

REPORT
OF THE
NSAC SUBCOMMITTEE ON FACILITY CONSTRUCTION

AUGUST 4, 1986

UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

Department of Physics, FM-15

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Dr. Alvin Trivelpiece, Director
Office of Energy Research
Department of Energy
Washington, D.C. 20585

Dr. Harvey Willard, Director
Division of Physics
National Science Foundation
Washington, D.C. 20550

Dear Alvin and Harvey,

This letter is in response to that of May 15, 1986 from the Department of Energy and the National Science Foundation. In response to the request contained in that letter, the Nuclear Science Advisory Committee formed a Subcommittee on Facility Construction chaired by Dr. Eric W. Vogt, and consisting of Dr. Peter Braun-Munzinger, Dr. Harold C. Britt, Dr. Hall L. Crannell, Dr. Franz L. Gross, Dr. Ernest M. Henley, Dr. Harold E. Jackson, Jr., Dr. Malcolm H. MacFarlane, and Dr. Robert E. Tribble. The Subcommittee reported to NSAC at a meeting held on June 16 and 17, 1986.

The enclosed NSAC subcommittee report responds to the charge of evaluating the scientific capabilities of the planned Brookhaven Relativistic Heavy Ion Collider (RHIC) facility and reviewing for scientific merit four upgrade proposals. The review was to reflect on "the impact of each of the upgrades on the short-term and long-term health and balance of the field of nuclear physics." The background for this study was NSAC's 1983 "Long Range Plan for Nuclear Science", as reaffirmed by NSAC in 1984, and, consistent with it, the Department of Energy's decision to place its highest priority for new construction on the CEBAF electron accelerator with the next priority being the RHIC facility at the Brookhaven National Laboratory. NSAC endorses the subcommittee report.

The subcommittee report is totally consistent with the Long Range Plan for Nuclear Science. Indeed, it points out that science developments over the past few years further strengthen "the very high scientific merit for the RHIC project proposed by Brookhaven." The subcommittee finds "that the facility as proposed is fully capable of achieving the scientific goals of the long range plan", and that the RHIC "will provide nuclear science in the US with a unique world-leading facility with almost unparalleled potential for new discovery." NSAC strongly endorses these findings of the subcommittee.

Similarly, consistent with the long range plan, NSAC finds the science proposed at the upgrades of existing electron and heavy ion facilities to be of foremost scientific interest and to complement the new high energy nuclear facilities (CEBAF and RHIC) proposed for construction. In view of this, and the additional important roles played by MIT and the University of Illinois in the education of nuclear physicists, we strongly recommend that, among the upgrade proposals, these two electron facilities be given the highest priority. The cost effectiveness and choice of a heavy ion facility upgrade in the 1-2 GeV region should be examined carefully.

Although the subcommittee believes that the upgrades can be achieved with a constant manpower, a detailed study has not been carried out. However, the committee notes that the proposed upgrades of electron facilities at the two universities should attract more high quality students to the field.

Finally, NSAC stresses the importance of improved operations budgets. The impact of the construction and operations costs of the major new facilities will require considerably improved funding for nuclear science. The failure to obtain such increases in operating funds, also recommended in the Long Range Plan for Nuclear Science, will severely impact ongoing high priority research programs. We urge the agencies to make major efforts to obtain these necessary increases.

Sincerely yours,



Ernest M. Henley, for NSAC,
NSAC Chairman

cc. D. Hendrie ✓
NSAC members
Subcommittee members

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Appendix

1. EXECUTIVE SUMMARY

This Subcommittee was established by NSAC in early May of 1986 to evaluate the Relativistic Heavy-Ion Collider (RHIC) proposal of Brookhaven and to review and evaluate for their scientific merit the upgrade proposals of the Massachusetts Institute of Technology, University of Illinois, Lawrence Berkeley Laboratory, and Oak Ridge National Laboratory. The charge to the Subcommittee and its membership is given in Section 2.

The proposals under evaluation and review by the Subcommittee belong to two important areas of nuclear physics: electromagnetic and heavy-ion research. In addition to reporting our findings on the individual proposals we report on the perspective to which they belong: on a structured program of electromagnetic research for the nation and, similarly, on a structured program in heavy-ion physics. Within the scope of our review we report on the impact of these structured programs and of the individual proposals on the health and balance of nuclear physics research in the United States. With CEBAF now planned by The Department of Energy to begin construction in fiscal year 1987 to provide cw electron beams up to at least 4 GeV to study the effects of nucleon substructure in atomic nuclei, it is timely to reassess the other complementary parts of the structured electromagnetic research program which have, for many years, had high priority in NSAC's Long Range Plan. Similarly, with RHIC making excellent progress toward a funding decision and with a strong existing United States program in low-energy heavy-ion physics it is appropriate to consider the scientific merit of facilities operating with heavy-ion beams of medium energy between these two extremes.

Our findings are as follows.

- 1.1 Relativistic Heavy-Ion Collider (RHIC) of Brookhaven National Laboratory
 - a. The recent development of the field of relativistic heavy-ion physics has further strengthened the very high scientific merit for this project identified in NSAC's December 1983 "Long Range Plan for Nuclear Science" and its subsequent review and affirmation by NSAC in 1984. These reports gave RHIC the highest priority for the next major new construction (assuming that CEBAF, which has already been approved for construction by DOE will, in turn, receive Congressional approval for construction);
 - b. The facility as proposed is fully capable of achieving the scientific goals identified by NSAC;
 - c. As the project proceeds toward construction the heavy-ion research community will need to continue to pursue vigorously the ideas in the underlying theory and the development of detectors appropriate for the research program; and
 - d. RHIC will provide nuclear science in the United States with a unique world-leading facility with almost unparalleled potential for new discovery.

- 1.2 Structured Electromagnetic Research Program

- a. There remains very high scientific merit for a cw electron accelerator at intermediate energy (up to 1 GeV) for high resolution studies of hadronic degrees of freedom in atomic nuclei.
- b. There remains high scientific merit for a cw electron accelerator at lower energy (up to several hundred MeV) for high-resolution studies of nucleonic degrees of freedom in atomic nuclei.

- 1.3 Massachusetts Institute of Technology (Bates Linear Accelerator Center)

The Bates upgrade proposal fully addresses the electromagnetic research program of very high scientific merit at intermediate energies. The whole capability will be unique on the national scene and match the best competition abroad: its combination of internal target capability and polarized beams for addressing important new areas of spin physics (the multipole structure of the nucleon and nuclear response functions) will be unique in the world. The upgrade will produce cw electron beams of excellent quality and very high intensity. It will be especially important for studying nucleon knockout and delta propagation in the nucleus. The proposal is exceptionally cost-effective because of the existence of the Bates linac and recirculator injector and of many of the requisite spectrometers and experimental facilities. It has very high institutional merit because of MIT's crucial role in graduate training for nuclear physics and its very strong support in theoretical physics. All these factors combine to create a singularly compelling upgrade.

- 1.4 University of Illinois

The proposed upgrade of the microtron facility fully addresses the electromagnetic research program of high scientific merit at lower energies. The upgraded accelerator will possess the exceptional beam quality and current of a microtron. Its physics and energy regime are complementary to those of Bates and, in turn, to those of CEBAF and will be unique on the national scene and will match or exceed the best competition abroad. A complete program of knockout reactions with electrons of several hundred MeV will lead to a much more incisive understanding of important nuclear physics questions. The proposal is very cost-effective. It has very high institutional merit because of the University of Illinois' vital role in graduate training for nuclear physics and its strong supporting program in theoretical nuclear physics.

- 1.5 Structured Program in Heavy-Ion Physics

- a. With the advent of its booster, the fixed target facility of AGS - operating at beam energies from 1 to 15 GeV per nucleon -

will support very important studies of the quark-gluon plasma in the high-density baryon-rich regime, thereby providing a very important precursor to the RHIC program.

- b. There is very high scientific merit for a fixed-target facility providing heavy-ion beams throughout the periodic table with energies up to 1 GeV per nucleon and with intensities much greater than those of the existing Bevalac. Such a facility could provide a very diverse program of research but is especially driven by the need to understand nuclear dynamics, nuclear matter and energy flow and the nuclear equation of state at moderate temperatures and densities. On the world scene only one facility operating in this energy regime is now under construction - at GSI in Darmstadt, West Germany. It is crucial to encourage a strong program in detector development for such facilities.

- 1.6 Lawrence Berkeley Laboratory

The proposed upgrade of the synchrotron would effectively address the important physics questions of very high scientific merit for heavy ions at intermediate energies (up to 1 GeV per nucleon). Its firm basis in the pioneering work on the Bevalac makes this upgrade particularly compelling. The upgrade is supported by a strong accelerator group and is cost-effective because it would build on the existing experimental facilities of the Bevalac laboratory. It would attract a sizable user community and would be likely to lead to a later request for a cooler/storage ring addition.

- 1.7 Oak Ridge National Laboratory

The proposed synchrotron-cooler combination is a machine well suited to address the important physics questions of very high scientific merit for heavy ions at intermediate energies (up to 1 GeV per nucleon). The cooler/storage ring which constitutes about half of the capital costs would be able to address many questions in light-ion physics, rare-isotope production and atomic physics, but these do not have quite the present urgency of the direct experiments with synchrotron beams of intermediate energy for the study of nuclear matter and its equation of state. The facility would attract a sizable user community and have strong university associations, particularly through the establishment at Oak Ridge of the Joint Institute for Heavy-Ion Research by the State of Tennessee.

- 1.8 General Impact and Balance Issues

The 4 GeV electron accelerator (CEBAF), the relativistic heavy-ion collider (RHIC), the electron accelerator upgrades and an intermediate-energy heavy-ion upgrade are essential to maintain a

world-leading position for the United States in the subfields of electromagnetic research and heavy-ion physics. Within a nuclear physics community of roughly the present size, we believe that the present initiatives can be pursued without damage to the other vital parts of the nuclear physics enterprise - especially physics with light ions, protons, mesons, antinucleons, neutrons and other probes - not addressed by us. The structured program of electromagnetic research, with CEBAF and two facilities at lower energy have always been expected to attract nuclear physics users from other areas. The expected changes are now happening and the appropriate community appears to exist to support the full structured program. RHIC promises to attract a substantial influx of users from the particle physics community as is already happening in the AGS program of relativistic heavy-ion physics at Brookhaven and also in the corresponding program in Europe. The intermediate-energy upgrades in both electromagnetic and heavy-ion research have the compelling science and the strong user communities to support a vital and balanced national program in these subfields for the next decade.

2. INTRODUCTION

The DOE/NSF Nuclear Science Advisory Committee (NSAC) was recently requested by Dr. Marcel Bardon (Director, Division of Physics, National Science Foundation (NSF)) and Dr. Alvin Trivelpiece (Director, Office of Energy Research, Department of Energy (DOE)) to conduct a review with two aspects;

- (1) to evaluate the scientific capabilities of the Brookhaven National Laboratory's planned Relativistic Heavy Ion Collider facility and,
- (2) to review for scientific merit four proposals which have recently been submitted to the Department of Energy and the National Science Foundation for the upgrade of nuclear physics accelerator facilities.

Background consideration for this study should include the recognition that, consistent with the NSAC's "Long Range Plan for Nuclear Science", the Department of Energy places its highest priority for new construction on the CEBAF electron accelerator and the RHIC facility.

The specific charge to NSAC was to:

"Review the plans for the Relativistic Heavy Ion Collider facility at Brookhaven National Laboratory to evaluate its potentiality for addressing the scientific goals identified in NSAC's December 1983 'Long Range Plan for Nuclear Science' and their subsequent review and affirmation by NSAC in November 1984. Evaluate the capability of the planned facility to support the scientific program required to achieve those goals. Identify those scientific and technological areas, if any, for which further study by the Department of Energy is deemed desirable.

"Within the context of existing or planned facilities, NSAC's December 1983 'Long Range Plan for Nuclear Science', and its subsequent review and reaffirmation by NSAC in November 1984, review and evaluate for their own individual scientific merit the proposals for the upgrade of facilities submitted by the University of Illinois, Lawrence Berkeley National Laboratory, Massachusetts Institute of Technology, and Oak Ridge National Laboratory. Your opinion should reflect your judgment of the impact that each of these upgrades would have on the short-term and long-term health and balance of the field of nuclear physics."

In turn, NSAC established the present Subcommittee whose membership is: Professor Peter Braun-Munzinger, State University of New York - Stony Brook; Dr. Harold C. Britt, Los Alamos National Laboratory; Professor Hall L. Crannell, Catholic University of America; Dr. Harold E. Jackson, Jr., Argonne National Laboratory; Professor Franz L. Gross, CEBAF and the College of William and Mary; Professor Ernest M. Henley, University of Washington (ex-officio, chairman of NSAC); Professor Malcolm H. Macfarlane, Indiana University; Professor Ulrich Mosel, University of Giessen, West Germany and Michigan State University; Professor Robert E. Tribble, Texas A&M University; and Professor Erich W. Vogt, TRIUMF (chairman). The Subcommittee was asked to carry out the requested study and to report its progress or findings to an NSAC meeting scheduled for June 16-17, 1986.

To carry out its work on such a short-time scale the Subcommittee made one-day site visits in mid-May to each of the laboratories whose proposals were under review or evaluation; it relied heavily on the written proposals and other material supplied by the laboratories. It benefitted from generally excellent presentations made at each of the sites and from the responses to its questions. Consideration of its findings and work on drafting the report was carried out by the whole Subcommittee following each of the site visits. The Subcommittee's study and its findings in response to the charge are given in the following sections. In the Appendix we give a brief synopsis of each proposal including a description of the facility proposed and its cost.

3. BROOKHAVEN NATIONAL LABORATORY (BNL) - RELATIVISTIC HEAVY-ION COLLIDER (RHIC)

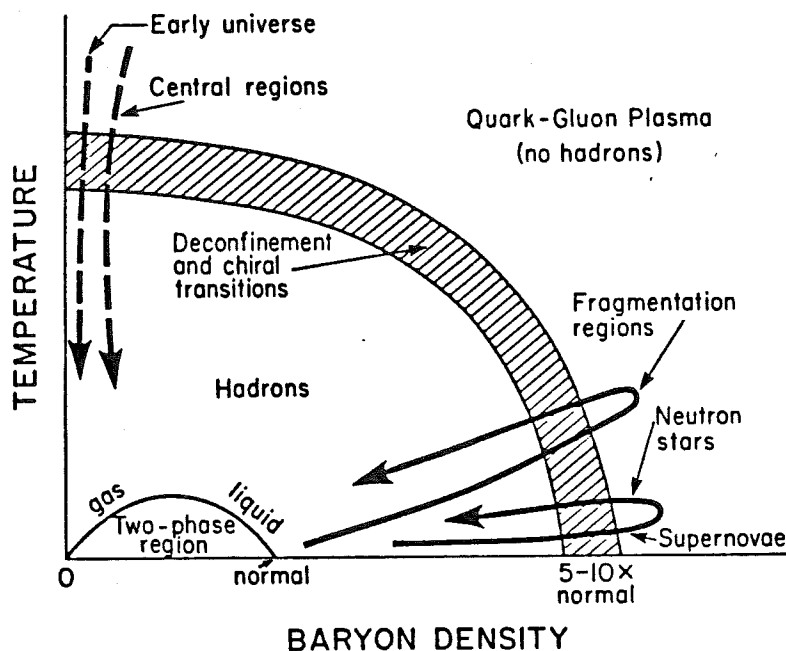
In NSAC's "Long Range Plan for Nuclear Science" of December 1983 and the subsequent review and affirmation of the plan by NSAC, in November 1984, the construction of a relativistic heavy-ion collider received the highest scientific priority for major new construction (assuming the CEBAF will receive Congressional approval for construction). The scientific goals identified by NSAC pertained to the study of hadronic matter under extreme conditions of high energy density and temperature and its possible transition, over significant volumes of space and time, to a deconfined plasma of quarks and gluons. This very interesting new state of matter, never before created in the laboratory, is believed to have existed in the universe only in the first microseconds after the Big Bang. Its study is important to an understanding of the large scale structure of quantum chromodynamics (QCD), the present theory of the strong interactions, and of the dynamics of strongly-interacting systems of hadrons. The Subcommittee considered how

the recent development of the field has affected those scientific goals and the potential of the RHIC proposal for addressing those goals.

Since its beginning in the early 1980's the field of physics associated with ultrarelativistic heavy-ions (beam energies much greater than 1 GeV per nucleon) has acquired increasing scientific momentum. Year by year its central ideas have been more clearly articulated and the interest of the scientific community as a whole has grown.

Figure 1.

Temperature - Baryon Density Phase Diagram of Hadronic Matter.



The underlying scientific ideas can be described in terms of a phase diagram (Fig. 1) for nuclear matter with density and temperature as thermodynamic variables. The scientific questions to be addressed concern physical properties and phases in the various regions of this diagram and the ability to attain these regions in heavy-ion reactions. In the presentations which we heard at BNL we were impressed with recent progress on both of these issues.

The important questions of the existence and nature of a phase transition to deconfined quarks can be studied theoretically using lattice gauge theory techniques to handle the difficult equations of QCD. Increasingly sophisticated computations incorporating colored quarks as well as gluons have recently strengthened the arguments for the occurrence of a deconfined plasma as indicated on Fig. 1. They also provide an increasing understanding of the physical parameters governing the phase transitions and the properties of strong interaction (QCD) thermodynamics. A substantial theoretical community, cutting across the traditional boundaries of nuclear and particle physics, has emerged.

Better understanding is being achieved of the trajectories in phase space that heavy ions follow in pursuit of the physics of phase transitions. The ability of ultrarelativistic heavy-ion reactions to achieve high

temperature and density is strongly supported by recent investigations of proton-nucleus collisions with high energy (> 20 GeV) proton beams. Contrary to simple extrapolations from pp collisions, these experiments indicate large rapidity shifts in central collisions and much harder transverse energy distributions. Even for the fragmentation regimes of the 'nuclei' emerging from the collision these new results imply a much greater width in rapidity space. This new work implies that the creation of a baryon-free central region of deconfinement requires colliding heavy-ion beams of about 100 GeV per nucleon, which corresponds to the design energy of RHIC.

Although this was not a technical review of RHIC the Subcommittee was very impressed with the accelerator design put forward in the proposal and recently approved by an internally-appointed committee of accelerator experts. The magnet and lattice design are highly developed. The proposed design of the interaction region and the attainable luminosities and beam lifetimes are well within the range necessary to perform experiments even at sub-millibarn cross sections. The choice of the accelerator parameters matches well with the current understanding of the physics of collisions between ultrarelativistic nuclei. The design appears flexible enough to allow future upgrades of both luminosity and beam energy.

We also found considerable progress in understanding the physics of the various possible signatures for the phase transition to a quark-gluon plasma, as well as the essential features of the required detectors. The baryon-free central region in an ultrarelativistic collision is likely to provide the highest initial temperatures. Penetrating probes, such as direct photons and leptons pairs, will convey information about the early stages of the produced system. Pions and kaons could be useful probes for the later stages and the transition to hadronic matter, as well as for testing the equilibrium between different quark species. Nevertheless, much further work on signatures is needed. In particular, it is important to establish stronger connections between the experimental observables and the more theoretical lattice QCD calculations. An important step in this direction will be relativistic hydrodynamic calculations based on the quark-gluon equation of state as obtained from QCD. Attention also needs to be focussed on finite size effects, hadronization of the plasma, and non-equilibrium phenomena.

The detectors for RHIC must be capable of studying the various expected experimental signatures. This is a very important part of the whole project and, again, the recent developments reported to us are very encouraging. A workshop held at BNL in April 1985 resulted in conceptual designs for four major detectors and showed that the necessary complexity is within the current standards of technology developed mainly at high energy physics laboratories. Further substantial progress is presently being made in bringing on line the complex detectors necessary for the fixed-target relativistic heavy-ion program at CERN and at AGS at BNL. Experience gained in this area will be very valuable for the design and development of detectors for RHIC and will also help to develop the necessary skills within the user community. BNL and LBL plan a further joint workshop on RHIC detectors. We consider further work in this area by the entire heavy-ion community essential.

Judging from the present activity in the field we see the potential of a large user community for RHIC, a critical element for an efficient experimental program to exploit the many aspects of its physics. An increasing number of high-energy experimentalists is being drawn into the field, attesting here, as in the theoretical studies of ultrarelativistic nuclear collisions, its great attraction even beyond nuclear physics.

By all available indications RHIC is ready to proceed to construction. An early funding decision will maintain the scientific momentum, will take advantage of the accelerator group presently assembled at Brookhaven for this purpose, will start the formation of experimental collaborations and will provide nuclear physics in the United States with a unique world-leading facility.

As a result of our evaluation of the RHIC proposal of BNL we find that:

- a. The recent development of the field of relativistic heavy-ion physics has further strengthened the very high scientific merit for this project identified in NSAC's December 1983 "Long Range Plan for Nuclear Science" and its subsequent review and affirmation by NSAC in 1984. These reports gave RHIC the highest priority for the next major new construction (assuming that CEBAF, which has already been approved for construction by DOE will, in turn, receive Congressional approval for construction);
- b. The facility as proposed is fully capable of achieving the scientific goals identified by NSAC;
- c. As the project proceeds toward construction the heavy-ion research community will need to continue to pursue vigorously the ideas in the underlying theory and the development of detectors appropriate for the research program; and
- d. RHIC will provide nuclear science in the United States with a unique world-leading facility with almost unparalleled potential for new discovery.

4. THE STRUCTURED PROGRAM FOR ELECTROMAGNETIC PHYSICS

The special role of the electron as a probe of nuclear structure is generally recognized. It stems from two basic facts. First, the electromagnetic interaction is well understood through quantum electrodynamics and weak enough for perturbative treatment. Second, the electron probe has great kinematic versatility; the energy and momentum transferred to the nucleus can be varied independently by choice of bombarding energy, energy loss and scattering angle.

A wealth of precise information about nuclear wave-functions, excitations, and charge-and-magnetization densities has been obtained from single-

arm electron-scattering experiments with electron accelerators of low duty factor. Advances in technology now permit the construction of continuous-beam (cw) electron accelerators with energies from tens of MeV to tens of GeV. These new accelerators will extend the power of electron probes to a wide range of new experiments wherein the possibilities of detecting reaction products in coincidence can be fully exploited.

We next discuss the elements of the structured program in electromagnetic physics advocated by NSAC long-range plans and committee reports on electromagnetic physics dating back to the Friedlander report of 1976. A key piece of this structured program, the CEBAF accelerator, is now firmly scheduled for construction by DOE and it is in this context that we frame our discussion. The structured program has its roots in the identification of distinct physical regimes in the response of nuclei to electron beams of varying energy and correspondingly-varying spatial resolution.

We distinguish three main regimes.

1. At spatial resolutions of a few fm or more, corresponding to electron momentum transfers up to a few hundred MeV/c, the nucleus responds as an assembly of nucleons exhibiting various aspects of single-particle and collective motions.
2. At momentum transfers from a few hundred MeV/c to a few GeV/c, the role of mesons and of excited nucleon states in the nuclear response assumes crucial importance.
3. At momentum transfers somewhere in the region of one GeV/c and above, with spatial resolutions much less than the size of the nucleon, the details of nucleon structure, its modifications in the nuclear medium, and the effect of the nuclear medium on quark confinement will begin to come into view.

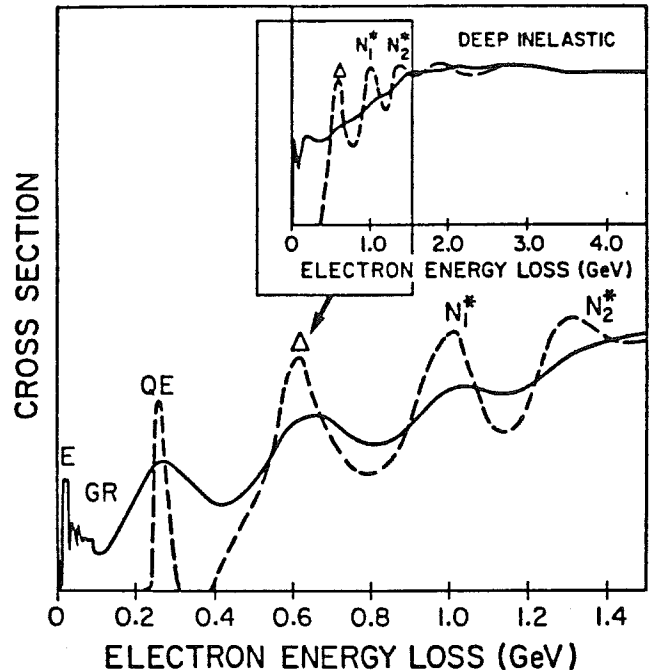
These three regions will be referred to as the nucleonic, hadronic, and confinement regimes, and the structured program in electromagnetic physics aims to use cw electron accelerators to study these three regions in a balanced, cost-effective way.

The idealized inclusive electron spectrum shown in Figure 2 illustrates the electron energies required for studies of each of the regions in a typical case. The dashed line represents scattering from a free proton, and the solid line scattering from a nucleus. For electron energy transfers of 100 MeV or less (the nucleonic regime) discrete nuclear states and giant multipole resonances are excited. At higher energy transfer the spectrum displays a series of broad bumps; the lowest such bump (labeled QE) corresponds to quasi-elastic scattering of electrons from individual nucleons in the nucleus, and the higher bumps to excitations of nucleon resonances. Because of recoil, all of these structures move out in energy as the momentum transfer is increased. While studies of the delta and N* region to the highest momentum transfers (a few GeV/c) will require the full energy of CEBAF, the proposed Illinois and MIT/Bates upgrades, taken together, will permit studies of discrete nuclear states, giant multipole

resonances and quasi-elastic scattering to unprecedented precision and will permit a broad range of detailed studies of the delta region.

Figure 2.

Idealized Inclusive (e, e') Spectrum. Some nucleon resonances and the quasi-elastic (QE) and giant resonance (GR) peaks are indicated.



In the nucleonic region, inclusive (e, e') cross sections yield access to the multipole components of longitudinal and transverse electric and transverse magnetic response functions. Polarized beams and targets and coincidence measurements of decay products will permit a complete separation of multipoles of these nuclear response functions. It is also of great scientific interest to study the behavior of these response functions at large momentum transfer. This work promises to shed new light on the limits of the mean-field description of nuclei and on the role of non-nucleonic degrees of freedom in low-lying states. It is especially important to apply to these studies the whole panoply of spin physics which becomes possible at facilities which provide polarized beams and targets of sufficient quality.

In the quasi-elastic region, the central physical questions concern the mechanism of reactions such as ($e, e'p$), ($e, e'n$), ($e, e'2N$) and what they tell us about one- and two-nucleon response functions. These response functions reveal the ability of a nucleus to release nucleons in definite shell-model orbits with specified energy and momentum. Here, too, polarization measurements will be of great importance, as will complementary studies, with hadronic probes, of reactions such as ($p, 2p$), (p, pn) and ($\pi, \pi'p$). Studies of one- and two-nucleon knock-out probe the structure of deeply-bound hole states, measure the fractional occupation numbers of single-particle levels below and above the Fermi surface and yield information on two-particle correlations. In short, they examine the limitations of the mean-field description of nuclei.

At still higher energy transfers, coincidence studies of reactions such as $(e, e'\pi)$ and $(e, e'\pi N)$ in the delta region will yield information on the propagation of pions and deltas in the nuclear medium. Pion scattering experiments at LAMPF and elsewhere have yielded valuable information on such questions, but fundamental gaps in our knowledge remain, particularly in connection with the role of multi-nucleon processes and the channel dependence of the interactions. Electromagnetic studies, because of their unique kinematic flexibility and theoretical simplicity, provide an indispensable complement to experiments with hadronic probes.

We conclude that the complementary Illinois and MIT/Bates upgrades will give access to a range of important new physics in the nucleonic and hadronic sectors of the structured program in electromagnetic physics. Because of the variety of the physics to be explored, the technical excellence of the proposed facilities and the caliber of their scientific staffs, they are likely to be world leaders in a lively field with significant foreign competition.

We find that, with CEBAF now firmly scheduled by the Department of Energy to begin construction, it is time to pursue the other, complementary parts of the structured electromagnetic research program which have, for many years, had high priority in NSAC's long-range plans. Specifically:

- a) There remains very high scientific merit for a cw electron accelerator at intermediate energies (up to 1 GeV) for high-resolution studies of hadronic degrees of freedom in atomic nuclei.
- b) There remains high scientific merit for a cw electron accelerator at lower energy (up to several hundred MeV) for high-resolution studies of nucleonic degrees of freedom in atomic nuclei.

5. MASSACHUSETTS INSTITUTE OF TECHNOLOGY (BATES LINEAR ACCELERATOR CTR.)

The MIT-Bates Laboratory proposes to upgrade the existing accelerator facility to provide high duty factor (>85%) operation with electron energies up to 1 GeV by means of a pulse stretcher ring complex which will provide both conventional external beams with an internal beam capability hitherto unavailable anywhere. The experimental program will focus on studies of spin observables in nuclear reaction studies and coincidence measurements of hadronic reaction products.

The proposal builds on a vigorous ongoing program in medium-energy electromagnetic physics. That program began in 1974 with the commissioning of the 400 MeV electron linear accelerator and is a distinguished part of a long tradition of nuclear physics at MIT. In its initial configuration the facility furnished electron beams with energies up to 400 MeV and duty factors of less than 1%. In parallel with a flourishing research program, the laboratory has pursued a sustained effort to upgrade the accelerator and its associated facilities. With the installation of an isochronous single-pass recirculator, the maximum unloaded beam energy was raised from 435 MeV to 850 MeV. With the current upgrade of the RF system, which includes the

operation of the recently commissioned sixth modulator system, pulsed operation will be possible next year with maximum unloaded energies of 1060 MeV.

In parallel with these improvements in accelerator performance, the laboratory has assembled a complement of spectrometers and related experimental equipment which provide the essential capabilities to exploit cw beams in the 0.3-1.0 GeV range. As part of the upgrade the laboratory proposes to extend the existing recirculator in order to double the intensity of the cw beam to 100 μ A.

The technical option chosen to obtain cw beams, the linac-stretcher ring configuration, appears to make the most effective use of the existing Bates Laboratory. The existing linac will serve as injector into an extended single-pass isochronous recirculator. An energy compression system, consisting of an achromatic-nonisochronous transport segment and an r.f. accelerating section, will reduce the inherent beam energy spread to 0.04%. The resulting beam will be injected into a pulse stretcher ring designed to operate in the energy range of 0.3-1.0 GeV with peak circulating currents up to 80 ma. External beams of 100 μ A will be obtained by half-integer resonance extraction of the circulating beam. The duty factor of the extracted beams is expected to be >85% and the excellent beam quality of the injected beam, an emittance typically 0.01 π mm-mr, will be preserved in the storage and extraction process. Construction of an internal target hall to facilitate use of the circulating beam without extraction is also part of the proposal.

The facility design appears to present little technical risk since most of the technology is proven state-of-the-art. Multiturn high-efficiency injection into a stretcher ring has been demonstrated at the Lund storage ring project and slow resonance extraction of circulating beams has been demonstrated at the Tohoku University storage ring facility. The energy compression technique has been successfully used in existing linac facilities.

The internal target capability is unique to the Bates proposal. The combination of ultrathin targets, high luminosity, and easily controlled spin polarization and direction will offer exciting opportunities for basic measurements such as the neutron charge form factor as well as for systematic nuclear structure studies in complex nuclei.

Unpolarized internal targets of the required densities have been available for many years. A major technical challenge appears to be the development of polarized gas targets of sufficient density. Several projects aimed at developing optically-pumped polarized targets of deuterium, helium and alkali nuclei are in progress. Prospects for a system of acceptable target thickness are good.

The MIT proposal fills extraordinarily well the requirements for a cw electron accelerator up to 1 GeV to which we assigned very high scientific merit (Section 4). It has full spin capability and all of the tools necessary to pursue high-resolution studies of hadronic degrees of freedom. In addition it has substantial capability for nuclear structure, e.g., for coincidence studies of giant resonances with internal targets.

The availability of an injector and a powerful array of supporting experimental equipment makes this proposal particularly cost-effective. A high resolution energy-loss spectrometer, three large acceptance broad range magnetic spectrometers, and a π^0 spectrometer are operational. A high intensity real photon facility has been commissioned and a polarized electron source is scheduled for operation in the near future (It was in fact achieved in June, 1986). While the Subcommittee did not attempt precise estimates of the real replacement costs of this complex as well as of the existing accelerator, it is clear that much of the estimated \$82M capital cost of these facilities is saved through their use in the proposed upgrade. Since that is much more than the cost of the upgrade, this proposal indeed has high cost-effectiveness.

Institutional aspects of the Bates proposal are especially relevant to the Long Range Plan for Nuclear Science in the United States. The laboratory is a leading source of young physicists, recently providing an average of seven Ph.D.'s per year. Since 1977, 48 Ph.D.'s have been produced by the Bates research program. The program serves a national community of an estimated 250 active users and 2/3 of the beam time is currently given to non-MIT users. The future research is seen as part of a national program complementing CEBAF and NPAS and activities at Bates are expected to include simultaneous commitments to research at CEBAF in areas of strong overlap with the scientific interests of Bates users. As the sponsoring institution, MIT continues a strong commitment to nuclear physics. As part of the financial plan a waiver of \$2M in overhead charges has been extended to the construction project. The Laboratory of Nuclear Science continues a world-class effort in theoretical nuclear and particle physics; currently approximately 25% of the academic staff of the MIT Physics Department are nuclear physicists. Appointments of faculty continue in this area in spite of severe restrictions on new faculty appointments.

The upgraded MIT/Bates Linear Accelerator Center will compete with the cw electron accelerators in the same energy range at Mainz and likely also at Saclay. Because of its outstanding staff, its unequalled array of supporting experimental equipment and the unique possibility of internal-target experiments, we believe that MIT/Bates will retain a world-leading role as an intermediate-energy electromagnetic physics laboratory.

As a result of our review and evaluation of the MIT/Bates upgrade proposal, we find that:

The Bates upgrade proposal fully addresses the electromagnetic research program of very high scientific merit at intermediate energies. The whole capability will be unique on the national scene and match the best competition abroad: its combination of internal target capability and polarized beams for addressing important new areas of spin physics (the multipole structure of the nucleon and nuclear response functions) will be unique in the world. The upgrade will produce cw electron beams of excellent quality and very high intensity. It will be especially important for studying nucleon knockout and delta propagation in the nucleus. The proposal is exceptionally cost-effective because of the existence of the Bates linac and recirculator injector and of many of the requisite spectrometers and experimental facilities. It has very high institutional

merit because of MIT's crucial role in graduate training for nuclear physics and its very strong support in theoretical physics. All these factors combine to create a singularly compelling upgrade.

6. THE UNIVERSITY OF ILLINOIS NUCLEAR PHYSICS LABORATORY

The proposal submitted by the University of Illinois requests funds for construction of a cw race-track electron microtron producing currents of $100\mu\text{A}$ and energies up to 450 MeV. This facility will produce beams of electrons and photons which will provide precise probes for the study of nuclear structure and dynamics, properties of the continuum, pion-threshold phenomena, and low energy delta dynamics.

The University of Illinois has operated a superconducting cw electron microtron for a number of years and it has been the only cw electron accelerator in the United States. The initial program of research conducted at this 67 MeV accelerator was severely restricted by the low current ($<0.5\mu\text{A}$) available. Replacement of the accelerating structure two years ago increased the current to $10\mu\text{A}$ and greatly expanded the range of possible experiments.

The instrumentation effort of the University of Illinois group has concentrated on the development of detectors for use with cw electron and photon beams. This effort has led to the completion of several coincidence experiments [(e,e' γ), (e,e'n), (γ ,pn)] which have produced new results in nuclear physics and have provided a tantalizing glimpse of the potential power of the proposed accelerator. With the kinematic flexibility offered by the energy range of the proposed accelerator from 40 to 450 MeV, it will be possible to extend measurements of transition strengths to the point where transition densities of giant resonance states can be determined. These coincidence electron scattering measurements performed at Illinois require a very clean beam with no halo, and demonstrate the need for the excellent beam quality, typical of that produced by microtrons.

The cw feature of an electron beam can be used to produce mono-energetic beams of photons of reasonable intensity by individually detecting the electrons that radiate the photons (tagging). At Illinois, off-axis tagging has been employed to produce a beam of polarized photons. The power of this new technique has been demonstrated by the observation of most of the energy-weighted isovector magnetic-dipole giant-resonance strength in ^{206}Pb , thus solving a problem that had been the subject of numerous investigations over the past twenty years.

Photons with energies from threshold to approximately 400 MeV provide a well understood probe for the production of deltas in nuclei. The observation of the propagation and decay of these deltas will permit the study of some aspects of delta dynamics in nuclei. The energy of this accelerator is chosen to be optimal for photoproduction studies, but will be insufficient for the complementary electroproduction studies.

An integral part of the new proposal is new experimental areas and facilities appropriate for the increased current and energy, in particular, a magnetic spectrometer with large solid angle and momentum acceptance. The

increase in beam energy and beam current plus the increase in spectrometer solid angle will increase the counting rate for many important coincidence experiments by a factor of a thousand.

The proposed accelerator has been the subject of an intensive research and development effort for several years, and almost all of the major components have been prototyped and extensively tested. The successful operation of microtrons at Illinois and in other countries gives added confidence that the proposed accelerator can be built and successfully operated and that it can be expected to provide superior beam quality and performance. The staff of the nuclear physics laboratory is clearly qualified and prepared to build this accelerator.

One novel feature of the proposed accelerator will be a system for extracting up to three simultaneous beams with independently controlled current capabilities. It will also be possible to provide two independent energies. This system will clearly increase the flexibility and usefulness of the facility, as well as providing excellent access for the user community.

The Illinois proposal matches very well the need for a cw electron accelerator to study nuclear structure -- the nucleonic degrees of freedom -- to which we assigned high scientific priority in Section 4.

The University of Illinois has had and continues to have a very strong program in both experimental and theoretical nuclear physics. The department had graduated several dozen Ph.D.'s in nuclear physics in the past 10 years. The number of graduate students now working in the nuclear physics laboratory has more than doubled during the past 4 years (to 25), in part reflecting the increased capability of the present accelerator. The University has demonstrated its commitment to this program by the addition of a number of excellent members of the faculty during the past 10 years and by agreeing to contribute \$7M of University resources to the construction of the new accelerator.

The proposed accelerator will be the only facility in the United States where high duty factor beams of electrons and photons in the energy range below the lower limit of Bates, 300 MeV, will be available. Indeed, on a worldwide scale this facility will be unique in its energy range with the combination of current and beam quality offered by a microtron.

As a result of our review and evaluation of the University of Illinois upgrade proposal we find that:

The proposed upgrade of the microtron facility fully addresses the electromagnetic research program of high scientific merit at lower energies. The upgraded accelerator will possess the exceptional beam quality and current of a microtron. Its physics and energy regime are complementary to those of Bates and, in turn, to those of CEBAF and will be unique on the national scene and will match or exceed the best competition abroad. A complete program of knockout reactions with electrons of several hundred MeV will lead to a much more incisive understanding of important

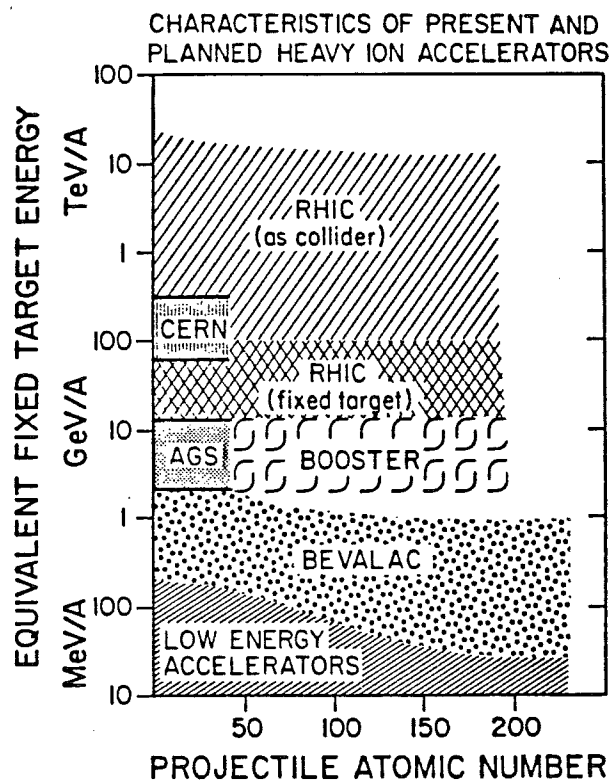
nuclear physics questions. The proposal is very cost-effective. It has very high institutional merit because of the University of Illinois' vital role in graduate training for nuclear physics and its strong supporting program in theoretical nuclear physics.

7. SCIENCE IMPACT OF A MEDIUM-ENERGY HEAVY-ION ACCELERATOR - WITHIN A STRUCTURED NATIONAL PROGRAM ON HEAVY-ION PHYSICS

A major question confronted by this Subcommittee was the scientific importance of a medium-energy heavy-ion facility of the kind proposed by both ORNL and LBL. The two rather similar proposals are discussed in the next two sections. Here we look at the science which they both address, at the international competition they face and at the impact that either would have on the national nuclear physics program. Because of the size, scope and user interest of a medium-energy heavy-ion facility it was clear to the Subcommittee at the outset of its deliberations that it would not be appropriate for the United States to construct more than one such facility.

Figure 3.

Characteristics of Present and Planned Heavy-Ion Accelerators.



The role of a medium-energy heavy-ion accelerator can be placed in the context of a structured national program of heavy-ion research. Different accelerators in different energy regimes address a range of different nuclear physics questions as was the case in the structured program of electromagnetic research. As Figure 3 shows, the very highest energies for

heavy ions throughout the periodic table are to be provided by RHIC. The studies here pertain to the major excursions into the temperature-density plane (Fig. 1) toward a quark-gluon plasma, as discussed in Section 3 above.

At energies below those of RHIC the fixed-target capability of the Brookhaven AGS — with its booster now under construction — will allow limited investigations of the high density, baryon-rich portion of the quark-gluon plasma and set the stage for the broad exploration of this new phase of nuclear matter when RHIC becomes operational. The experience at AGS and CERN with heavy-ion beams and with the detectors now being developed should be invaluable for the RHIC studies which follow.

At energies in between those of the AGS and low-energy heavy-ion accelerators of many other laboratories there is a considerable range of energies in which the LBL Bevalac presently operates. For more than a decade the Bevalac has been a facility (for relativistic heavy-ion physics) unique on the world scene. It has been a pioneering tool of immense importance for initiating and testing the ideas for heavy-ion physics above the low-energy regime. Recent detector developments point to rapid progress in this area especially for kaon, antiproton and dilepton studies, but these and other measurements relevant to the equation of state studies are severely limited by the intensity and quality of the beam delivered by the present Bevalac. Ongoing programs which utilize improvements in detector techniques can be expected to maintain the present vitality of the equation of state efforts utilizing the unique capabilities of the Bevalac for a few more years. Then, however, we expect to have available the full heavy-ion capability of the AGS at higher energies and a new strong focussing synchrotron in the Bevalac energy region with large improvements in beam intensity and quality at the GSI in Darmstadt, West Germany. The increased potential of these facilities will undoubtedly result in a shift away from the leading role the United States has played in this promising field of intermediate energy heavy-ion physics. A possible counter to this trend would be an upgraded synchrotron facility in the U.S.A. to allow the continuation of the current vigorous effort in this field. With this in mind, the Subcommittee considered the importance of the physics in the regime from 0.2 to 1 GeV per nucleon. What is its importance within the structured program in the United States? What would be the likely impact of such an upgraded facility on the national nuclear physics program as a whole?

Although our Subcommittee evaluated the RHIC program and reviewed the two medium-energy proposals for heavy-ion physics, it did not review the considerable low-energy heavy-ion program based on many active accelerator laboratories. Much important physics undoubtedly remains to be done with low-energy heavy ions. In our opinion the physics interest for medium-energy heavy ions is most closely related to the high-energy programs at AGS, CERN and RHIC. It is then primarily in the context of their complementarity to RHIC that we evaluate and review the medium-energy proposals and their impact. We concentrate on the evaluation and review of the medium-energy proposals in the context of their impact on a balanced program of equation of state studies in which medium energies are most appropriate

for studying nucleonic degrees of freedom, while the higher energies of the AGS and RHIC programs will lead us into the new quark-gluon phase.

The most compelling physics justification for intermediate-energy heavy-ion accelerators appears to be their potential for exploring the thermodynamical properties of nuclear matter and its equation of state (EOS). There are many interesting additional physics questions accessible to such facilities -- some of which are described below -- but in our opinion the driving force will be what one can learn about the phase diagram of Figure 1. In the considerable region of this diagram lying between the conditions of normal nuclear matter and the extreme conditions pertaining to deconfinement, there is much new information especially accessible to a medium-energy facility. Hints of this physics have been given by present Bevalac research and by some experiments at lower energies at MSU and at similar facilities abroad.

The energy "window" between 0.1 and a few GeV per nucleon is the EOS regime. In heavy-ion reactions below 0.2 GeV per nucleon, not enough compression is achieved to go significantly above normal density. At energies far above 1 GeV per nucleon, nuclear reactions achieve large compressions but the reaction dynamics are determined by individual nucleon (NN) collisions and can be successfully described by intranuclear cascade models.

In the imprecisely-defined intermediate region, the collision dynamics reflect the energy needed to achieve compression, that is, to the EOS of nuclear matter, even though NN collisions play a significant role. The theoretical analyses permit treatment of mean field effects and NN collisions on an equal footing. It is found that the observed hydrodynamical flow of nuclear matter is very sensitive to the EOS employed in the theoretical analyses.

The importance of transverse matter flow in studies of the EOS has emerged from the recent experimental program at the Bevalac. The observed hydrodynamical flow-angle is largest around 300 to 400 MeV per nucleon, in agreement with the theoretical arguments given about the diminishing sensitivity of the results of the nuclear EOS at very high energies.

The need for much higher heavy-ion intensities is that the exploration of this region of the EOS will require experiments which go beyond the measurement of the angle of hydrodynamic flow. It will require a coordinated effort to study systematically and simultaneously many additional observables, for example, strange particle and direct-lepton production. The production can occur from processes which depend on the compressional energy, but NN collisions can produce these particles directly. It will be essential to study the separation of these two production processes in the energy window, both as a diagnostic tool for the EOS and to provide a basis of the analogous separation at the much higher energies of RHIC. In addition to accelerator improvements these experiments will require a strong detector development program to effectively exploit much higher-intensity and higher-energy beams.

The thermal behavior of nuclear matter at the temperatures and densities attainable with a medium-energy heavy-ion facility should be very interesting. As indicated on Figure 1, the present theory of infinite nuclear matter predicts the existence of a phase transition from the liquid to the gaseous phase with a critical point for nuclear matter at half normal density and a temperature of about 18 MeV. At this point the nuclear liquid, as it is found in the nuclear ground state, and the nuclear gas would be in equilibrium. Does this phase transition really occur in the finite charged interaction zones produced in heavy-ion collisions? Although relevant measurements of this thermal behavior can be carried out at moderate energies, many of the crucial measurements require high quality heavy-ion beams in the energy region of a few hundred MeV per nucleon.

In addition to the EOS studies there are many important areas of research for a medium-energy heavy-ion facility especially with the added capability of a storage-cooler ring. Some of these additional areas are: the direct excitation and fragmentation of nuclei in the very large electromagnetic fields available for beams of very heavy nuclei; the atomic physics of high-Z one-electron systems; the spectroscopy of exotic nuclei far from stability produced in fragmentation reactions and stored or cooled in a storage-cooler ring; the investigation of charge transfer and delta matter with light-ion beams of very high quality. In our opinion the physics made possible by the addition of a storage-cooler ring is very attractive but not so compelling as the EOS studies.

The Bevalac has been a pioneering facility, unique in the world for the past decade. Its work has attracted an international community which has used it to pioneer the field of relativistic and medium-energy heavy-ion physics. Its experiments have established the need for a next-generation facility -- a medium-energy heavy-ion accelerator of greatly increased beam quality and current. Such a facility is now under construction at GSI in Darmstadt, West Germany, with completion expected in 1989. It will have a large user community in Europe. Although U.S. physicists will be welcome at GSI there are, in our opinion, a sufficient and active U.S. community and sufficient physics interest to justify one of the two medium-energy upgrades. Without such an upgrade the structured program of heavy-ion physics in the United States would lack its medium-energy component and would be severely handicapped.

As a result of our evaluations and deliberations we find that:

- a. With the advent of its booster, the fixed target facility of AGS - operating at beam energies from 1 to 15 GeV per nucleon - will support very important studies of the quark-gluon plasma in the high-density baryon-rich regime, thereby providing a very important precursor to the RHIC program.
- b. There is very high scientific merit for a fixed-target facility providing heavy-ion beams throughout the periodic table with energies up to 1 GeV per nucleon and with intensities much greater than those of the existing Bevalac. Such a facility could provide a very diverse program of research but is especially driven by the need to understand nuclear dynamics,

nuclear matter and energy flow and the nuclear equation of state at moderate temperatures and densities. On the world scene only one facility operating in this energy regime is now under construction - at GSI in Darmstadt, West Germany. It is crucial to encourage a strong program in detector development for such facilities.

8. LAWRENCE BERKELEY LABORATORY (LBL)

The LBL upgrade proposal builds on existing facilities and scientific experience. When the Bevatron began operation with proton beams three decades ago, it was a world-leading facility for particle physics. When it no longer competed on the high-energy frontier, it began a second career in 1974, as the Bevalac, intended to pioneer the field of relativistic heavy-ion physics. During the past decade it has been unique in the world in providing beams up to 2 GeV per nucleon, and with improvements in the Bevalac's vacuum system, it has produced beams of even the heaviest ions.

The Bevalac program has provided the ideas and the user community for the present pursuit of physics centered on the EOS questions in medium-energy heavy-ion physics. Its pioneering work attracted strong teams from across the nation and around the world. It required the development of appropriate detectors to measure the many particles emitted in reactions of medium-energy heavy-ions. Serious limits are now placed on the research program by the poor beam quality and intensity of the current Bevalac. Further, the research has been hampered by the beam sharing at the Bevalac between nuclear research and medical radiotherapy and the inadequacy of the beam switching techniques for such sharing.

The LBL proposal would replace the existing Bevatron with a modern strong-focusing synchrotron. The new synchrotron would utilize the existing SuperHILAC and local injector as ion sources. The system would be capable of accelerating light ions up to 2 GeV per nucleon and the heaviest ions up to 0.87 GeV per nucleon. It also permits the fast switching between ion beams needed to accommodate simultaneously the radiotherapy and nuclear science programs. The intensities would be several orders of magnitude above those of the existing Bevalac. The project appears to be straightforward requiring only a modest amount of further research and development.

The upgrade does not include a storage/cooler ring, viewed here as an attractive later addition. It is, we believe, fully able to address the physics centered on the nuclear-matter EOS - the physics we regard as the most compelling justification for a medium-energy facility.

The LBL upgrade would make some use of existing experimental facilities - such as the heavy-ion spectrometer system, the dilepton spectrometer and the streamer chamber - but it would very much need a new 4π multitrack detector. One such detector, the time-projection chamber (TPC), is discussed in the LBL upgrade proposal. The lack of such a detector in the Bevalac program, with the shift of the Plastic Ball and most of its users to CERN, is a serious deficiency. The development of a new

generation of 4π detector would be valuable even with the present Bevalac and would be essential as a part of the program on an upgraded accelerator.

The LBL upgrade proposal is particularly compelling because it builds on the Bevalac program with its user community and experience. It is timely to provide the United States with a medium-energy heavy-ion facility of world rank. The LBL proposal is supported by a number of institutional strengths. LBL has one of the nation's strongest accelerator research groups and considerable expertise in detector technology. The laboratory has a strong effort in nuclear theory in support of the medium-energy program. The Bevalac program has produced a considerable number of graduate students, especially through its close connection with the Chemistry Department of the University of California at Berkeley (UCB). One would hope and expect that the compelling science of the upgrade would, in addition, command the interest of the UCB Physics Department.

As a result of our review and evaluation of the proposal of LBL, we find that:

The proposed upgrade of the synchrotron would effectively address the important physics questions of very high scientific merit for heavy ions at intermediate energies (up to 1 GeV per nucleon). Its firm basis in the pioneering work on the Bevalac makes this upgrade particularly compelling. The upgrade is supported by a strong accelerator group and is cost-effective because it would build on the existing experimental facilities of the Bevalac laboratory. It would attract a sizable user community and would be likely to lead to a later request for a cooler/storage ring addition.

9. OAK RIDGE NATIONAL LABORATORY (ORNL)

The proposed upgrade of the Holifield Facility at ORNL to produce medium-energy heavy ion beams would use the existing 25 MeV tandem accelerator as an injector into a set of three synchrotrons. A booster ring would accept the beam from the tandem and prepare it for injection into the main accelerator ring. The main accelerator ring would achieve energies up to 1.5 GeV per nucleon for light ions and up to 0.5 GeV per nucleon for the heaviest ions, with high beam quality and beam intensities about 1000 times larger than those of the existing Bevalac and at least as great as those of the proposed LBL upgrade. The third ring would provide slow extraction (100% duty factor), a cooled beam of extraordinary brightness and would store and accelerate secondary beams of radioactive ions. It therefore has the full capability of the medium-energy heavy-ion facility to which we assigned very high scientific priority for EOS studies and would also provide from the outset the capabilities provided by a storage/cooler ring.

As an institution to support a national medium-energy heavy-ion facility ORNL has many strengths. It has a long history in low-energy heavy-ion physics. Its scientists have recently become involved in experiments of higher energy at the Bevalac and at CERN; it is probably the world's foremost site for the production of rare isotopes. It is a large national laboratory with great depth of technical support. It has close

association with the University of Tennessee at Knoxville and with Vanderbilt University of Nashville, particularly through the development of the Joint Institute of Heavy Ion Research (JIHIR) between ORNL and the former University. It has a growing theory group of considerable strength. It promises to provide facilities for a large number of user groups from other laboratories and universities.

As a result of our review and evaluation of the proposal of ORNL we find that:

The proposed synchrotron-cooler combination is a machine well suited to address the important physics questions of very high scientific merit for heavy ions at intermediate energies (up to 1 GeV per nucleon). The cooler/storage ring which constitutes about half of the capital costs would be able to address many questions in light-ion physics, rare-isotope production and atomic physics, but these do not have quite the present urgency of the direct experiments with synchrotron beams for the study of intermediate energy of nuclear matter and its equation of state. The facility would attract a sizable user community and have strong university associations, particularly through the establishment at Oak Ridge of the Joint Institute for Heavy-Ion Research by the State of Tennessee.

10. HEALTH AND BALANCE OF NUCLEAR PHYSICS

The Subcommittee was asked to examine the proposed upgrades in relationship to "the short-term and long-term health and balance of the field of nuclear physics." In view of the proposals before it, the Subcommittee naturally concentrated on the nuclear physics which can be carried out with electromagnetic and heavy-ion probes. However, it should be realized that the health of nuclear physics requires other probes to explore fully the many facets and questions in the field. For example, investigations with nucleons, antiprotons, mesons (particularly pions and kaons) muons and neutrinos are required to explore questions related to basic hadronic forces in nuclei and weak interactions. We believe that the balance of the field requires high quality beams of these particles to fully explore important questions of basic forces, of structure and of the dynamical laws which govern nuclei.

Equally important to the health of the field is a strong community of nuclear physicists. We have addressed the science of structured programs in both electromagnetic research and heavy-ion physics. Both would appear to require some influx of researchers. Is such an influx reasonable considering the balance and health of the field?

In our discussion of the health and balance of the field, we were asked to assume that the nuclear physics community in the United States will remain of roughly constant size. This we feel to be an unduly pessimistic assumption particularly based upon the mistaken assumption that this community will be the only source of users for the new facilities. First, the great interest of the physics accessible to CEBAF, RHIC and the proposed upgrades should attract able young people in significant numbers into the field. Second, the university upgrades will directly enhance the recruit-

ment of graduate students. Third, the research programs of CEBAF, RHIC and the upgraded facilities will attract foreign users and users from today's particle physics community. Given adequate support, the prospects for a significant growth of the nuclear community are good.

Furthermore, it has always been understood that the electromagnetic research program, central to the NSAC Long Range Plan, would attract a growing proportion of the nuclear physics community. The users and user interest appears to be there. The relativistic heavy-ion program, in turn, has the potential of drawing in a substantial number of users from both the existing nuclear and particle physics communities. A broad measure of this potential is the rate of growth of activity over the past few years. Starting from a relatively small community centered at the Bevalac, we have seen relativistic heavy-ion physics grow to the level where there are now eight major experiments approved and at various stages of completion to run at AGS and CERN. In addition, there has been considerable effort by a large group on the planning and development of RHIC and its detector-systems. Recent experience with the relativistic heavy-ion programs at AGS and CERN suggests that perhaps half the users of RHIC will come from the high-energy physics community. There also promises to be considerable interest among high-energy physics users for the experiments which use medium-energy protons, antinucleons, mesons, muons and neutrino and medium and high-energy electrons as probes. Although we have not been able to carry out a proper analysis of the user community, these considerations suggest the existence of a potential user community adequate to carry out the structured programs we have addressed while maintaining the health and balance of the field.

In summary then we find that:

The 4 GeV electron accelerator (CEBAF), the relativistic heavy-ion collider (RHIC), the electron accelerator upgrades and an intermediate-energy heavy-ion upgrade are essential to maintain a world-leading position for the United States in the subfields of electromagnetic research and heavy-ion physics. Within a nuclear physics community of roughly the present size, we believe that the present initiatives can be pursued without damage to the other vital parts of the nuclear physics enterprise - especially physics with light ions, protons, mesons, antinucleons, neutrons and other probes - not addressed by us. The structured program of electromagnetic research, with CEBAF and two facilities at lower energy have always been expected to attract nuclear physics users from other areas. The expected changes are now happening and the appropriate community appears to exist to support the full structured program. RHIC promises to attract a substantial influx of users from the particle physics community as is already happening in the AGS program of relativistic heavy-ion physics at Brookhaven and also in the corresponding program in Europe. The intermediate-energy upgrades in both electromagnetic and heavy-ion research have the compelling science and the strong user communities to support a vital and balanced national program in these subfields for the next decade.

APPENDIX: SYNOPSES OF PROPOSALS

A.1. Brookhaven National Laboratory:

Brookhaven National Laboratory proposes the construction of a Relativistic Heavy Ion Collider (RHIC). With a top energy of 100 GeV per nucleon for beams of gold nuclei, RHIC would allow exploration of the baryon-free central region of rapidity, as well as studies of high-energy and high-baryon densities in the nuclear fragmentation region. The construction of RHIC makes use of the existing Alternating Gradient Synchrotron (AGS) and the Tandem facility, for the injector source of heavy ions, and the remaining tunnel (3.8 km circumference) and facilities from the former Colliding Beam Accelerator (CBA) project. A construction project which links the Tandem and the AGS is in final stages of commissioning. Completion of that project will provide heavy ions of about 14 GeV per nucleon kinetic energy with masses up to 32 (sulfur). The addition of a booster synchrotron to the AGS, initially funded in FY 1986, will extend the mass range to the heaviest ions ($A = 200$, gold). Only the heavy-ion collider itself is requested in the present proposal.

The collider will consist of two rings of superconducting magnets capable of accelerating and storing beams at energies up to 100 GeV per nucleon for the heaviest ions. Average luminosities of 10^{26} to 10^{27} $\text{cm}^{-2} \text{sec}^{-1}$ are predicted for gold-on-gold collisions at full energy depending on the details of the experimental insertion layout. The collider will cover the entire range from 7 to 100 GeV per nucleon. By operating one of the rings in an internal fixed target mode, the energy range can be extended downward to overlap with AGS fixed target capabilities (see Figure 3 of the text).

The physical plant for the collider, for the most part, exists and only a modest expenditure is required to complete all the remaining conventional facilities. The existing tunnel configuration provides six experimental areas where the ring beams cross. The RHIC cryogenic system features a helium refrigerator which is fully installed.

The total estimated cost is \$178.2M in 1986 dollars. This includes a 17% contingency. A four-year construction period is proposed. The estimated cost of the detectors needed for the research program is an additional cost of \$62M. The estimated incremental operating cost of the RHIC facility is \$29.7M. A conceptual design report has been prepared. Some further R&D work is needed to complete the design of the accelerator as well as to complete the design and development of the superconducting magnets. By the summer of 1986 four full-length RHIC magnets will have been built in collaboration with industry.

A.2. Massachusetts Institute of Technology:

The Massachusetts Institute of Technology proposes an upgrade of the Bates Linear Accelerator Center to provide high-duty-factor (cw) electron beams in the energy range of 300 MeV to 1 GeV. The proposed experimental program would focus on studies of spin observables in nuclear reactions and coincidence measurements of hadronic reaction products. The central

element in the proposal is a Pulse Stretcher Ring (PSR) which, when fed by the existing accelerator/recirculator system, would produce electron beams with a duty factor of ~85%, output emittance $\sim 10^{-8}$ m-rad, and energy spread ~0.04%. A proposed internal target hall, a 40' x 50' structure intersecting the ring, would allow a very important program of internal target experiments. An extended recirculator is also proposed which would allow doubling of the pulse length to be injected into the ring for energies between 500 MeV and 1 GeV. This would effectively double the average current and would improve beam quality for the upper half of the accelerator energy range. The experimental facilities needed to exploit the cw capability (four magnetic spectrometers, neutral pion and photon detectors) already exist.

The cost of the proposed construction project is \$22.1M in 1986 dollars and includes 20% contingency. The annual incremental operating cost is estimated to be \$1.6M. In addition to the written proposal, a draft conceptual design report and a management plan has been prepared.

A.3. University of Illinois:

The University of Illinois proposes to replace the existing 10 microampere, 100 MeV microtron at the Nuclear Physics Laboratory with a 100 microampere, 450 MeV cascade microtron. This facility will produce beams of electrons and photons which will provide precise probes for the study of nuclear structure and dynamics, pion threshold behavior, and low energy delta dynamics. The proposed accelerator is a two-stage microtron. Each stage uses a pair of 180-degree bending magnets as part of a system that recirculates the electrons through a room-temperature linac. Also proposed is the construction of new experimental areas that will house a high-resolution, large-solid-angle electron spectrometer, a photon monochromator capable of producing polarized photons, and a bremsstrahlung irradiation facility. The facility is capable of delivering simultaneous beams to the three experimental areas.

The incremental funding from Federal sources required for construction including a 15% contingency, is estimated at \$10.7M in FY 1986 dollars. The incremental annual operating cost is estimated at \$3.0M from Federal sources. The proposed accelerator has been the subject of an intensive R&D effort for several years, and almost all of the major components have been prototyped and extensively tested.

A.4. Lawrence Berkeley Laboratory:

The Lawrence Berkeley Laboratory proposes a major upgrading of the Bevalac accelerator complex by replacing its heavy-ion synchrotron - the Bevatron - with a modern, strong-focusing, 18-Tm synchrotron. The dominant theme of research is expected to be the creation and exploration of nuclear matter under extraordinary conditions. Other research avenues with heavy-ion beams will be opened, especially through the use of high-intensity beams of

secondary radioactive nuclei. The upgraded accelerator would deliver beams over essentially the same energy range as the existing accelerator (up to 1 GeV per nucleon for uranium), but of more than a factor of 100 greater intensity and with improved duty factor. The possibility of single-turn extraction of the beam will enable pulse-to-pulse beam sharing and would allow the upgraded Bevalac to accommodate simultaneously the medical therapy and nuclear science programs. The upgrade would also significantly improve the facility's operational reliability and economy. The upgrade does not include a storage/cooler ring, viewed as an attractive later addition.

The total estimated cost is \$32.5M in FY 1986 dollars including a 40% contingency, and the project is expected to be completed in three years. Facility operating costs are expected to be smaller by several million dollars annually than at present. A preliminary proposal has been written. R&D funding has been requested from DOE for the development and prototyping of accelerator ring magnets, vacuum system, rf system, and other components.

A.5. Oak Ridge National Laboratory:

Oak Ridge National Laboratory proposes a major addition to the Holifield Heavy Ion Research Facility. The expanded facility would provide beams of mass 1 to 238 at energies up to 1.5 GeV per nucleon for the lightest ions and to 0.9 GeV per nucleon for the heaviest. These beams would provide a broad diversity of new research opportunities in medium-energy, light-ion physics, photonuclear physics, nuclear structure physics, atomic physics, and astrophysics. The beam intensities at full energy would range from approximately 10^{11} ions/second for ions such as carbon to approximately 10^{10} ions/second for the heaviest ions. The complete facility would consist of the existing 25 MV tandem accelerator as the injector, a 4-Tm rapid-cycling accumulator/booster ring, a 15-Tm main synchrotron accelerator ring, and a 10-Tm storage/cooler ring. In addition to experimental space within the existing complex, a new building would provide 18,000 sq. ft. of high-bay experimental area. The 15-Tm ring could slow-extract beams to any of the experimental areas and fast-extract to the cooler ring. The cooler could provide electron cooling for very high quality primary beams. The transfer line to the cooler contains a target to allow production of secondary beams which could be separated and captured in the cooler ring. Stochastic cooling is proposed for good quality radioactive beams that could then be transferred back to the 15-Tm ring for acceleration or deceleration.

Total estimated cost of the facility, including a 25% contingency, is \$68.4M in FY 1986 dollars. Incremental operating costs are estimated at \$6.5M annually. The total time for completion of the project is six years. A preliminary proposal has been written. R&D funding has been requested from DOE for development and prototyping of accelerator subsystems such as pulsed magnets, rf systems, ultra-high vacuum systems, very-low-noise beam diagnostics, and accelerator controls.