distance components, such as the core repulsion due to vector meson exchange, is suspect. Instead, the core repulsion has been argued to derive from the one-gluon-exchange part of the quark-quark interaction. It is easy to confuse t-channel meson exchange (with free parameters) with quark-gluon interactions, because both of these can have the same flavor flow in the crossing quark lines. Of course both effects are present at some level, and their relative importance is at yet unclear. The many descriptions of the NN force in the literature in terms of heavier meson exchange may thus merely be parameterizations based on an incorrect physical model. It is clearly unsatisfactory that the basic interaction which underlies all of nuclear physics is poorly understood! One can make progress in this field most easily not by additional studies of the NN system, which is already accurately parameterized, but instead by studying hadron-hadron interactions in other sectors such as those with strangeness.

VI. Decays of the Kaon and Eta Meson

- *Precision measurements of important, rare, and forbidden kaon and eta-meson decays.* The $K^+ \to \pi^0 e^+ \nu$ decay can be used to determine V_{us}, the second element of the CKM matrix. Together with V_{ud}, this term allows a novel test of the Standard Model that is sensitive to the possible existence of supersymmetric particles. The $\eta \to \pi^0 \gamma\gamma$ rate and spectrum will test χPT to order p^6. Several C- and CP-violating decay modes of the η can be studied.

Rare and forbidden kaon decays have been in the core of research at the AGS for many years, and they are expected to continue with support from the High Energy program. They can not be discussed here in detail. Some experiments of current or future interest include: (1) $K^+ \to \pi^+ \nu\overline{\nu}$ (E787), which can provide a uniquely stringent test of the Standard Model and its parameters; (2) $K^+ \to \pi^+ \mu^+ e^-$ (E865), for testing lepton-flavor number violation; and (3) $K_L^0 \to \pi^0 \nu\overline{\nu}$ (E926), a measure of direct CP violation.

Decays of the η meson are also important for studying non-perturbative QCD such as Chiral Perturbation Theory.

K^+ Decays

The universality of the coupling constant of all weak interactions is an important feature of the Standard Model. It implies, very naively, the equality of the *reduced* decay rates of the superallowed β-decays of the π, K, ρ mesons and several light nuclei, ^{10}C, ^{14}O, ..., ^{54}Co. The universality property provides a direct link between intermediate-energy and traditional nuclear physics. There is a complication arising from the fact that the weak quark eigenstates and strong (QCD) quark eigenstates are not the same, but are related by a unitary matrix known as the CKM matrix V_{ij}.

Wolfenstein has given a practical parameterization of the CKM matrix in terms of four constants λ, A, η, and ρ. Defining $\lambda \equiv |V_{us}|$, one can expand the matrix in powers of $\lambda \approx 0.22$ and obtain

$$V_{ij} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\beta - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ -\lambda^3(1-\beta-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right). \tag{3}$$

Note that λ appears in all but the last element of V_{ij}. Thus, λ is the "cornerstone" of the CKM matrix. It shows up in all kaon and B meson decay-rate formulas, for instance, $\Gamma\left(K_L \to \pi^0 \nu\overline{\nu}\right) \sim \lambda^{10} A^4 \eta^2$.

The universality of the weak interactions implies the unitarity of the CKM matrix which implies, for example,

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \tag{4}$$

This relation is strictly valid unless there are new elementary constituents such as supersymmetric (SUSY) particles which are predicted to cause a small deviation from the unitarity relation. Because V_{ub} is known to be small, $V_{ub} = 0.003 \pm 0.001$, this very important test of the Standard Model depends on accurate determinations of V_{ud} and V_{us}.

CKM Matrix Element Values

The V_{ud} element can be determined from the beta decay of the neutron (*e.g.*, with ultracold neutrons) or the pion. Currently, the best value is determined from the average of the $\log(ft)$ values of the superallowed β-decays of nine light nuclei. After the application of some non-trivial corrections, the result is $V_{ud} = 0.9741 \pm 0.0006$. The few existing data sets for neutron decay are not internally consistent.

In principle, V_{us} can be determined from the β-decay of K-mesons and hyperons. In practice one is limited by the theoretical uncertainties resulting from the correction for the differences in the masses of the strange and up quarks (called the hadronic corrections). However, first-order hadronic corrections are absent in $K_{e3} = K^+ \to \pi^0 e^+ \nu$ decay and second-order hadronic corrections are evaluated at about 2% by chiral perturbation theory. Existing K_{e3} data yield $V_{us} = 0.220 \pm 0.002 \pm 0.006$.

Substitution of the above values into Eq. 4 yields:

$$1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = (27 \pm 14 \pm 15) \times 10^{-4} \; . \tag{5}$$

The dominant uncertainty in this test comes from the errors in V_{us}. Precision measurements of the K^+_{e3} decay rate, Dalitz plot, and radiative components are possible with the Crystal Ball detector at the AGS. Full 4π solid-angle coverage will be achieved by outfitting the detector with a tracker and an endcap in the entrance and exit tunnels.

Other K^+ Decay Modes

In the K^+_{e3} experiment all K^+ decays will be registered. Other interesting physics to result from this experiment include:

1. *"The decay rate and $\pi^0\pi^0$ spectrum of $K^+ \to \pi^0\pi^0 e^+ \nu$."* These data in conjunction with existing and new $K_L \to \pi^+\pi^0 e^- \nu$ and $K^+ \to \pi^+\pi^- e^+ \nu$ data from Fermilab and the AGS will provide a crisp test of the $\Delta I = \frac{1}{2}$ rule.

2. *"The spectrum and decay rate of $K^+ \to \pi^0 \mu^+ \nu$."* These measurements yield a new value for f^-, the second form factor in semi-leptonic K^+ decay. We will also provide a new test of the Callan-Treiman relation for f^- and f^+ which is a test of chiral perturbation theory.

3. *"The Dalitz plot of $K^+ \to \pi^0\pi^0\pi^+$."* This is another test of χPT.

4. *"The decay rate and spectrum of $K^+ \to e^+\nu\gamma$ and $K^+ \to \mu^+\nu\gamma$."* These data yield the vector and axial vector form factors.

Decays of the η Meson

Eta decays are an excellent testing ground of χPT expansions because their first-order electromagnetic and strong decays are suppressed at $\mathcal{O}(p^2)$, making them sensitive to higher-order terms [$\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$] of the expansion, which have not been well tested. One example where this expansion is important is in the calculations of the hadronic corrections for the anomalous magnetic moment of the muon. The so-called light-by-light correction is dominated by the $P\gamma^*\gamma^*$ vertex which requires a model-dependent calculation because the photons are off-mass-shell. This calculation is sensitive to the p^6 term. Thus, it is important to know how well χPT does at this level of the expansion.

Eta decays have also played an important role in tests of C invariance because the η, like the π^0, is an eigenstate of C. The current best test of C comes from the decay $\eta \to \pi^0\mu^+\mu^-$, which places a limit on the C-violating amplitude of only 10%. The limit on $\pi^0 \to 3\gamma$ is not nearly as sensitive due to a much smaller phase space.

The physics goals include:

- Measure the rate and spectrum for $\eta \to \pi^0\gamma\gamma$.

  The electromagnetic transition $\eta \to \pi^0\gamma\gamma$ is forbidden at $\mathcal{O}(p^2)$ in the chiral expansion, and even at $\mathcal{O}(p^4)$ it is very small. The latter is a result of the fact that resonance contributions, which enter the chiral expansion for the amplitude through the so-called low-energy constants of the effective chiral Lagrangian, do not show up for this process until order p^6. This η decay thus provides a window on $\mathcal{O}(p^6)$ (and higher) χPT terms. The branching ratio of 7×10^{-4} is twice the current χPT prediction and has generated much discussion. The experiment has a large background from $\eta \to 3\pi^0$. A new careful measurement with a 4π detector is needed. In addition to the decay rate, χPT also predicts the photon spectrum for $\eta \to \pi^0\gamma\gamma$. No data on the latter are available. With an initial set of 10^9 η's, a realistic number at the AGS, a sample of 10^3 events of this decay mode can be obtained. Another good test of χPT is the π^0 slope parameter in $\eta \to 3\pi^0$. It can be investigated simultaneously with the $\eta \to \pi^0\gamma\gamma$ decay. The available data are modest in size and show a larger slope than the theoretical prediction.

- Search for the forbidden decays: $\eta \to 3\gamma$, $\eta \to 3\pi^0\gamma$, and $\eta \to 4\pi^0$.

  The η undergoes flavor-conserving strong and electromagnetic decays, a domain that lacks tests of C-invariance. The strong decay of the η is suppressed by five orders of magnitude by G-parity conservation, and the electromagnetic decays are down by α^2. At the level BR $\lesssim 10^{-7}$, η decays probe the weak interactions, which violate C.

  The decay $\eta \to 3\gamma$ is forbidden by C. For reasons of phase space it is much more sensitive than the related reaction $\pi^0 \to 3\gamma$. The decay $\eta \to 3\pi^0\gamma$ is a novel test of C. Experimentally it is a very clean case as it involves η decay into seven photons, of which six make three π^0's. The sensitivity is readily evaluated from a comparison with $\eta \to 3\pi^0$.

The decay $\eta \to 4\pi^0$ is forbidden by CP. It is also a very clean process with eight photons matching up to four π^0's which combine to have the invariant mass of the η. It does not suffer from the background problems that plague another test of CP, namely, $\eta \to 2\pi^0$.

With the installation of a cylindrical drift chamber in the Crystal Ball spectrometer, decay modes that involve charged particles could also be measured. Some of these modes, such as $\eta \to \mu^+\mu^-\gamma$, are important for understanding the $P\gamma^*\gamma^*$ vertex in hadronic interactions. Another decay, $\eta \to \pi^0\mu^+\mu^-$, is forbidden by C and currently has an upper limit of BR=5×10^{-6}. This limit can be improved by an order of magnitude or more, depending upon the running time.

VII. The Impact of Hadron Physics on Nuclear and Particle Physics

The studies in the preceding sections are well justified on their own merits for addressing the basic issues in non-perturbative QCD. But they are also important for issues in other areas of nuclear, particle, and atomic physics. In addition, several of the particular studies complement and are fundamentally inseparable from the research that is or will be carried out at the new facilities at JLab and RHIC. Summaries of these connections are discussed here.

- *Hadronic physics plays a key role in obtaining the forefront physics that is expected to be delivered by the new US nuclear RHIC and JLab facilities.*
  Some examples are:

  1. *The hadronization of the quark-gluon plasma.* An important objective for RHIC is finding and studying the quark-gluon plasma. A possible signature for the creation of such a plasma is the rate of production of tell-tale hadrons, for example, J/ψ, and leptons such as e^+e^- pairs. The interpretation of such data is severely hampered by the lack of a good theory of the hadronization of quarks and gluons and especially the absence of a practical theory of confinement.

     The production of lepton pairs has a large contribution from the e^+e^- and $e^+e^-\gamma$ decays of the π, η, ρ and ω mesons. The origin of most η, ρ and ω mesons are the heavy N^* and Δ^* resonances which make up that part of resonance matter created in heavy ion collisions. The study of the baryon decays from the resonance region into the meson channels is particularly important for the interpretation of the expected wealth of RHIC data.

  2. *The determination of the radiative decay and the electromagnetic form factors of baryon resonances.* A vast output of high-quality data on the photo- and electroproduction of light mesons, the π, η, ρ, and ϕ mesons, is expected to come from the Jefferson Laboratory, especially from the CLAS facility. These data may be used for baryon spectroscopy, in particular for the determination of various multipole amplitudes, which in turn provide information on the γN helicity couplings and on the electromagnetic transition form factors of N and Δ resonances. To capitalize fully on the new electromagnetic data, it is highly

desirable to have data of comparable quality for the complementary hadronic reactions. In order to extract γN helicity couplings from photoproduction data, it is, in fact, *essential* to have at least the magnitudes and relative phases of the corresponding hadronic decay amplitudes. The measurement of these amplitudes requires incident pion beams.

3. *Hyperon spectroscopy.* The spectroscopy of the Λ^* and Σ^* hyperons with electromagnetic probes is limited to secondary processes because hyperons cannot be produced directly in electromagnetic interactions. Instead they originate through the formation of N^* or Δ^* resonances, for instance $\gamma + p \to N^*(1710) \to K^+ + \Lambda$. Establishing the excited hyperon states and determining their decay properties requires the use of intense beams of K^- mesons.

   To achieve the full potential of the large CLAS experiments, it is necessary to determine the required hadronic amplitudes by using π^- and K^- beams.

4. *Strange hadronic matter and/or strangelets.* It is possible that strange nuclear matter is the true hadronic ground state. Entire stars might be made of strange nuclear matter, a possibility that led the late Carl Dover to describe the strangeness $S = -2$ sector as the "gateway to the stars." A basic understanding of $S = -2$ nuclei, of the $\Lambda\Lambda$ system, and of their interrelations with a possible H dibaryon remains the key for an understanding of possible multi-strange matter. Such matter, in various forms (strangelets, strange hadronic or strange quark matter), has for many years received significant attention in relativistic heavy ion physics and even in astrophysics (composition of neutron stars).

- *Hadronic physics plays a key role in the determination of many of the input parameters to QCD and the electroweak Standard Model, as well as in many precision tests of these two theories.*
  Some examples are:

1. *The masses of the quarks.* The "infrared slavery" property of QCD makes it impossible to measure directly the masses of the six quarks. To complicate matters further, the mass "parameters" in the QCD Lagrangian depend on the renormalization schema and on a scale parameter. Values of the quark mass ratios have been obtained by using effective QCD-Lagrangian models, particularly chiral perturbation theory. Critical experiments which test the applicability of various orders of expansion of χPT are thus very important.

2. *The value of α_s, the strong coupling parameter, and its energy-scale dependence.* The limit of precision of various methods for determining α_s, even at very large Q^2, comes from the hadronic and quark-mass corrections.

3. *The CKM quark-mixing matrix.* The accurate determination of the 9 different elements of the CKM matrix requires measurements of various weak interquark transitions, each with its hadronic correction. The V_{us} matrix element, for example, can be obtained from K_{e3} decay (see Sect. VI).

4. *The energy scale dependence of α_e, the electromagnetic coupling parameter of QED.* The dominant theoretical uncertainly in the interpretation of precision

data are the non-perturbative QCD contributions to vacuum polarization.

5. *The hadronic "corrections" to precision tests of QED and the SM such as the new muon g-2 experiment.* The new measurement of the muon g-2 factor at BNL (E821) will provide a high-precision test of QED of sufficient accuracy to observe electro-weak contributions. The goal is an accuracy of 4 in units of 10^{-10}. The pure QED contribution is known to an accuracy of 0.2 units, and weak part is 15 units. The hadronic correction (vacuum polarization and photon-photon, combined) is 692 ± 10 units, giving an uncertainty that is more than twice that of the E821 goal.

6. *New tests of CP violation in rare kaon decays.* The decay of neutral K mesons into $\pi^0\pi^0$ and $\pi^+\pi^-$ pairs provides important information on the nature of CP violation. The interpretation of results is limited by the hadronic corrections, the most important of which is due to isospin breaking from the π^0-π^+ mass difference and π^0-η mixing. The KTeV experiment at Fermilab plans to measure the CP parameter ε' to an accuracy of 1×10^{-4}. Estimates of the uncertainties in the hadronic corrections vary all the way to 30×10^{-4}. Thus, a better understanding of the $\pi\pi$ systems is important for the interpretation of a crucial experiment on CP violation.

   Some other very rare kaon decays such as $K_L \to \pi^0\mu^+\mu^-$ and $K_L \to \pi^+\pi^-e^+e^-$ are being considered as new probes of CP violation. The amplitude for these decays has two components, a short-range CP-violating part and a long-range CP-conserving part. The magnitude and phase of the latter cannot be measured directly but must be calculated. Particularly useful for this purpose is Chiral Perturbation Theory.

VIII. Current Facilities and Future Requirements

The topics discussed in this paper represent only a fraction of the whole field of non-perturbative QCD or hadron physics. Many scientists in the U.S., Canada, Japan, and Eastern and Western Europe are pursuing aspects of the basic issues by a variety of means. Indeed, there are well-developed plans in Japan for a large medium-energy hadron physics facility by the middle of the next decade. Furthermore, many of the important lines of research at electron accelerator laboratories are similarly directed to several of the topics addressed here, but in different ways. Also presented at the Workshop were some current and future opportunities for physics with hadron beams at facilities other than the AGS, such as Fermi Lab.

Out of the broad range of issues, this paper has focussed on opportunities for making significant advances on the basic issues at an existing facility: the AGS at the Brookhaven National Laboratory *because of its unique secondary beams.* It is anticipated that the AGS will be needed as an injector for RHIC only a few hours a day, and that resources will be available to run key experiments of interest to High Energy Physics in some of the secondary beam lines during the other hours. The experimental program outlined here requires only a few other beam lines, namely the C6/8 lines, the D line, and possibly the B line.

Existing detector facilities include the Neutral Meson Spectrometer (NMS), the Japanese Ge-Ball, the Cylindrical Detector System (CDS), the "Moby Dick" magnetic spectrometer, and the Crystal Ball Spectrometer (CB). Portions of the Multi-Particle Spectrometer (MPS) are anticipated to be relocated to JLab in 1999. The CB will be utilized for the baryon spectroscopy studies, the K_{e3} decay experiment, and the η-decay experiments. Some additional features such as an internal charged-particle tracker and an end cap will be needed. The CB and the NMS are currently located on the C6/C8 lines, and can be used alternately. The important higher-momentum component of the baryon spectroscopy will require the D line. The strangeness studies will mainly utilize the Ge-Ball and the CDS, and most of them will also require the D line. An additional beam line, perhaps up to 4 GeV, may eventually be needed. Although the current meson spectroscopy program will not be continuing in the near term, the recent evidence for an exotic meson and the importance of the physics issues for non-perturbative QCD should lead to new proposals. An idea under development for later years is to combine the remaining portions of the MPS with the CB, possibly on the B line, in a novel approach to search for exotic mesons.

Future studies of hypernuclear systems could be considerably enhanced by developing or obtaining a magnetic spectrometer comparable to or better than the SKS spectrometer at KEK. It would be sensible to consider relocating that spectrometer to the upcoming JHF, as part of the U.S. participation in the Japanese facility. Further avenues in baryon spectroscopy could be pursued with the development of a polarized hydrogen target.

The presence of an active AGS experimental program will also provide opportunities for test beams for RHIC and JLab detector components, color-transparency studies, fixed-target heavy ion measurements, and experiments with antiproton beams or polarized proton beams.

Because a significant portion of the cost of supporting operations of the fixed-target area are expected to come from the DOE High Energy Program, the additional costs to the Nuclear Physics Program are modest. Current estimates for facility support are about \$3–5M per year. In view of the excellent likelihood that the set of experiments discussed in this paper will be able to advance our understanding of non-perturbative QCD significantly, and in view of the great benefits that the results of these studies will bring to other important programs such as those at RHIC and JLab, the investment seems to be an especially opportune and effective one.

Appendix: Workshop Steering Committee and Speakers

Steering Committee

B. Bassalleck	University of New Mexico	
W. Briscoe	George Washington University	Workshop Host
R. Chrien	Brookhaven National Laboratory	
J. Comfort	Arizona State University	Editor in Chief
D. Hertzog	University of Illinois	
N. Isgur	Jefferson Laboratory	
R. Jaffe	Massachusetts Institute of Technology	
M. Manley	Kent State University	
B. Nefkens	University of California, Los Angeles	Workshop Organizer
H. Spinka	Argonne National Laboratory	
S. Vigdor	Indiana University	

The following people gave oral presentations at the Workshop.

T. Barnes	ORNL and University of Tennessee
G. Bock	Fermi National Accelerator Laboratory
D. Bugg	QMWC, London
J. Cameron	Indiana University Cyclotron Facility
R. Carey	Boston University
S.-U. Chung	Brookhaven National Laboratory
R. Eisenstein	National Science Foundation
S. Heppelman	Penn State University
T. Johansson	Uppsala University
B. Keister	National Science Foundation
P. Kitching	TRIUMF, Canada
D. Lowenstein	Brookhaven National Laboratory
W. Marciano	Brookhaven National Laboratory
J. Matthews	Massachusetts Institute of Technology
S. Nagamiya	KEK, Japan
B. Nefkens	University of California, Los Angeles
S. P. Rosen	Deapartment of Energy
K. Seth	Northwestern University
W. Tippens	University of California, Los Angeles
U. van Kolck	California Institute of Technology
M. Zeller	Yale University