September 27, 1984
File: 84-f-vogt.901,
NSAC/final

Report of the NSAC Ad Hoc Subcommittee on a 4 GeV CW Electron Accelerator for Nuclear Physics

1. Recommendation and Summary

The subcommittee unanimously reaffirms the nuclear science community's commitment to CW electromagnetic studies as a major focus for addressing a broad range of fundamental open questions in nuclear physics and its interface with QCD. The subcommittee endorses the recommendation that the first priority major construction project for nuclear physics be a 4 GeV CW electron accelerator. We view this facility as the major component of a structured electromagnetic research program providing world-leading new capabilities for exploring atomic nuclei, particularly the effects of nucleon substructure.

Exploration of the interface between nuclear physics and QCD necessarily also involves complementary studies, including those with relativistic heavy ions recommended as the aim of the second major construction project in the 1983 Long Range Plan. The 4 GeV electron accelerator, the electromagnetic program, and the relativistic heavy ion studies are important components of the whole U.S. program for future frontier studies in nuclear science.

2. Introduction

In the light of the very recent decision of the Congress to "defer without prejudice the construction of the Continuous Electron Beam Accelerator Facility", Dr. George Keyworth, Director of the Office of Science and Technology Policy requested advice on the scientific justification of a 4 GeV electron accelerator for nuclear physics. The following subcommittee of the DOE/NSF Nuclear Science Advisory Committee was formed for this purpose: Prof. Gordon Baym* (Univ. of Illinois), Prof. D. Allan Bromley* (Yale Univ.), Prof. Glennys Farrar (Rutgers Univ.), Prof. Steven Koonin (California Institute of Technology), Prof. John Negele (Massachusetts Institute of Technology), Prof. John Schiffer* (Argonne National Laboratory and University of Chicago), Prof. Ingo Sick* (Univ. of Basel), Prof. Erich Vogt*, Chairman (Univ. of British Columbia), Prof. Dirk Walecka (Stanford Univ.). The asterisks indicate those members of the subcommittee who are also members of NSAC.

The following was the charge to the subcommittee:

> In 1982 the DOE/NSF Nuclear Science Advisory Committee endorsed the report of its Subcommittee on Electromagnetic Interactions and subsequently, in 1983, it endorsed the recommendation of its Panel

> Electron Accelerator Facilities, that a 4 GeV continuous beam electron accelerator be constructed. The primary scientific justification for 4 GeV was the importance of the studies to be conducted on the developing interface between nuclear physics and QCD - the theory expressing our present best understanding of elementary particles in terms of a quark-gluon substructure. In the face of our latest scientific understanding, is the original recommendation, to build a 4 GeV CW electron accelerator still the most effective strategy for nuclear physics and, especially, for exploring this important frontier of the field?

The subcommittee met to begin its deliberations in Washington, D.C. on July 13 and 14, 1984. It also met at that time with Dr. Keyworth and with Dr. Alvin Trivelpiece, Director of Energy Research, Department of Energy. As a result of these discussions with Dr. Keyworth and Dr. Trivelpiece, it was clear to the subcommittee that it was intended to concentrate on the physics of a 4 GeV facility and not to address other matters, such as the management or the site of the facility, which are the direct responsibility of DOE and OSTP. In the subcommittee's view these other matters are indeed important and our recommendation in support of a 4 GeV facility is based on the premise that this facility will have the outstanding management, scientific leadership, and technical competence which are needed for its timely completion and the realization of its potential for world leadership in the field. The subcommittee's recommendation is also based on the assumption that the 4 GeV facility can be constructed and put into operation within the fiscal structure set forth in the report of the Bromley Panel (NSAC Panel on Electron Accelerator Facilities, 1983). The subcommittee was requested to report to NSAC as soon as possible. Taking into account the charge, the time interval for response, and the previous history of NSAC decisions, the subcommittee considered the dominant question to be the scientific justification for a 4 GeV CW electron accelerator and particularly whether or not recent developments in our understanding of the relevant physics might have significant impact on its scientific justification.

The subcommittee met to continue its deliberations in Washington, D.C. on August 4th, in Chicago on September 14th, and in Washington on September 23rd and 24th, 1984. Before reaching its conclusions, it discussed the frontiers of electromagnetic interactions and nuclear physics with reference to the Barnes Report (NSAC Subcommittee on Electromagnetic Interactions, 1982) and the Bromley Report. It also discussed extensively the questions raised by recent theoretical developments, particularly in regard to the interface with QCD. Further, it reconsidered, in the light of the physics opportunities, the energy choice and duty factor of an electron accelerator and its position within a structured system of electron facilities and within the other components of the 1983 NSAC Long Range Plan for nuclear physics. Its assessment of these matters is given below.

3. Electromagnetic Interactions and Nuclear Physics

Recommendations of the nuclear science community over the last decade have recognized consistently that electron beams are the tool of choice for a significant fraction of the rapidly evolving field of nuclear physics. The electron probe is particularly powerful for nuclear physics because it is so clean. The electromagnetic force is well understood - in terms of quantum electrodynamics (QED). Further, electromagnetic probes are among those which have great kinematic versatility: the momentum and the energy imparted to the target can be varied independently. Beams with very low emittance, and detection techniques developed for attaining excellent energy resolution, have led to high precision. For nuclear physics the electron has been particularly effective and versatile as a probe because it interacts not only with the nuclear charge density but also with convection currents and the magnetization density. In sum, electron scattering provides an unambiguous determination of the electromagnetic structure of atomic nuclei; our understanding of nuclei is then advanced by interpreting this structure in terms of the particular degrees of freedom relevant at various distance scales, as discussed in Sec. 4.

What has been lacking heretofore in nuclear physics with electron beams is accelerators, at appropriate energies, with high duty factor. The duty factors have typically been 0.01 or less. Continuous beams will extend the advantages of electron probes to a wide range of new experiments involving the detection of particles in coincidence. It was the advent of the technology for such continuous beam electron accelerators in the GeV range which, together with the development of the physics, led to the scientific momentum for a CW electron accelerator at several GeV.

Beginning with the Friedlander Report (1976) in pre-NSAC days and subsequently in the NSAC reports of 1977, 1979, 1982 and 1983 a full account has been given of the development of recent electron accelerator technology and of nuclear science with such machines - including their impact on nuclear structure and dynamics, which we summarize here. Their potential for exploring the QCD interface is discussed in the next section.

The most precise knowledge we have of nuclear structure comes from single-arm electron scattering experiments. This includes the shape and radial distribution of the charge density, the distribution of ground state magnetization density, the microscopic spatial distributions of transition densities, the properties of giant resonances, the structure of collective and high-spin magnetic excitations, the presence of meson exchange currents, and the structure of single-particle and single-hole states in nuclei. Going beyond these the Barnes Report describes the rich nuclear structure which can be studied by CW electron facilities spanning the energy range from a few hundred MeV to several GeV: the complete characterization of nuclear multipole amplitudes including measurement of spin observables, the study of deep-lying hole states through nucleon knockout reactions, the production of delta particles and their propagation in the nuclear medium, and the use of two-nucleon knockout as a probe of short-range correlations in the nucleus.

The study of nuclear structure with electromagnetic probes - and, indeed with other probes as well - promises to be a fertile field of science far into the future. The nuclear many-body system has many important aspects and many separate frontiers while at the same time retaining a fundamental unity. It is because of the special nature of our subcommittee's charge that we emphasize electromagnetic probes and, more specially in the next section, the use of electromagnetic probes for issues of the QCD interface.

4. Electromagnetic Interactions and QCD

If one asks how to describe the nucleus in terms of the behavior of its constituents, the answer changes with the spatial resolution of the probe. At distances greater than about 1 fermi, which can be resolved with electron beams of a few hundred MeV, one has the familiar picture of neutrons and protons (nucleons) undergoing individual and collective motion in the nucleus. With somewhat higher energies, approaching 1 GeV, the contributions of mesons and nucleon excited states to the electromagnetic structure of the nucleus can become important.

As one increases the energy still further, distances small compared to the size of the nucleon itself become accessible and a more explicit account must be taken of the fundamental structure of nucleons as composites of colored quarks interacting through gluon exchange. At this spatial resolution one expects observable effects arising from the overlap of extended nucleons within the nucleus, and the physics of confinement becomes relevant. In this regime QCD is non-perturbative (it cannot be handled by the standard approximation technique of perturbation theory) and the analysis of such effects is correspondingly difficult. At substantially higher energies (tens or hundreds of GeV) one begins to enter the asymptotic regime in which perturbative QCD is applicable and greatly simplifies the analysis of experiments. The analysis of the EMC effect, in which high energy electron or muon scattering measures the difference between the distribution of quarks within a free nucleon and those inside a nucleus, beautifully illustrates this application of perturbative QCD.

The interface with QCD is a fundamental and rapidly evolving frontier of nuclear science. Based on our current understanding, we distinguish two complementary types of electromagnetic studies of this interface, namely, those involving subasymptotic physics at moderate energies and those involving asymptotic physics at high energy.

In the subasymptotic regime for the nucleus we have at present no precise framework or language to describe the physics when nucleons overlap. We use here terms such as "hadronic physics" when we wish to refer to the possible internal excitation of nucleons, or to meson degrees of freedom, and "confinement physics" to refer to the possibility that the quark constituents of different nucleons overlap in their motion. At modest bombarding energies, in the vicinity of a GeV or more, one can produce the lowest excited state of the nucleon - the delta particle - and begin the study of its interactions in the nucleus. A number of very important hadronic studies are accessible only with several GeV electron energy and high intensity. These include better determination of nucleon and few-nucleon form factors measured to higher momentum transfer, and studies of higher excited states of the nucleon in the nucleus.

The confinement issues are of great importance for all of physics, and nuclei are unique laboratories for their study. The initial focus will likely be on simple few-nucleon systems, where new aspects of nucleon substructure might first be revealed. To find such aspects one would like to go to excitation energies above 1 GeV which marks the region where sharp nucleon resonances in the nucleon response function disappear and the behavior is dominated by the broad response of point-like constituents.

Addressing the problem from a different point of view, one should also search for physics at the interface in terms of the concept of "degrees of freedom" of the nuclear many-body system. Experience with other quantum many-body systems indicates that there may be opportunities here for discovering new physical phenomena. Systems of fermions, such as electrons in a conductor, liquid ^{3}He and, indeed, atomic nuclei display interesting quasiparticle structure in strongly interacting regimes. More generally, a knowledge of the forces, even when they are reasonably tractable (as in the case of QED) does not necessarily allow one to predict fascinating new physics. For example, in the absence of experimental discovery, superconductivity would not have emerged from our theoretical understanding of the underlying electromagnetic interactions in the form of QED. The search for new nuclear degrees of freedom and the relationship of nucleon-meson degrees of freedom to quark-gluon degrees of freedom in nuclei is one of the most challenging and fundamental questions of physics, which must be explored with facilities spanning both the subasymptotic and asymptotic regimes.

Studies in the range of tens to hundreds of GeV can exploit the simplicity of asymptotic QCD to determine precisely defined properties of quark distributions in nuclei. Indeed, the EMC studies mentioned above have given tantalizing hints of new effects arising when quarks are embedded in nuclei rather than in isolated nucleons. Further studies carefully separating longitudinal and transverse contributions, isolating the most important corrections to the asymptotic contribution, exploring isospin dependence, resolving specific final products, and making comparisons with neutrino scattering offer great promise for exploring the interface of nuclear physics with QCD.

In addressing developments in our scientific understanding during the past year which are germane to the physics of a 4 GeV electron accelerator, it is particularly relevant to consider the applicability of asymptotic freedom. Some have hoped that the simplifications of perturbative QCD might be brought to bear on exclusive 4 GeV electron nucleon and electron-nucleus scattering. This optimism was not widely accepted, and indeed, the consensus of the subcommittee is that fully asymptotic predictions of QCD are unlikely to be applicable to exclusive processes at these energies.

> The theoretical progress of the past year properly reemphasizes that the scientific interest at the QCD interface of an electron accelerator in this energy regime rests in the hadronic and confinement issues of QCD rather than in asymptotic freedom; most investigations will focus on the subasymptotic domain of QCD, on the properties of interacting quarks, and on the mechanism leading to confinement.

5. The Choice of Energy and Duty Factor

The accelerator of choice must have a high duty factor - it must be CW - to perform a wide variety of coincidence experiments. Although substantial progress will have been made on single-arm electron scattering before such an accelerator is operating, experience with other nuclear probes and with other many-body systems has shown that measurement of the final state (even partially) is of vital importance in clarifying the dynamics. CW operation is crucial for the whole range of coincidence experiments with electron beams. Furthermore, high intensity (of the order of 200 microamperes) is crucial for providing the multiple beams required for a national multi-user facility. The subcommittee has no hesitation in strongly reaffirming the dominant importance of CW operation.

The precise energy range of the accelerator was the subject of considerable discussion within the subcommittee. The judgment about the best energy was similarly difficult for the earlier Barnes and Bromley subcommittees. This subcommittee unanimously agrees on the outstanding research program afforded at energies up to several GeV and the majority of the subcommittee supports the full 4 GeV capability. The physics begins to be accessible at a beam energy of about 2 GeV. There is no known sharp threshold for new physics above 2 GeV but one gains kinematic flexibility, which can increase both the rate at which experiments can be carried out and the information they provide. Our discussion concerned the scientific priority of the extra flexibility.

In assessing the priority to be given to the full energy, the subcommittee considered again the list of experiments and the kinematic diagrams the Barnes Panel provided in its report. Doing this we found that the physics dealing with nucleons, nucleon resonances and mesons either is or begins to be accessible by 2 GeV. This includes determination of nuclear and nucleon multipole amplitudes, the study of deep-lying hole states, the nucleon spectral function in nuclei, two-body correlation functions through one and two nucleon knockout, and the study of pion and delta propagation in the nuclear medium through coincidence experiments. Some significant studies of few-nucleon systems can also be undertaken at 2 GeV, as well as a beginning of the study of hypernuclei above the threshold for their production. The spatial resolution accessible with 2 GeV electron beams is smaller than the size of the intrinsic structure of nucleons, so that new aspects of nucleon substructure and the physics of confinement should begin to be accessible. Important tests of fundamental symmetries can be performed below 2 GeV. The single-arm deep inelastic studies of complex nuclei cited by the Barnes Panel are beginning to be explored at NPAS (SLAC), but the coincidence studies which that panel emphasized must await CW beams. In sum, a significant part of the program of studies outlined in the Barnes report could be carried out with a 2 GeV CW facility.

The increased kinematic flexibility of a 4 GeV electron beam, relative to 2 GeV, can be exploited to probe smaller spatial scales and larger energy losses. In terms of spatial scales, the extra resolution (in the vicinity of 0.2 fermi) is important for the physics at the QCD frontier. The very small cross sections for electromagnetic processes mean that counting rates often determine the feasibility of a particular experiment. Higher energies allow higher counting rates by using a smaller scattering angle to achieve a given momentum transfer. The higher energy is desirable for the important separation of longitudinal and transverse response at large momentum transfers. A higher energy allows one to carry out two-baryon knockout under appropriate kinematic conditions to study the short range influence of the nuclear medium. Further, a significant program of hypernuclear physics carried out via the (e,e'K+) reaction with good energy resolution appears to require energies of at least 3 GeV. The higher counting rates at smaller working angles at 4 GeV may also be valuable for tests of fundamental symmetries, for example, measurement of parity violation in electron scattering from the nucleon, which will become practical with counting experiments once CW beams allow large solid angle detectors.

On the basis of the above considerations, the majority of our subcommittee supports the full 4 GeV energy for the CW electron facility, as did the earlier Barnes and Bromley subcommittees.

6. Structured Program of Electromagnetic Research

The 4 GeV electron accelerator must continue to be considered the central component of a structured program of electromagnetic research. The Bromley Report and NSAC made strong recommendations not only about the scientific priority of the 4 GeV accelerator, but also about the other elements of a world-leading national program which would be complementary to it. The program should include:

- Lower energy capabilities providing CW electron beams. A 1 GeV facility would be relatively inexpensive and would emphasize very high resolution. At still lower energies other CW facilities would, in turn, be complementary to such a 1 GeV facility. All of these lower energy facilities are likely to be the natural extension and continuation of presently operating facilities.

- Vigorous use of existing high energy facilities. These are beginning to be used now to address the implications of QCD for nuclei and should be used more extensively in the future. Prominent among the capabilities at high energy laboratories are the 20 GeV electron beam at SLAC and the 800 GeV muon beam soon to be completed at Fermilab. With these beams, the crucial exploration of nuclei in the regime of asymptotic QCD will be carried considerably beyond our present understanding, and we see such a set of measurements as an essential component of a structured program. The NPAS program is another example of utilizing capabilities at high energy laboratories, and is a forerunner of the full experimental program at the CW facility. Other opportunities should appear in the future with high energy accelerators and storage rings; it is important that these opportunities be pursued in a timely and judicious way.

- Increased general support of the whole nuclear physics research program, as outlined in the 1983 NSAC Long Range Plan. In recommending the CEBAF facility within the Long Range Plan, and in subsequent communications, NSAC stressed that the vitality and growth of the ongoing nuclear physics program required a one time real increase in operating funds, to be used for better utilization of facilities, development of instrumentation, training of young scientists, and support of user groups. While this recommendation cuts across the whole field of nuclear physics it is of special importance in discussing a new frontier area where such an increment is most likely to have a major scientific impact. We reassert this recommendation, from the perspective of our charge, very strongly.

7. Strategies for Exploring the Interface of Nuclear Physics and QCD

The charge to the subcommittee refers to the broad question of the most effective strategy for exploring an important new frontier, the developing interface between nuclear physics and QCD, with particular attention to the scientific justification for a CW electron accelerator of several GeV. We have answered by reaffirming this project as the first major construction project for nuclear physics, within a structured program of electromagnetic physics. Other projects related to the issues of nuclear physics and QCD must surely follow and indeed, the 1983 Nuclear Physics Long Range Plan identified a relativistic heavy-ion collider as the following major construction project.

Going beyond our dominant question, we turn here to the general question of exploring the interface of nuclear physics and QCD. The richness of QCD will give rise to a diversity of phenomena requiring study with a corresponding diversity of probes. As is clear from the Long Range Plan, effective exploration of the interface between nuclear physics and QCD necessarily involves, in addition to electromagnetic facilities, consideration of relativistic heavy ion collisions and of hadronic probes which address complementary fundamental aspects of this interface:

Electromagnetic probes have been utilized for decades to explore nucleons and nuclear structure. They are a highly-developed, well-understood tool whose further exploitation is motivated by the precision and interpretability they provide. As elaborated above, they explore two key aspects of the QCD interface, namely hadronic and confinement physics at several GeV and the asymptotic region at tens to hundreds of GeV. The knowledge of nuclear structure obtained with electromagnetic probes will continue to be a prerequisite for the interpretation of experiments with many other probes of nuclei.

Relativistic heavy ion collisions offer the opportunity for a major new complementary initiative, the exploration of an entirely uncharted regime: regions of high energy density and baryon density of sufficient spatial extent to produce new phases of matter - for example, the possible creation and study of a quark-gluon plasma.

Light hadronic probes (nucleons, pions, kaons, antinucleons, etc.) have the potential for exploring many other important aspects of the QCD interface. These probes could be provided by the primary and secondary beams of a high-intensity proton accelerator operating at several tens of GeV. Such a facility lies beyond the 1983 Long Range Plan.

In advising on the implementation of the 1983 Long Range Plan, NSAC will need to consider, in the context of the overall balance of nuclear science, the evolving possibilities for a full attack on the QCD issues as well as the various components and options of the electromagnetic program on which we have focussed. Such consideration by NSAC must continue to take account of the science opportunity and the cost effectiveness of each option and each approach.

8. Conclusions

The subcommittee reaffirms a 4 GeV CW electron facility as the first major construction project for nuclear physics. It did not arrive at this decision lightly, for nuclear physics is a broad and vital field with other important frontiers, which we have not addressed in this report. The 1983 Long Range Plan for nuclear physics was developed following consideration of the scientific priorities for the field. We concur with the overall balance for nuclear science outlined in that Plan.

The United States remains in a position for world leadership in electromagnetic research in nuclear science. Vigorous action on the whole program in this area is essential both for the strength of nuclear science in this country, and for maintaining this leadership position in the face of plans abroad for operating several CW electron accelerator facilities, in the vicinity of 1 GeV, within three to four years. Our report and recommendation are intended to promote that action.