A LONG RANGE PLAN FOR NUCLEAR SCIENCE

DECEMBER 1979

The DOE/NSF Nuclear Science Advisory Committee

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December 21, 1979

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Dear Neal and Jim,

I enclose a copy of "A Long Range Plan for Nuclear Science", a report requested by the NSF/DOE letter of May 14, 1979. The report describes the long range plan as finally developed by NUSAC and its consultants in a week long meeting held July 30 through August 4, 1979. As the Preface points out, it was not possible in the short time span available to respond to all the issues raised in the NSF/DOE letter. The report restricts its considerations to identifying the important scientific questions to be attacked in the next decade as perceived by the Committee and upon the capabilities which are thus required. We have developed what we feel is an extraordinarily exciting program. Its successful execution will undoubtedly lead to advances of fundamental importance and wide significance.

It is to be emphasized that the long range plan formulated by the Committee is a minimal program including only those components which are essential for the U.S. nuclear science community to be able to address the important scientific issues of the next decade. It by no means permits the optimal utilization of manpower and facilities. This would require considerable additions particularly to the funding for operations and capital equipment as recommended in Recommendation A of the Friedlander panel. The Committee, as stated in the Preface, regards its implementation of first importance. However, the recent history of the U.S. funding of the Nuclear Science has not been encouraging in this regard. It is our intention during the coming year to develop an impact statement demonstrating the losses to Nuclear Science and to the nation following from the underutilization of our resources.

The report does not discuss at any length important institutional issues. One of these, "The Role of Universities in Nuclear Science", will be addressed in the coming year by a subcommittee of NUSAC. I am especially concerned, as is the Committee, with respect to this issue. It is important that the many talented nuclear scientists at universities be able to participate effectively in resolving the significant problems in our field. A closely related concern is the low rate with which young people are entering the field, a problem of importance to all of physics but particularly to nuclear science. We hope in the next year to present to you concrete and realistic suggestions in this regard.

It is appropriate at this time to transmit to you our keen disappointment with the allocation for Physics in the FY1980 NSF budget. We view the essentially zero increase in the funding (when inflation during FY79 is taken into account this corresponds in 78$ to a reduction of more than 10%) for Nuclear Physics in this NSF budget as inexcusably destructive. It is to be hoped that efforts now in progress to increase the budget will be successful and that the particularly severe impact of the present NSF budget will be avoided.

As the report repeatedly emphasizes, the schedules proposed by the Long Range Plan must not be considered as rigid. "It will be necessary to revise the details of both the budget and construction schedule each fiscal year. Revision may be necessary because of the possible impact of scientific and technological advances which make different goals important and accessible. Revision may be necessary because the yearly allocations in the Federal budget which are finally adopted by the President and Congress will differ from those recommended in this report." "Revision in the construction schedule will be necessary. . .after a review of the specific proposals which are submitted for consideration at that time." In addition it should be noted that specific details of the plan are subject to change since such precision in planning is neither possible nor desirable. "It was [for example] clearly understood [during the Orleans meeting] that recommendations concerning facilities are fairly general at this time since no presentations of specific proposals were made before the Committee. Cost estimates are quite approximate "

The Committee would like to bring to your attention some of its recommendations which relate to the implementation of the Long Range Plan. "In view of the fact that the R and D expenditures are, in some cases, of the same order of magnitude as facility construction costs, the panel recommends very strongly that the Committee be informed by the agencies of such large R and D proposals so that it may comment upon them. In these cases especially it must be clear that a large investment in R and D does not guarantee approval of construction." Secondly, it is the recommendation of the Committee that construction of medium sized or large facilities should not be funded unless "a clear plan of action is developed that shows that the required balance in [national] capability can be retained." Indeed, it is not possible "to fund the incremental cost for the operation of such a new (medium sized) facility by shutting down several small installations. Such a procedure would destroy important needed capabilities" where "capability" refers to both manpower and facilities. Indeed, if incremental funding is not made available the construction of such a facility should be accompanied by the reduction of support of a major facility.

It is a fortiori not possible to include funding for very large accelerators which are under consideration and which are estimated to have construction costs exceeding $100M in the Long Range Plan budget. Inclusion would have resulted in the destruction of the overall balance of the nuclear science program if the funding levels contemplated in the Long Range Plan are to be maintained. "Moreover, the operating costs of such a facility together with the equipment and user costs will be too large to be accommodated within the present funding levels without destroying the base which is needed for the meaningful interpretation of the research conducted at such a large facility. Such very expensive projects must be justified separately as required by important national goals, requiring special construction allocations, and must be provided with substantial (additional) operating costs."

The Committee also urges more participation of users in construction and design of ancillary equipment, the work to be done at the home institutions. This last phrase is of particular importance since it is the most cost effective method of involving talented users, their students and post docs.

The Committee and I would welcome the opportunity to discuss this Long Range Plan with you. We would like to transmit to you our enthusiastic support reflecting the scientific opportunities offered by the plan. We believe that the plan is fiscally responsible and presents a systematic approach to the future of an important component of the national basic science program. We are, of course, very interested in your response and more generally of the DOE and NSF to the Plan.

Sincerely yours,

Herman

Herman Feshbach

Enc.

HF/mbr

LONG RANGE PLAN FOR NUCLEAR SCIENCE

A Report by the
Nuclear Science Advisory Committee

July 30 - August 4, 1979

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PREFACE

It has been apparent with the formation of the DOE/NSF Nuclear Science Advisory Committee in October 1977, that it was essential for it to recommend a long range national plan for nuclear science. That plan should provide for an orderly development and evolution which takes full advantage of the opportunities which nuclear science presents now and will present in the future for significant insights into the properties of matter, into the underlying forces of Nature, and into the history of the Universe; opportunities which have become apparent because of the essential and leading role played by nuclear science in the progress toward each of these objectives.

The letter of request from the Department of Energy and the National Science Foundation for a long range planning study is given in Appendix A. The report, which follows this preface, does present a long range plan which is based principally upon the scientific opportunities of our field. It was not possible, in view of the time scale, to respond to ancillary issues raised by the DOE/NSF letter. The Committee is sensitive to the important role played by universities engaged in nuclear science. It is sensitive to the need to provide opportunities for able young people in the field of nuclear science. It is sensitive to the underutilization of our capabilities. These are some of the issues of great importance which will need to be resolved within the context of the long range plan. They will be addressed in the course of the coming year.

The N.A.S. "Friedlander" report, the "Future of Nuclear Science" serves as the starting point for this report. Important progress has been made since that report was written (1976) with regard to a number of the important scientific questions described in its Chapter 2. New phenomena have been discovered, in part because of technical advances which have permitted an expansion in the range of experimental parameters and an increase in precision in measurement. Of equal importance in this regard have been the advances in understanding which have led to greater precision in posing the objectives and in the interpretation of the results of both experimental and theoretical studies.

This report presents a long range plan which is designed to maintain the scientific strengths of the U.S. program permitting U.S. scientists to continue to make major discoveries of unique importance for the understanding of nuclear structure and dynamics. It is a plan that provides a forefront capability making it possible for nuclear scientists to investigate the important scientific issues, to create as well as take advantage of scientific opportunities. It is not a plan which optimizes the utilization of that capability. Optimization would require implementation of Recommendation A of the Friedlander panel*. The Nuclear Science Advisory Committee strongly supported this recommendation as demonstrated by the letter dated April 14, 1978, transmitted by W. A. Fowler, Chairman. Briefly, it reminded both agencies of the "serious effects of the low level of operating funds, instrumentation, user group support and the capital equipment budget" and affirmed our "strong support in principle for Recommendation A of the Friedlander report." To date, there has been no budgetary response to this recommendation.

The long range plan does not differentiate between the programs of the two agencies. But it should be noted that the joint role played by the NSF and the DOE in providing fiscal support for basic nuclear science in this country is crucial. The programs supported by the two agencies are quite different but together form a balanced national research effort within the field. The balance is struck not only between universities and national laboratories, but also within the scientific subfields of nuclear science.

During the spring of this year (1979), working groups were set up to develop the necessary background material using input solicited from the community. These, as they were finally constituted, are listed below.

1. Weak Interactions — G. Garvey*
2. Electromagnetic Interactions — J. O'Connell*, G. Garvey, R. Pollock and E. A. Knapp
3. Light Ions and Neutrons — T. Fortune*, W. Haeberli, G. Garvey, D. Robson and J. Huizenga
4. Heavy Ions — R. Stokstad*, J. Huizenga, B. G. Harvey, S. Koonin, D. Scott, T. Suighara and G. E. Brown

*That recommendation states: "To remedy the underutilization of existing facilities, the panel recommends as its highest priority item an immediate step increase of about 13 percent in operating support for nuclear science. It further recommends additional increases, . . . , reaching by fiscal year 1983 a level approximately 60% in real purchasing power above fiscal year 1976 . Increased capital equipment budgets, at the level of 12-15% of operating budgets are also recommended".

5. Pions — R. Burman* and M. Johnson
6. Kaons and Anti-protons — P. Barnes*, C. Dover, E. A. Knapp and I. Halpern
7. Nuclear Theory — G. E. Brown* and D. Robson
8. Nuclear Science Related Research and Applications — W. Fowler*, T. Sugihara, J. Huizenga and L. Grodzins
9. Planning Committee — R. Pollock*, F. Ajzenberg-Selove, D. Robson, P. Barnes and P. Parker

In addition, the panel had available subcommittee reports on Instrumentation (G. Garvey*) and Manpower (F. Ajzenberg-Selove*) as well as a report by I. Halpern on "Nuclear Science in the User Mode" and "Nuclear Science at the Universities." A subcommittee to deal with the problems of the universities in participating in nucelar science research has been authorized but has not yet been constituted. We are grateful to Stephen Vigdor for supplying an extensive set of comments on nuclear physics with light ions. Starred names indicate chairpersons of the working groups.

The tasks for working groups 1-8 follow.

a. Identify the achievements within each subfield during the past five years. These should be related to the fundamental questions given in Chapter II of the Friedlander report. What aspects of a given question have been answered? What new questions have been raised? What was the role of the newly constructed facilities?

b. What is the present situation in each subfield? What facilities are operating, how many scientific man-years (SMY) are involved, what is the budget?

c. What experimental and theoretical programs would be pursued in the next five years and in the five years following these? These programs should be related to the fundamental scientific questions of part (1). What facilities, manpower (in terms of SMY) will be needed? Will new facilities be required? What are the costs?

d. Set priorities for each of these programs in terms of scientific importance, scientific feasibility, technical feasibility, costs.

e. Formulate a "core" program consisting of experimental and theoretical programs discussed in Chapters 3 and 4. This core should represent a balanced program for the subfield and should contain those experiments which should be performed in the next five years to ensure the viability of the subfield. Bear in mind the priority criteria of Chapter 4 and also the impact on other subfields, on other sciences and on the application of nuclear sciences.

f. Choose a number of "adventurous" experiments which may (or may not!) yield important advances.

g. Discuss costs, manpower and facility needs of the core program. Discuss the effect on the relation between the university and national laboratories.

Group 9 was asked to develop the principles and constraints which would guide the panel in the formulation of a long range plan. What would be the impact of a particular partition of the total funding into operating funds, construction funds and funds for capital equipment? What level of scientific man years do these scenarios require and what are the consequences for Ph.D. production? How should one take account of the obsolescence of facilities? This phase of Group 9's activities was designated the "General Considerations."

This working group was also asked to be ready to translate the recommendations of the panel into budget allocations.

The final decisions regarding the long range plan were made at a meeting of the panel at Orleans, Massachusetts, during the period July 30, 1979, through August 4, 1979. The program began with the discussion of the goals of the meeting by the Chairman, statements by the agency representatives, J. Leiss (DOE) and H. Pugh (NSF). These were followed by a presentation of the core program and "adventurous" proposals by each of the groups 1-8, a review of the budget history, a review of the instrumentation subcommittee report, Group 9's report on General Considerations, a proposal by F. Ajzenberg-Selove and finally representatives of the concerned socieities APS (E. Henley and P. Axel) and ACS (V. Viola and J. Unik) who were present at nearly all the meetings of the panel and were asked for their comments. We are grateful to them for their constructive contributions to our discussions. These presentations were then followed by the development of the long range plan. The procedures used are described in the main body of the report. The result necessarily represents a compromise among the various competing requests made in behalf of the subfields of nuclear science.

It is to be emphasized that this long range plan differs from those produced by other panels chaired by G. Friedlander*, J. Weneser**, S. Hanna*** and H. Feshbach*** in one very important respect. The present committee is a continuing body. It can and intends to review this long range plan at regular intervals. Revision will be necessary to take into account the response of the NSF and DOE as well as the actual allocations adopted by the President and Congress. Most important revision will be needed in order to take into account new discoveries, the development of new scientific and technical concepts, and generally the consequences of the scientific and technical advances in nuclear science.

* The Future of Nuclear Science, 1978.
** Physics in Perspective, Vol. II, 1972, D. A. Bromley, Chairman.
*** Physics: Survey and Outline, 1966, G. E. Pake, Chairman.

SUMMARY

The long range plan for nuclear science presented in this report aggressively pursues those initiatives which promise to generate the important scientific advances of the coming decade. It presents the budgets for operation, for capital equipment, and for construction required to provide the necessary capabilities to perform and interpret the decisive experiments and to carry out the significant theoretical studies.

The description and origin of nuclear forces continues to be a major challenge. What is the force between nucleons when they are close together? How does the quark structure of the nucleon affect this interaction? How is the nucleon-nucleon force related to forces acting between the nucleon and other baryons such as the strange baryons, the lambda and the sigma, the excited states of the nucleon, such as the delta, and the antiproton? The collision of nucleons with nucleons and antiprotons, of kaons, pions and electrons with nuclei will provide the needed information.

The search for the simple modes of nuclear motion, the "elementary particles" of nuclear physics, will be enlarged and extended, using new probes such as the pi and K mesons, using the more familiar ones such as electrons, protons, neutrons and the light ions operating at higher energies and in new ranges of the other experimental parameters. Collision with heavy ions should prove to be extremely fruitful in this regard.

The study of charge distribution in a variety of nuclei using high energy electron beams has already paid important dividends. The next years should see measurements of the charge current distribution inside nuclei. The few experiments which have already been performed have presented a number of surprises. First measurements of the matter distribution using high energy protons have been made. With improved accuracy, measurement with protons, pions and kaons should yield the matter current and the matter distribution to an accuracy which will provide significant tests of the theory of nuclear structure.

It is now known that the nucleus does not consist of only protons and neutrons. What is the probability of finding mesons of various kinds and isobars of the nucleon

such as the delta inside the nucleus? How do the properties of these particles change in the nuclear environment? How do the excited states of the strange particles behave inside nuclei? Experiments with electrons, pions and kaons are indicated.

The properties of nuclear matter and nuclei under extreme compression and with large excitation energy remains one of the great challenges for future research. Will new forms of nuclear matter be formed when the density is large? Will large numbers of pions condense out to form a pion condensate? Are systems with large values of strangeness long lived? For what values of the density will the nucleons dissolve into quarks forming nuclei composed of quark matter? Are there islands of stability outside the main valley of stability of nuclei?

Present experiments with heavy ions have uncovered an entirely new and unsuspected reaction mechanism in which the projectile kinetic energy is almost totally converted into internal energy in a relatively short time. Collisions of heavy ions with nuclei have been shown to lead to the production of nuclei with large rotational velocities with a consequent change in shape of the nucleus reflecting a change in internal structure. At sufficiently high rotational velocities the nuclei will undergo fission. New phenomena and new surprises can be anticipated as the energy per nucleon of the heavy ion projectile increases. These will be expected to occur at an energy of roughly 12 MeV/nucleon, as the velocity of the ion exceeds the sound velocity in a nucleus, as the energy per nucleon increases still more up to the energy of the most energetic nucleon inside a nucleus (at 36 MeV/nucleon), and then beyond to the thresholds for the production of pions (at energies of 260 MeV/nucleon) and then of other mesons, finally becoming relativistic (energy per nucleon about 1 GeV/nucleon) and then ultrarelativistic at still higher energies (such as the proposed 10 GeV/nucleon). Unusual phenomena have already been seen with ultrarelativistic proton projectiles.

Heavy ions, energetic protons and pions can produce new nuclear species far from the stable ones we now know, providing thereby a severe test of our description of nuclear forces.

Pions may be able to probe the nature of the correlations inside nuclei. The importance of correlated structures within nuclei, referred to as "clusters," will be investigated using light and heavy ions, as well as energetic electron and proton projectiles.

A new form of baryonic matter with unit strangeness, the hypernuclei, has been created by the collision of kaons with nuclei. What are the properties of the hypernuclei? What can one learn about nuclei from these properties? What can one learn about the interaction between strange particles and nucleons?

Do the proton and antiproton form nearly stable systems? What do these and more generally the collision of antiprotons with nucleons tell us about the behavior of nuclear forces when the distance between the interacting particles is small?

The existence of weak neutral currents has already been demonstrated. Their detailed nature will be revealed through the collision of polarized electrons, neutrinos and protons with nuclei. Only in this way will the various theories unifying the electromagnetic with the weak interactions be tested.

Astrophysics and condensed matter physics interact particularly strongly with nuclear science to the mutual benefit of both. Nuclear processes are intimately involved in the production of stellar energy and stellar evolution. Neutron stars and the cooling of stars, the production of solar neutrinos are examples of recent topics of interest. Treatment of materials and the preparation of new materials using ion implantation, the study of the structure and forces acting within crystals are examples from the field of condensed matter. A whole new set of methods for the determination of fossil age has recently been discovered and is in the course of now being developed and exploited by the geosciences and archeology.

Applications of the discoveries of nuclear science and the development of new techniques based on its instruments continue at an unabated pace. The development of a new x ray source based on nuclear accelerator design has had a world wide impact on cancer therapy. The probes of nuclear physics, neutrons, protons, heavy ions and pions are now being tested for their efficacy in the treatment of malignancies. Industrial applications are many, as for example the use of ion implantation in the manufacture of integrated circuits, the use of nuclear techniques for characterizing materials and manufacture of new alloys. It is not possible to predict what new opportunities for applications will occur in the next decade, but there will undoubtedly be many.

The Long Range Plan

The fulfillment of the scientific program summarized above requires the dedicated participation of the nuclear scientists and their students, the orderly development of new capabilities such as detectors of the required sensitivity and precision, ion sources of increased intensity and quality, sources of polarized projectiles and polarized targets and the construction of new facilities. The scientific program calls for the upgrading of accelerators now operating by increasing the energy and quality of the beams they produce, and improving their reliability. Heavy ion facilities which can cover the range from 20 MeV/nucleon and beyond to a few hundred MeV/nucleon can be made available by upgrading existing accelerators. It calls for accelerators which produce high energy electron beams continuously rather than in bursts. The scientific program calls for the construction of facilities with more intense pion, kaon and antiproton beams and with higher energy proton and heavy ion beams. It calls for improved facilities for calculation in support of theoretical studies. This wide range in type of capabilities reflects the multi-dimensional nature of research in nuclear science and the need for a collective approach.

The panel has developed a plan which will provide the necessary personnel and capabilities to perform what it anticipates to be the important experiments of the next decade. It provides support for a commensurate theoretical effort which is essential for the success of the scientific program. The plan, with one exception, calls for relatively constant manpower. This, together with the plan for equipment and facilities, will maintain the scientific effectiveness of the U.S. program in nuclear science permitting U.S. nuclear scientists to continue to make major outstanding and unique contributions to the understanding of nuclear structure and nuclear dynamics. The plan calls for increases of $0.5M/yr for 5 years in the support of nuclear theory.

The overall aspects of the plan are contained in Table VI. Over a five year period, operating funds would increase from $113M in 1980 to $132.4M in 1986 (in '79 dollars) at the rate of somewhat more than 3% a year. Capital equipment would increase to $14M/yr while facility construction would grow from $16.2M/yr to about $20M/yr. In the first five years, 1982-1986, the construction plan includes a kaon channel providing increased kaon intensity, a neutrino horn providing relatively low energy neutrinos, three upgrades of light and heavy ion accelerators, an electron accelerator to provide continuous beams of electrons of intermediate energy and, at the end of this period, the start of the construction of a continuous beam, high energy electron accelerator which would be a national facility. The plan includes a substantial expenditure in behalf of computational facilities for theorists, while the budget for operating funds includes the cost of their operation. Funds were allocated in support of research and development for the electron accelerator as well as for an accelerator which would produce heavy ion beams of ultra relativistic energies and for an accelerator which would produce copious numbers of kaons, as well as high energy pions and nucleons.

Funds were thus allocated for needed research and development activity on accelerators of the future. These funds are directed to projects without the implication that the R and D effort will necessarily lead to a construction project.

The proposed plan will serve as a guideline. Departures from it will come from several causes. The funding pattern developed by the NSF and DOE and the Federal Government more generally will depart in detail from the plan. The actual time order of the construction of new facilities will depend on the merit of individual proposals and thus will not conform to the time order suggested by the long range plan. And most important, scientific and technical advances may require a reordering of priorities. It is thus essential that the long range plan be regularly reviewed by the Committee in order to take account of the actual flow of relevant events.

PART I

CHAPTER 1: RECENT ADVANCES AND SCIENTIFIC OPPORTUNITIES

Introduction

Most of the mass of the universe is in the form of nuclear matter. Stellar energy has its origin in the energy made available by nuclear reactions. Nuclear forces, weak and strong, together with the gravitational and electromagnetic forces determine the physical history of the universe, the evolution of stars, the formation of the elements. These same fundamental interactions, gravitational forces excepted, determine the structure of nuclei and the dynamics of nuclear reactions. Because of the great variety of nuclei and projectiles, it is possible to separate and study both the strong and the weak nuclear interactions and compare them with the well known electromagnetic interaction. It is thus not surprising that nuclear science plays an essential role in the progress being made by modern science in its effort to understand nature and discover the natural laws. It is noteworthy that at the same time nuclear science plays an equally significant role in the development of modern technology for the service of society.

The intense postwar research effort in nuclear science culminated in one of the most important achievements of modern physical science. The nucleons (neutrons and protons) making up the nuclei interact strongly. Under these circumstances, the procedures developed in atomic physics, which rely heavily upon the weakness of the interaction, are grossly inadequate. The resolution of this difficulty was based upon a selectively systematic study of nuclear properties. It was possible to show that each of the nucleons move, on the average, in a slowly varying average field generated by all the nucleons in the nucleus. That average field may be spherical or it may be deformed (aspherical). This remarkable and unanticipated result is important for the understanding of strong interactions generally and is being applied, appropriately modified, to the study of the quark structure of the nucleons and other hadrons.

With this result, it is possible to understand the properties of the ground state and low lying levels of nucleus. It was also possible to apply it to low energy nuclear reactions in apparent contradiction to the presence of resonances. The names shell model, rotational model and optical model are associated with these developments.

Much of the late fifties and sixties were spent in exploiting and further developing this result. The application to newly discovered "simple states" such as the giant resonances and the isobar analog states, the dependence of the average field on nuclear species, on spin and isospin, the nature and effect of the fluctuations away from the average field are examples of the topics treated in this period. There were many successes, and important extensions of the underlying concept were developed. However, it also rapidly became clear as experiments began to be done with new probes, as the energy of the probes was increased, as the variety of nuclear species that could be studied grew, and as theory became more sophisticated that there were domains in which the average field concept was inadequate or not applicable. On one hand, the interpretation of some of the experimental results, upon which the shell model was based, was found through the use of new probes, which permit a much more detailed study of nuclear properties, to require revision. The use of new probes, particularly the hadronic ones like the pion and kaon and heavy ions, involved new kinds of phenomena so that generalizations of the average field concept are needed. It has been clear for some time that the assumption that nuclei consist only of neutrons and protons is incorrect. It now appears possible to determine quantitatively the nature of the other participants such as the pion. The behavior of highly excited nuclei (that is, nuclei with large internal energy), the properties of nuclei under extreme conditions such as very large rotational velocities, the properties of nuclei far from the stable valley, the search for new forms of nuclear matter, and the understanding of the short range behavior of the forces between free nucleons and nucleons inside the nucleus will most probably require the introduction of new concepts and new ways of describing nuclear properties. In some situations it will be necessary to take account of the effects of special relativity and indeed directly study the space-time properties of the nuclear interaction. Of course, the new ideas now being formulated must be consistent with the average field concept where it is applicable. On the other hand, they may be strikingly different when applied to the new range of experimental variables now accessible or to be accessible for study. It is, in fact, a very exciting prospect.

These opportunities will be described in the subsequent chapters of Part I which supplement and revise, because of recent developments, the thorough discussion in Chapter 2 of the Friedlander report entitled, "Fundamental Scientific Questions." In the remainder of this introduction, a number of recent important discoveries will be described and a number of new significant issues will be raised.

Resonances in the Proton-Proton System

The first topic discussed in Chapter 2 of the Friedlander report is entitled the "Nature of Nuclear Forces." Since that section was written, a surprising new phenomenon has been discovered — namely, the presence of resonances when protons collide with protons indicating the existence of nearly bound states of the diproton system. The existence of these resonances demonstrates the importance of the heavier baryons in the nucleon-nucleon interaction and provide a measure of their interaction with nucleons.

Nuclear Matter

The difficult mathematical problems associated with the calculation of the properties of nuclear matter from nuclear forces have been resolved, and the deviation from the experimental value of the density must be interpreted as a consequence of an inadequate description of the nuclear forces employed.

Charge and Matter Density

Among the reasons for providing higher energy electron and proton beams was the possibility that it would become possible to observe the variations of charge and matter densities inside nuclei. The electron accelerator, acting like an electron microscope, has indeed made it possible to measure the charge density for a variety of nuclei to a very high accuracy. The proton accelerator, or similarly the proton microscope, has also fulfilled this promise although the accuracy is not yet equal to that obtained with electrons. It now appears possible to extract the matter density. We have thus obtained and are in the process of obtaining a series of pictures of representative nuclei of various types which are remarkably informative, and which have already required significant modifications in the theory of nuclear structure.

Giant Resonances

The discovery of simple states of the comple nuclei has been one of the hallmarks of nuclear research and the source of new insights into nuclear structure. The single particle and rotational states are two examples. During the same era, the giant dipole resonance was discovered and led to a dramatic change in the sophistication of the models for nuclear structure. Recently two new giant resonances occurring in a variety of nuclei were uncovered. These are the giant quadrupole and giant monopole resonance. In the latter, which is seen only in the heavier nuclei, the nucleus is said to "breathe," that is the nucleus dilates and compresses, a motion which is directly dependent upon the compressibility of the nucleus. This quantity is of great interest since it is a characterization of nuclear matter which goes beyond the density and therefore provides a stringent test of the theory of nuclear structure.

Hypernuclei

Nuclei in which one of the constituent particles is a "strange" particle, the lamda (Λ), have been known to exist for some time. Recently a systematic way of forming these nuclei, referred to as hypernuclei, in a well defined state has been found and several such states in a variety of nuclei have been formed. These experiments will on the one hand provide important information on the Λ-nucleon interaction and on the other hand will yield important insights on nuclear structure. The Λ is a strongly interacting probe similar to the nucleon in mass and spin but not identical to the nucleon so that its interaction with the nucleons in the nucleus is not limited by the Pauli exclusion principle. As this was being written, we were informed of a very surprising and exciting discovery of the formation of a new kind of hypernucleus in which the strange particle is a , a particle considerably more massive than the .

Deep Inelastic Scattering

This refers to a recent discovery of an unexpected type of nuclear reaction which occurs when heavy ions collide with nuclei. In these collisions, most of the kinetic energy of the incident projectile is converted into internal energy of the projectile and target nucleus. This is accompanied by the exchange of mass and charge. In addition, the collision time is relatively short. This is an extraordinary phenomenon which is of great importance for strong interaction physics. Revealed for the first time in nuclear experiments, its understanding will have a wide impact. Much effort has been and is being devoted to its quantitative understanding. Novel macroscopic theories involving the concepts of nuclear viscosity and friction have been proposed as well as more microscopic theories which attempt to give a detailed description of the process.

Time Dependent Hartree-Fock

One such microscopic theory involves a direct but approximate integration of the time dependent equations of quantum mechanics. The nucleons are placed in orbitals whose character is allowed to change with time. This method has already yielded qualitative insights into the deep inelastic process.

Nuclei with Large Rotational Velocities

One of the possible reaction products of heavy ions with nuclei are nuclei that are rotating with very large rotational velocities. Nuclei with angular momenta considerably greater than $30\hbar$ have been observed. The experiments show that as the rotational velocity increases, a nucleus changes from a spheroidal shape to an oblate one. Interpretation of this transition in terms of the corresponding change in nuclear structure provides a quantitative understanding of the behavior of nuclear matter under the extreme conditions accompanying large rotational velocities.

Nuclear Molecules

The collisions of carbon with carbon nuclei and with oxygen nuclei exhibit a series of resonances extending up to surprisingly large excitation energies with progressively increasing spin. A semiquantitative understanding of this phenomenon has been obtained in which the carbon nuclei orbit about each other for a relatively long time. Hence the name "nuclear molecules." The search is on to uncover other examples among other nuclei. This is another example of the discovery of particularly simple modes of nuclear motion.

Space-Time Development of a Nuclear Reaction

Because of the time dilation associated with a rapidly moving projectile, e.g., a proton or pion, with energies of many GeV, it becomes possible to observe the development in time of the collision of the projectile with the nucleus. Several rather remarkable phenomena signal the effect of time dilation. An example is the fact that the multiplicity of production of fast charged particles by an incident pion of 100 GeV with a uranium target was roughly only twice that which results when the target was hydrogen.

The Delta Resonance Inside the Nucleus

The fundamental theoretical insight into the dynamics of the interaction of a pion with a nucleus has been obtained. The theory assumes that the incident pion is absorbed by a nucleon of the nucleus to form an excited state of the nucleon referred to as the delta resonance. The new nucleus so formed consists of the delta plus the remaining nucleons. This delta-nucleus system is found to have relatively long lived states of a rather simple character which naturally play an important role in the pion-nucleus interaction. The behavior of a resonance such as the delta inside a medium in the presence of strong interactions and its impact on the medium is of fundamental interest for many body problems so that the resolution of this problem should have a wide impact.

Exchange Currents

Electron scattering and photon interactions with nuclei, particularly the very light nuclei, have clearly and unambiguously demonstrated the existence of currents in nuclei carried by mesons, demonstrating the presence of mesons inside nuclei.

Conserved Vector Current

The recently proposed theories unifying the electromagnetic and the weak interactions predict a definite relationship between the probability for the decay of a nuclear state by emitting a gamma ray and aspects of the beta decay of an appropriately related state. This is referred to as the conserved vector current hypothesis in Sec. 2.2 of the Friedlander report. One of the important results of recent years has been the verification of this predicted relationship.

Accelerator Radiochronology

Accelerator radiochronology refers to the use of accelerators as ultrasensitive mass spectrometers permitting the determination of the presence of long lived isotopes even with very small samples. The application of this method to the detection of ^{14}C, ^{10}Be, ^{36}Cl and a number of other radioactive isotopes has resulted in the extension of the time scale over which each of these isotopes can be used as clocks from the 50,000 years provided by the familiar ^{14}C dating to the order of a few million years. This represents a "breakthrough" of great importance for geoscience and archeology.

New Tests of Quantum Electrodynamics

By stripping atoms of most of their electrons by, for example, passing heavy ions through a foil, and studying the energy levels of the resulting ions one can make studies of the Lamb shift in the presence of very strong electromagnetic fields. The close collisions of heavy ions give rise to even stronger fields permitting the study of quantum electrodynamics in a new domain.

Application in Industry

Ion implantation is now widely used in the manufacture of large integrated circuits. Nuclear science techniques are used to characterize materials, fabricate new alloys not accessible by other means, and as a diagnostic tool for solar cells.

Cancer Therapy and Diagnosis

The use of radioactive isotopes for diagnosis and treatment of malignancies continues to expand. X rays produced by over 1000 electron linear accelerators, direct descendants of nuclear science accelerators, are used world wide for cancer therapy. The use of neutrons, pions and heavy ions for therapy and in particular for tumors not responsive to treatment by x rays is under study.

Scientific Opportunities

A complete discussion of the "Scientific Opportunities" would duplicate most of the discussion in the second chapter of the Friedlander report "Fundamental Scientific Questions." We, therefore, refer the reader to that analysis and restrict the discussion which follows to a progress report in which the impact of recent discoveries and insights will be reviewed. It is obviously convenient to use the same framework as that used by the Friedlander panel. The quotations which precede the discussion are taken from that report.

Nature of Nuclear Forces

> "Nuclear scientists seek to describe the fundamental strong forces underlying the structure of matter and the history of the universe. They ask a double set of questions: (a) What are the characteristics of the strong interactions between two nucleons, between nucleons and other elementary particles, and among three or more strongly interacting elementary particles? (b) How completely can the properties of nuclei be derived from a detailed knowledge of these interactions?"

The discovery of the new resonances in the proton-proton system points to the importance of intermediate states in which one or both of the nucleons are in more massive isobar states. The present analysis assumes these to be the resonance. The consequences of this assumption need to be determined and compared with experiments involving not only the two nucleon system but more massive systems as well. Indeed, it should become possible to determine the probability of finding a Δ inside a nucleus.

The discovery of the resonances also highlights the importance of the use of polarized beams and targets. Perhaps there are more surprises at other energies and in the neutron-proton system which still remains inadequately studied although much progress has been made since the Friedlander report.

A most exciting opportunity is provided by the development by particle physicists of a description of nucleons in terms of quarks and gluons and the development of a theory describing their interaction known as quantum chromodynamics. This description permits for the first time consideration of the short range description of nuclear forces which up to the present has simply not been possible.

A new area of importance which is now being opened to investigation promises to reveal the forces which exist between a proton and antiproton and between a nucleon and strange particles such as the lamba (Λ) and the sigma (Σ). Possible dibaryon systems which are not resolvable into two baryons have been predicted by quark theory. Besides their intrinsic interest, these results are essential for the development of a complete theory of nuclear forces.

The properties of nuclear matter have not been correctly described by popular phenomenological nucleon-nucleon potentials. This remains an open problem with the onus for the failure being put on these potentials rather than in the theory of the many body system.

The Nucleus as a Microscopic Laboratory

> "From nuclear studies came the discoveries of the weak interaction and the general symmetry law of isospin conservation that are important in all of physics. How, using the nucleus as a microscopic laboratory and choosing the required static and dynamic conditions, can the universal symmetry and conservation laws be tested? How can the nature of the weak interactions be further explored with the aid of specific nuclear properties and transitions?"

The experimental tests of recently proposed unified theories of the weak and electromagnetic interactions involve a comparison between observable effects of each interaction as exemplified by the study of the conserved vector current mentioned earlier. The study of the scattering of polarized electrons has proved to be another most fruitful source of information bearing upon a very critical component of these theories, the so-called "neutral" interaction. By investigating the scattering by selected nuclei, it should be possible to determine the spin and isospin character of the neutral interaction providing still another test of the unified theory. Neutral interactions will also mediate the scattering of neutrinos by nuclei. These experiments, and other neutrino induced reactions, will yield, not only information on the weak interactions and on aspects of nuclear structure, but also on a process important for the cooling and evolution of stars. The question of the relationship between different types of neutrinos may also be answerable. In discussing these experiments, it is important to realize that these are technically feasible with currently achievable neutrino fluxes and detectors.

A new and unforeseen use of the nucleus is for the study of the space-time development of a nuclear reaction induced by very energetic projectiles. Although the spectacular effects of relativity on these reactions have been observed their quantitative understanding has not yet been achieved, nor have their consequences been adequately studied. These represent exciting new areas of investigation.

The Constituents of Nuclei

> "Neutrons and protons are the principal constituents of nuclei, but: (a) How complete is the description of nuclei in terms of nucleons? (b) How can we experimentally determine the presence of other particles such as pions and excited states of nucleons in nuclei? (c) What is the influence of the nuclear environment on elementary particle resonances, and, in turn, how can the nuclear environment be proved using these resonances?"

The naive picture of nuclei consisting of only neutrons and protons is in the process of being transformed into a more complete and accurate description which includes the possible presence of mesons, baryons of various kinds, and eventually quarks. As mentioned earlier, the electromagnetic probes have played and will continue to play an important role in this regard. Use of the pion in the energy range corresponding to the pion-nucleon resonance, permits one to focus on the properties of the Δ in the nucleus. The achievements already obtained regarding this system give us considerable confidence that not only will the behavior of the Δ be understood, but that it will be possible to apply the experimental and theoretical methods developed to study the   to study the behavior of other baryon resonances such as the strange particle resonances, for example the Y*.

Experiments designed to directly observe pions inside the nucleus are now being performed. Experiments which produce the vector boson, the ρ, have been performed. But the issue of its properties inside the nucleus have not been carefully studied. When matter becomes sufficiently dense, pion condensation, that is the presence of a macroscopic number of pions, in nuclear matter becomes possible. The question arises as to whether, in ordinary nuclei, there is any evidence which reflects this possibility.

Charge, Current, and Mass Distributions

"A knowledge of the spatial structure of the nucleus and the way in which this structure transforms in nuclear excitation is essential. The well-understood electromagnetic interactions are specific probes of the electric charges and currents. Probing the mass distribution requires the use of strong interactions, and the conceptual framework required to extract nuclear matter densities from the data is still being developed. (a) What is the spatial structure of the static and dynamic nuclear charge and current distributions? (b) What reactions are most suitable and interpretable for mapping the mass distributions and their flow? Using these, what picture of the distribution and motions of nuclear mass can be obtained?"

We mentioned earlier the considerable progress which has been made toward the determination of the electric charge and current distributions within nuclei. Transition currents and charge distributions are similarly being investigated successfully. The measurement of the mass distribution obtained with high energy protons needs to be improved and extended so that matter currents are also observable. Similar remarks may be made regarding transition currents and distributions connected with inelastic processes induced by protons. Surface properties can also be probed with pions, antiprotons and heavy ions, while volume properties are probed with positive kaons and low energy pions. Beams of these particles at energies far above the energy at which they resonate with nucleons will be useful.

Simple Modes of Motion and the Interacting Shell Model

> "Remarkably, even though nuclear forces are strong, nuclei exhibit such simple modes of motion as the single particle motion underlying the shell model, the rotational motion of deformed nuclei, and the vibrational motion of the giant dipole resonance. The discovery of these and other simple modes has played a decisive role in the history of nuclear physics. (a) Are there other simple modes of motion? If so, how can their existence be interpreted? (b) What is the nature and importance of multi-pole resonances other than the giant dipole? (c) What are the couplings between different modes of motion? How do the the simple modes enter into more complex configurations? (d) Have the limits of validity of the rotational model been reached? What is the interaction between vibrations and rotations? (e) The interacting shell model has served as the phenomenological framework for the interpretation of much of nuclear structure and dynamics and for a unified understanding of the simple modes of motion. How complete is the description of nuclei in terms of the interacting shell model? (f) What unusual shapes can nuclei assume, and how can they coexist with known shapes?"

Progress in the understanding of nuclear structure has depended to a great extent on the study of especially simple states. Those lying at low energy are of this character and their study has led to the development of the interacting shell model. Much of nuclear research has the discovery of such states as its primary goal. Once these are isolated, the next phase of study is of the interaction between these various simple modes of motion. The continuing study of the character of the giant resonances, using a variety of probes, light ions, electrons, pions, etc., examining their fragmentation into narrower peaks in experiments with increased precision and the possibility that in a given nucleus other examples of a giant resonance exist in which the excitation is from an excited state of the nucleus rather than from the ground state is an example of this second phase of study of the simple states. In these studies, the use of polarized beams and polarized targets has proved to be of great value.

New simple modes of motion which have been observed include those in which a number of nucleons in a nucleus are excited leaving behind empty orbits referred to as "holes" and a number of nucleons in excited orbits are added. These states can now be more readily excited with the use of heavy ion projectiles which make possible the transfer of several particles and the mutual excitation of the interacting nuclei. The fundamental question is: when will these excitations from the ground state result in simple forms of motion? And if so what are their character and the implications for the theory of nuclear structure?

Another simple mode of motion which has recently become more accessible with the increased capability of nuclear facilities is briefly entitled "Nuclear Molecules," and described in the preceding section. The nature of these motions and in particular the conditions for their occurrence is under investigation.

As the energy of excitation of a nuclear system, that is, as its internal energy increases, it becomes more difficult to select the simple state both experimentally and theoretically. The first requires the discovery of appropriate probes and analysis; with respect to the latter, the usefulness of the interacting shell model becomes evanescent as the excitation energy increases because the possible number of states which need to be considered according to that model becomes astronomical. A theoretical method which selects those states which bear an especially simple relation to each other, usually expressed in group theoretical terms, has been recently proposed. The experimental consequences are being evaluated and the relation to the interacting shell model is being determined. Another complementary proposal uses statistical measures so as to obtain various average properties.

The recent availability of projectile probes such as the high energy electrons and protons, and the pion have presented important scientific opportunities. Reactions induced by pions, or those in which pions are produced, have been found to be structure sensitive. New opportunities are available with kaon beams, particularly as a consequence of the ability to form and study hypernuclei. Their formation will be structure sensitive while the properties of the hypernuclei will depend upon the structure of the host nucleus as it interacts with the Λ.

Pair and Multiparticle Correlations

"Short range pair correlations among nucleons must exist in nuclei as a result of the short range components of nuclear forces. (a) What is the pair correlation function, and how can the interactions of nucleon pairs in a nuclear environment be probed? (b) Are multiparticle correlations important in nuclei, and how can their existence be demonstrated?"

The direct observation of short range pair correlations remains an elusive goal. Experiments in which a positively (negatively) charged pion is transformed into a negatively (positively) charged one referred to as double charge exchange scattering is one possibility. The feasibility of these experiments has been recently demonstrated. Another is the absorption of a pion by a pair of nucleons. Other methods listed in the Friedlander report such as large angle elastic scattering of high energy hadrons, and coincidence measurements of the emerging electron and the nucleon "knocked out" by an electron striking a nucleus are being or will soon be ready to be tested. Recent experiments of backward production of energetic particles in a reaction involving energetic incident projectiles may be another source of information.

Clusters are a rather special example of multiparticle correlations. Their reality has been difficult to establish directly although it appears to have been shown that alpha particle clusters can be found in the surface of nuclei. Knockout by high energy projectiles is one way of getting at the clusters. A first experiment of this type has been recently performed. Other possibilities include the study of multiparticle transfer reactions in which a cluster is transferred to (or from) the target nucleus colliding generally with a heavy ion projectile.

The Domain of Very High Angular Momenta

"The domain of very high angular momenta, accessible through the collision of heavy ions, includes both a variety of nuclear phenomena and one of the boundaries of nuclear stability. When the angular momentum of a nucleus reaches large values, fundamental changes in its shape and internal structure occur. These changes can be revealed in several ways — by the manner in which the energy increases with increasing angular momentum or by changes in transition rates and in other modes of decay. (a) What do these changes reveal about the forces underlying the interaction between the rotational degrees of freedom and the internal states of the nucleus? (b) The phenomenon has been studied at moderate angular momenta, but what happens as the nucleus spins still faster? (c) At what critical value of the angular momentum does the nucleus come apart?"

The energy levels of a rapidly rotating nucleus have been interpreted in terms of rotational bands with substantially different internal structure of the rotating nucleus. As the rotational frequency increases, the type of deformation that the nucleus will exhibit will depend upon the interplay between the macroscopic distortion effect, due to the rotation, and the change in internal structure of the nucleus as a function of rotational frequency. The shape, which at low rotational frequencies might be prolate, may at large rotational frequencies become oblate, or it may first become triaxial (that is ellipsoidal) and then possibly oblate at still larger values. Eventually the spinning nucleus will break up, that is undergo fission, being unable to maintain its integrity because of the large forces involved in the rotation. Observation of the sequence of shapes is as yet incomplete, although properties of the gamma ray spectrum which would signal the presence of the oblate shape have been proposed and their existence verified. In summary, the answers to the questions raised by the Friedlander panel are far from complete although considerable progress has been made.

Properties of Nuclei under Extreme Conditions

"The range of conditions — temperature, density, composition — over which it has been possible to study nuclear properties is remarkably small. Attempts to explore and understand the properties and behavior of nuclei under extreme conditions such as high temperature, high compression, and unusual neutron/proton ratio are among the important and exciting areas of current and future research in nuclear science. (a) What reactions will achieve such conditions, and how will the resulting unusual properties manifest themselves? (b) What can be determined about the equation of state for nuclear matter?"

Up to this time, the formation of domains of highly compressed nuclear matter in the laboratory has not been firmly established. Under the circumstances that, first, this is possible and, second, that deexcitation could occur without substantial density changes, new types of nuclear matter may be formed. A number of proposals have been made. There is first, the possible formation of a pionic condensate, that is nuclear matter containing a large number of pions. A second is the possibility that nuclear matter with a substantial value of strangeness might be nearly as stable as normal nuclear matter. Density isomers, that is, states of nuclear matter whose density differs significantly from that of normal matter and nevertheless have a relatively long lifetime, have also been suggested.

A somewhat older speculation, namely the existence of stable islands of nuclei, beyond the stable valley of nuclei, with larger atomic and mass number, the so-called superheavies, is still open. However, current knowledge of the structure of nuclei in the lead-uranium region is now sufficiently precise to allow the prediction of long lived "supertransuranics," that is, nuclei considerably more massive than uranium.

The discovery of any of the above forms of nuclear matter would be of extraordinary importance, not only for nuclear science but for chemistry, astrophysics and in some cases for technology. The collision of heavy ions with nuclei is the only experimental approach for the production of these exotic nuclei available at the present time. More guidance is needed for choosing the appropriate experimental variables.

The collisions of heavy ions and energetic projectiles generally with nuclei have produced and will produce nuclei far from the region of stability. Of some 10,000 species expected to have sufficiently long lifetimes to be observed, more than 8,000 have not as yet been studied. These investigations will test our understanding of nuclear structure in regions where the delicate balance between attractive nuclear forces and the repulsive electrostatic forces can be very easily destroyed. In addition, the new nuclear species promise important new applications in the fields of nuclear medicine and technology.

Nuclear Hydrodynamics

"Is there a nuclear quantal hydrodynamics? Are concepts such as dissipation, friction, and inertia appropriate, and how should they be formulated? What phenomena are predicted, and how can they be investigated?"

Substantial progress can be reported in this area. Several formulations deriving equations for the description of heavy ion collisions using macroscopic variables have been proposed and applied, for example, to deep inelastic scattering. These involve generalizations of the familiar derivations in the kinetic theory of gases and the theory of plasmas of similar macroscopic equations of motion but with the important addition of quantum effects.

Nuclear Reaction Mechanisms

"Nuclear reactions are the principal source of information regarding nuclear systems; they encompass an extraordinarily rich and diverse set of phenomena. By observing the effects of a variety of projectiles in various energy ranges probing nuclei, by forming new nuclear systems, a set of overlapping views of nuclei and nuclear dynamics can be obtained. The selection of those phenomena that are most informative and extraction from the corresponding data of quantitative measures of the properties of nuclear systems are the most important general problems of nuclear reaction studies. What are the mechanisms involved in the transfer of mass, energy, linear momentum, angular momentum, charge, and strangeness in the course of a nuclear reaction? The delineation of the mechanisms involved and their relation to the underlying strong forces form the fundamental problems of nuclear dynamics.

"Because the subject of nuclear reaction studies encompasses essentially all of nuclear science, it is possible to give the flavor of current research concisely only by choosing examples. Of the two areas we shall consider, one focuses primarily on the simple modes of motion, the other deals with the rich spectrum of phenomena involved in the interaction between complex heavy nuclei. Among the specific questions of interest are the following: (a) When will a single particle description (the optical model) suffice to describe the interaction between a nucleus and a baryon, a light or heavy ion, a pion or kaon? When is it possible to establish a quantitative connection between the optical model potential for the projectile nucleus interaction with the projectile nucleon scattering amplitudes? (b) When will two step and multistep processes be important? What are the important intermediate states, and what will their signatures be? When will there be intermediate structure in the energy dependence of the cross sections? Through what sequence of configurations does a dynamical system evolve during the course of a nuclear reaction? (c) How do the phenomena occurring in heavy ion collisions with a target nucleus depend on impact parameter? What transfer reactions are favored and under what kinematical circumstances? When will fusion occur, and when will a significant fraction of the kinetic energy of the incident projectile be converted into internal energy ('strongly damped collisions')? When will the system formed by fusion decay by fission? By evaporation? What features of the experimental data will reflect these various modes of interaction? How will the phenomena change as the energy changes from the sonic through the supersonic and the mesic to the relativistic regions?"

A wide spectrum of these problems has been considered since the Friedlander report. As has been mentioned earlier, the scattering of pions in the resonance region appears to be understood with applications to the kaon-nuclear system in prospect. The theory of nuclear reactions has been extended so as to bridge the region between the domains dominated by the direct and evaporation processes. Several approaches have been made to heavy ion reactions. Examples include their description in terms of the Fokker-Planck diffusion type equation, the use of semi-classical methods, generalization of the statistical theory of reactions to multi-step processes and the microscopic time dependent Hartree-Fock theory. A major problem in these analyses is the potential contribution of a large variety of processes which can be involved. Considerable theoretical and experimental effort is required in order to determine which are the significant ones for the dissipative mechanisms underlying deep inelastic scattering of heavy ions, for the process of putting nuclei together (fusion) or taking them apart (fission). The structure of the interacting nuclei will also play an important role. These problems are central problems in many body physics. Their resolution promises to establish new concepts and laws which will be widely important.

A whole new set of problems come into focus as experiments with highly energetic particles become possible. What are the effects of special relativity on high energy electron scattering by light nuclei, or of the collision of hadrons such as protons with energies of several GeV and beyond? What can be said about the production of pions and kaons by these particles? What changes will occur if the incident particle is a heavy ion? At what heavy ion energies will it be most likely that regions of high nucleon density are formed and what will be the experimental observations that will signal that such matter has been created? The fundamental nature of these questions hardly needs emphasis.

The use of energetic projectiles leads to the production of many particles. Experimentally and theoretically, the question of what variables are important in their description is a central one. Multiplicity is, of course, one such variable. Correlations among the particles are obvious candidates, but which correlations are most revealing?

CHAPTER 2: NUCLEAR THEORY

Nuclear theory stands at the threshold of a new era. Whereas in the past we worked with nucleons as the fundamental constituents of nuclei, and described their interactions in terms of the evanescent mesons, continuously exchanged, there is now, for the first time, a growing belief that strong interactions can be understood at a more fundamental level. High energy scattering experiments tell us that within a small, but sharply delineated region, nucleons have a substructure in terms of quarks. Quarks interact through the exchange of colored gluons, just as electrons in atoms interact through photon exchange. This poses the challenge to nuclear theorists to extend the meson exchange picture, which referred to the region external to the quarks, to the internal region in which quarks must be confined since they are not observed in isolation. At the same time, this presents us with definite models to economically describe the short distance interactions, which previously have only been phenomenologically parameterized.

Thus, we have the exciting perspective of being able to extend the description of the nucleon-nucleon force to short distances of as small as 10^{-14} cm. We must expand our present understanding of the meson presence in nuclei, and our present description of meson exchange currents, to include the quark-gluon degrees of freedom.

Different mixes of nucleon-meson and quark-gluon descriptions are needed to describe new states of dense matter, such as pion condensates and quark matter. Pion condensates appear in matter when the density is sufficiently high. They begin with nucleons emitting pi mesons, which then makes possible additional pion-nucleon interactions. If the matter is sufficiently dense, these interactions are so attractive that they outweigh the mass energy $m_\pi c^2$, and the creation process goes on until macroscopic numbers of pions are present. These pion condensates may play a role in relativistic heavy ion physics and in neutron stars where their presence speeds up the rate of cooling by a factor of about one million. Thus seemingly disparate systems and processes, one of which takes place in 10^{-22} seconds and the other in thousands of years, are related through the same physical phenomenon.

If nucleons are squeezed together even more tightly, their cores should merge, with the appearance of quark matter. Ways to create such matter are being intensively investigated.

The prospect that nucleons and their excited states are not spherical but deformed, and hence have rotational bands, may allow conceptual connections between nuclear and particle theory. Whether or not these specifics are realized, it is clear that we are entering a period of reunification of nuclear physics, astrophysics and particle physics.

Nuclear astrophysics is enjoying a rejuvenation, with components of nuclear theory playing a strong role in describing the gravitational collapse of stars, formation and composition of neutron stars, and the whole supernova process. The latter is basic to astronomy; more specifically, to the production of heavy elements and probably, to the formation of our solar system.

Given a basic understanding of the nucleon-nucleon interaction, we are better equipped to confront problems of microscopic nuclear structure. We want to understand the relations between collective, cluster, and single particle modes of motion. Such an understanding should delineate the important features of the many body dynamics. In particular, it should tell the degree to which nucleons interact pairwise. Our theories of many body forces, which are now progressing from nucleon-meson to quark -gluon description, will be confronted with data.

Nuclear theory is aggressively combining both theoretical and empirical two-body forces with powerful many body methods to calculate the properties of dense matter encountered in nuclei, overlapping heavy ions, collapsing stars and pulsars. Consistent application of cluster theories has connected the theoretical attacks on nuclear matter and liquid ^{3}He and ^{4}He.

Nuclear theory enriches the nuclear experimental effort, not only by helping to direct new experiments so that they bear on fundamentals but also in cross correlating experimental information and relating concepts from various investigations.

In this regard, the theory of nuclear reactions plays a central role, providing a framework for interpreting experimental results, and so relating them to the basic elements which determine the course of the reaction. Recent observations using light and heavy ion projectiles require the full treatment of processes which, step by step, carry the system from its original state to its final configuration, describing the system after the collision has taken place. One asks, under what conditions will the system equilibrate and permit the use of concepts like temperature and entropy? In this formulation, nuclear reactions deal with nonequilibrium quantum statistical mechanics of systems containing a relatively small number of particles, a problem of wide applicability, not only within physics, but particularly to theoretical chemistry.

Another problem brought sharply into focus by the reactions induced by pion projectiles is concerned with the influence of the formation of an excited state of the nucleon in these reactions. The theory developed for this purpose can be used for many similar situations in nuclear reactions which can occur as the energy of the projectiles increases and the probability for the formation of the numerous "elementary" particles inside nuclei increases. There is wide applicability of these results to many fields of physics.

As new facilities in the U.S. become operative, the need for <u>calculable</u> reaction theories will become even more demanding. At present, only embryonic theories of multiparticle final states will be the dominant component of the reaction cross sections measured. An important question to ask is, what are the appropriate macroscopic variables required to describe these processes? Well above the pion threshold, it will be necessary to take into account the pion degrees of freedom explicitly.

An adequate confrontation of the many exciting problems in nuclear theory will involve forays into particle physics, condensed matter physics, and a substantial bridgehead in astrophysics. These will be facilitated by the reestablishment of links between the various subfields of physics. Particle physicists, astrophysicists and condensed matter research workers will have to be involved in joint attacks on problems of common interests. These interdisciplinary investigations will involve interpretations of a very broad range of data which necessitates the use of more manpower. We are confident that, with adequate funding, the manpower can be found.

CHAPTER 3: WEAK INTERACTIONS

In a remarkable reduction, the dynamic behavior of the material universe in both the small and the large is thought to be governed by only four types of interaction acting between the elementary particles. These are the strong interactions exemplified by nuclear forces, the electromagnetic interaction, the weak and finally the gravitational interaction. All except the last are important for nuclear phenomena. The weak interaction, the subject of this chapter, was first seen in nuclei in the form of beta decay in which, for example, a neutron would decay slowly into a proton plus an electron and neutrino of the electron type. Similar weak decays, manifestations of the weak interactions, were found for all the elementary particles. Pions, for example, can decay into a muon and a mu-neutrino which differs from an electron neutrino*. In the middle fifties, it was discovered that parity was not conserved in beta decay and a rather detailed theory was developed of the weak interactions incorporating this feature. That theory involved two currents, the vector and the axial. In addition, noticing that beta decay results in a change in charge of the decaying particle so that the currents are correspondingly charged, an extension involving neutral currents was suggested.

Not much later, the very strong analogies which exist between transitions induced by the electromagnetic and the vector weak interaction were uncovered and incorporated in the conserved vector current (CVC) hypothesis. In addition, another relation between the axial vector current and pions, the partially conserved axial vector current (PCAC), was postulated.

Recently, a far reaching proposal unifying the weak and the electromagnetic interactions has been made. In the nineteenth century, Maxwell achieved a unification of the electric and magnetic fields. Einstein attempted unsuccessfully to unify the electromagnetic and gravitational interactions. The theories unifying the weak and the electromagnetic are in the same spirit. Recent successes indicate that some form of this proposal, hopefully the simplest, will be found to be valid. Experiments

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* It also can decay into an electron and electron-neutrino.

with nuclei will play an essential role in choosing which of these theories is the correct one. Because of the existence of a wide variety of well characterized nuclei, it is possible to devise experiments which will selectively determine specific effects. One or another of the various possible unifying theories (we shall refer to them as unified gauge models) can give rise to parity nonconservation, to the existence of neutral currents and, in some extreme cases, to a violation of time reversal invariance.

Recent Accomplishments

Parity nonconservation in nuclear transitions has been observed demonstrating the existence of a weak interaction between nucleons in spite of the fact that it is seven orders of magnitude smaller than nuclear forces, a remarkable achievement. Progress has been made in delineating the nature of the nucleon-nucleon weak interaction and in relating it to the weak force between quarks.

Progress in preparing intense samples of specific radioactive nuclear species with a definite direction of their spin vectors has allowed an important class of experiments to be undertaken. Using samples of this kind and measuring the spectrum of emitted beta particles relative to the nucelar spin direction have shown weak transition rates (beta decay) to be related (to within 10%) to corresponding electromagnetic decay rates. This deep relationship between the electromagnetic and weak interaction was conjectured many years ago and termed the Conserved Vector Current Hypothesis (CVC). It is a cornerstone of the modern gauge theories and has only been tested in nuclear and mesonic decays. The detailed experimental agreement between the weak and electromagnetic decays further showed that the so-called "second class" axial vector interaction is small, if not totally absent. The absence of these second class currents is also a consequence of the gauge models of weak and electromagnetic interactions.

Other important model independent relationships are being established linking nuclear transition rates for weak axial vector processes to strong interaction cross sections involving pions. This approach involves the application of the principle of a partially conserved axial vector current (PCAC). The pion, the lightest meson, is treated as the sole source of the nuclear axial vector current and this point of view, while extreme, seems to adequately account for the processes observed to date.

Another fundamental symmetry, time reversal invariance, was observed some 15 years ago to be broken. In contrast to the vast jump in our understanding that followed the discovery of parity violation in weak decay, little progress has been made on the origin of this symmetry breaking because only one system, the strange meson, K_L, gives any evidence of this phenomenon. A breakdown of time reversal invariance would permit the neutron to take on an electric dipole moment, thus providing another possible example. A series of ever more refined experiments has pushed the limit on the neutron electric dipole moment down to $\sim 10^{-24}$ e cm, the most recent limit being obtained by a group from the USSR. As the radius of the neutron is 10^{-13} cm, the above limit is truly significant on a physical scale. The most popular version of gauge theories predicts the neutron to have an electric dipole moment on the order of 10^{-25} e cm.

The values of this small moment may present a real challenge to gauge theories. It is of utmost importance that we find other instances of the breakdown of time reversal invariance.

Opportunities

The next five years of study of weak processes involving nucleons and nuclei promise to be extremely interesting and significant to all of physics. With neutrino beams from LAMPF and FNAL and low energy neutrinos from reactors, questions of fundamental importance can and will be addressed: Do electron neutrinos regenerate into muon neutrinos as has been suggested? Does the neutral weak interaction produce a large neutrino scattering cross section from nuclei? These two questions are not only of great consequence in characterizing the weak interaction, but they also determine the neutrino coupling to nuclear matter, a most important interaction in the cooling and aging of stars.

Further investigation of parity violation is required to examine the weak interactions between nucleons and the neutral weak coupling between leptons and hadrons. We know little about these two important aspects of weak interaction other than that their existence and their overall scale is apparently given by the present day gauge theories. The difference of these couplings to neutrons and protons is not sorted out. In fact, the proper Lorentz invariant form of the interaction has not been experimentally determined. An experiment completed in 1978 at SLAC showed an interference effect between the neutral weak and electromagnetic interaction to occur at the level (10^{-5}) expected by gauge theories but detailed characterization of this interaction awaits the application of techniques in which the final states of the nuclear system are well defined. Electron accelerators presently in use and under consideration for nuclear structure studies seem to be especially suited for these investigations. To accomplish this, polarized sources must be added and a sizable fraction of their beam time must be dedicated to the investigation of this phenomenon. This series of experiments is of great importance, for they will enable us to determine the neutral weak interaction with both neutrons and protons and as well provide information on its spatial properties. Parity violation in simple atomic transitions also may provide significant information on the weak neutral couplings between electrons and nucleons, as will the scattering of neutrinos by nuclei, a most difficult experiment.

The investigation of the breakdown of time reversal invariance is of crucial importance to fundamental physics. The best hope of finding another case in addition to K_L decay is in the measurement of the electric dipole moment of the neutron. A few ingenious techniques involving the storage of ultracold neutrons in "bottles" for times up to 100 sec afford great promise in achieving sensitivity at the level of 10^{-25} e cm and below. All of these experiments involve the use of new ideas for cooling relatively large numbers of neutrons to velocities the order of a few meters sec^{-1}. The technical challenge of these experiments, as well as the importance of this result, make this measurement among the most exciting in all of physics.

Sensitive techniques for detecting rare, neutrino-less decay modes of the muon play a significant role in defining the proper forms of spontaneously broken gauge theories of the weak interaction. At present a strong collaboration at LAMPF has determined the best limit (by factor of 10) for the branching ratio:

$$\frac{\Gamma(\mu^+ \to e^+ \gamma)}{\Gamma(\mu^+ \to e^+ \nu_\mu + \nu_e)} \quad 1.9 \times 10^{-10}.$$

There is a planned program to improve on this limit by two orders of magnitude over the next four years. Other rare decay modes to be examined are $\mu^+ \to e^+ e{-}e^+$, $\mu^+ N \to e^{\pm} N$ and $\mu \to e\gamma\gamma$.

In their most complete form, unified gauge theories require an interaction between leptons and quarks with the consequence that protons would not, strictly speaking, be stable. It is clear from the fact that baryon conservation is observed to be strongly satisfied that this coupling must be very weak. In fact, the proton lifetime is estimated to be in the range of 10^{33}-10^{38} years. Considering the age of the universe to be 10^{10} years, the proton appears quite stable. However, the finite lifetime of the proton seems to be a direct consequence of a general unification scheme and its finite lifetime coupled with the breakdown of time reversal invariance indicates a way in which the "big bang" can produce unequal amounts of matter and anti-matter. The current best limit on the proton lifetime is $\tau_p > 10^{30}$ years, this result coming from observation in a neutrino detector located in a deep mine. The application of techniques well known to nuclear scientists who study neutrino interactions seems to offer the best promise of obtaining better limits on this lifetime. Experiments are now under design that can push the limit to 10^{32}-10^{33} years. Needless to say, this research is of great fundamental importance. The documentation of a finite lifetime for the proton would be an indication of predictive power of the concepts underlying modern unified gauge theories.

CHAPTER 4: ELECTROMAGNETIC INTERACTIONS

Characteristics of the Probe

It is through the electromagnetic interaction that we "see" the world, not only the everyday world but also the material world of the physical sciences. Studies with light and later with electron beams have played decisive roles in the history of physics from its very beginnings. The achievements of modern physics ranging from quantum mechanics and a profound understanding of the atom and the molecule to the discovery of the charmed quark and the "heavy electron," the tau, have relied upon the electromagnetic interaction. Nuclear science is, of course, no exception. The study of the electromagnetic transitions and the electromagnetic properties of nuclei provided much of the experimental basis for the shell model and was essential for the discovery of the rotating deformed nucleus. Their importance, abetted by the discovery of new detectors, continues undiminished to the present day and to the foreseeable future. They have been joined by studies of the spectroscopy of muonic atoms in which a muon orbits about a nucleus. Probably the most important new capability has been the recent construction of powerful accelerators providing high quality beams of electrons and the development of new spectrometers with extraordinary energy resolution and efficiency. These electron accelerators can be thought of as the electron microscopes of nuclear science enabling one to "see" the nucleus. The wave length of the electrons being used is considerably smaller than nuclear dimensions and facilities are being planned which will reduce it much further, thereby considerably improving the spatial resolution.

Among the many ways of studying nuclear structure, studies with photons and electrons possess the advantage that it is relatively easy to calculate the effects of these particles on the charges and motion of the charges within the nucleus. This is a consequence of the fact that the electromagnetic interaction is known, which substantially improves the validity of the calculation, and of the fact that the electromagnetic interaction is relatively weak. Thus, data obtained with electrons and photons can be readily compared with models of nuclear structure and nuclear reactions. A simple, albeit an important, example demonstrates the straightforward character of the physics involved. When the frequency of oscillation of an electromagnetic wave exactly matches the frequency at which a particular nucleus has a characteristic vibration, the wave is strongly absorbed by the nucleus. Thus, by varying the frequency of the wave and noting the changing probability of absorption, the pattern of nuclear energy levels can be found and their decay properties measured. The giant electric dipole resonance was discovered and its properties are being determined in this way. This kind of information forms the basis of our understanding of how nuclei are built from neutrons and protons and how this structure responds to a variety of external stimuli.

Research Highlights of the Last Few Years

A first question that can be asked about any physical object is: What is its size and shape? For the nucleus, this question has been answered to a high degree of accuracy by a series of electron scattering measurements on a representative set of nuclear targets chosen to span the table of elements. The analysis of this data has given charge density profiles of nuclei that display a variety of deformations (some are egg shaped, some are flattened) and interesting systematic trends in such properties as the radius as a function of neutron and proton number, charge densities at the center of the nucleus that are found to be relatively constant from calcium to uranium, and surface charge currents that vary from nucleus to nucleus. These results have shown that our understanding of nuclear structure has been too naive and has required the development of more sophisticated models. The charge density at the nuclear center is still not understood.

New issues emerge from this analysis. Fitting of the size and shape data requires that the nucleon-nucleon interaction inside nuclei differs from the interaction between two free nucleons. Fitting the charge current suggests that there are additional forces which act when three or more nucleons are close. Understanding of both of these results is a major goal of nuclear research.

These two results may be related to the following recent discovery. Electron breakup of the deuteron into a free neutron and proton has shown that the description of this reaction requires the pion, one of the mesons that binds the proton and neutron together, and the isobar of the nucleon, the delta ( ), be active participants in the reaction. In other words, it is not sufficient to regard the deuteron (or any other nucleus) as being composed solely of neutrons and protons. The extra particles (mesons, isobars) producing the force between the nucleons must be explicitly taken into account. As a consequence, the effective force between two or more nucleons does change according to the environment in which they find themselves. Confirmation of these ideas through the study of three body systems by electron scattering has been obtained. Although the existence of this phenomenon has been suspected for several decades, this is the first time that good data covering significant range of the experimental parameters has been obtained.

A second question that can be asked about a complex physical structure like the nucleus is: How does it respond to external stimulation? Electron and high energy x rays shake the nucleus as they pass by. At certain frequencies, the nucleus responds to this forced oscillation by resonating. In its excited state, the nucleus has a different size and shape than it did in the ground state because some of the nucleons change their motion. A particularly interesting class of such excited states are the giant resonances. These involve coherent movement by all the nucleons in a nucleus. Although one such giant resonance has been known for many years, three new giant resonances have been discovered in the last few years. All nuclei studied display evidence of these resonances. The properties of giant resonances are particularly interesting because they can be related to the average bulk characteristics of nuclear matter such as compressibility, viscosity, surface tension, etc.

Special states with unique properties have recently been found by inelastic electron scattering. One class that has a particularly simple interpretation is a group of narrow states at high excitation that behave as if only one nucleon changed its orbit and spin as a consequence of its interaction with the electron. Because of the simplicity of these states, these results are particularly useful in interpreting the excitation of these very same states by other nuclear projectiles (protons and pions). New information is obtained on how these probes interact with single nucleons inside the nucleus.

Many of the new findings in electromagnetic interactions have followed advances in instrumentation and accelerator technology. An exciting new development has been the application to electron accelerators of the phenomena of super conductivity (electrical energy flow without power loss on the conductors). Superconducting power cavities are very efficient structures for transferring electrical energy to electrons (which, in turn, can be used to produce high energy x rays).

A second novel development in accelerator design has been the demonstration of the concept of recirculation. An electron beam from a several meter long section of accelerator can be brought back and reinserted into the accelerating section by using bending magnets. Quite high electron energies can be obtained by multiple transversal through the generally costly part of the accelerator, the radio frequency accelerating structure. The advantages of these new developments have been improved beam properties (energy, size, etc.) and a steady stream of electrons. The importance of this later characteristic will be mentioned in the next section.

Prospects for the Immediate Future

The successes described above demonstrate the value of continued efforts to determine the spatial distribution of the charge and of the magnetization. Some systematic evidence is available for the first but very little for the second. Both have already presented us with some surprises and it would be important to determine how widespread these anomalies are and how they vary from nucleus to nucleus. Similar systematic studies for the charge and currents responsible for electron and photon induced reactions such as inelastic scattering will almost certainly be performed. The search for special states, such as the giant resonances, will continue and the properties of those already identified will be investigated by examination of energy, momenta, and spin of the particles, which these special states emit when they decay.

Because the energies available are low and because of the pulsed nature of the beam provided by present day accelerators, it is difficult to look carefully at phenomena in which pions are produced or to perform experiments which require correlation measurements. Correlation measurements with multiple detectors contain much more information about reaction mechanisms and nuclear structure than do the single detection measurements used in most experiments to date. For example, when electron scattering is used to excite one of the new resonances, one or more nucleons may come out of the excited nucleus. Detecting a nucleon together with the scattered electron will help to elucidate the special features of that giant resonance and how it differs from the others. More generally at the higher energies, reactions in which the final product involves more than one particle in addition to the residual nucleus, the so-called multiparticle final state, will be most probable. An electron knocking a nucleon or a cluster of nucleons out of the nucleus, and electron producing a pion, or the heavier mesons, an electron exciting a nucleon and thus producing an isobar are all examples of multiparticle final states, each of which will produce important information regarding the nucleus if appropriate correlation measurements are made. Another and quite different possibility is the study of the fission of nuclei using high energy x rays, thus identifying cases where the simple modes involve large clusters of nucleons acting as nearly independent units.

Higher electron energy will, of course, increase the spatial resolution, thus improving on the measurements of charge and currents which can be made at lower energies. But, in addition, the possibility of pion production allows the study of how pions travel through the nucleus. In particular, it is well known that the pion and a free nucleon interact in a resonant manner to form a nearly stable particle, the nucleon isobar, the Δ, when their relative velocities are in a certain range. The question for nuclear physics is "Does the pion act the same way when it and the nucleon are inside the nucleus?" Other complementary evidence regarding this question is obtained from pion-nucleus scattering. The quantitative explanation of the difference between free and bound pion-nucleon interaction from electromagnetic measurements will be an important ingredient for understanding nuclear behavior at high excitation energy.

Opportunities for the Future

On a longer time scale, the new challenges for electromagnetic interactions will lie with the study of the production and properties of the heavier mesons such as kaon , the rho, and the phi within the nuclear medium, and similarly the properties and production of the heavier isobars beyond the delta, and of the strange baryons. In the latter case, one can expect the formation of hypernuclei. As the energy increases, the possibility of probing the quark structure of nuclei and the associated quantum chromodynamics arises.

Experiments in which the correlation between the electron and the produced elementary particle is measured will be necessary. When an electron scatters from a nucleus, it transfers energy and momentum. By varying momentum transfer and noting the change in the probability of a specific nuclear reaction, say the production of pions, the experimenter can measure the size of the volume in which the fundamental electron-nucleon-pion interaction is taking place. One can then ask the fundamental question: Below what volume in nuclear matter is the internal structure of the nucleons important or, in other words, when does the quark structure become relevant? It is not clear what the signature of the involvement of quarks will be. But again, the fact that the electromagnetic interaction is known will simplify the analysis.

The correlations in direction and velocity of the reaction products is an essential feature of the kind of experiment we have been discussing. Experiments with electromagnetic probes in the high energy and momentum range interacting with nuclei have not been carried out to date because of the unavailability of electron beams with the necessary characteristics to perform the correlation measurements. All high energy electron accelerators are pulsed machines. Pulsed electron beams cause too many accidental correlations to occur among nuclear reaction products, that is, products originating from different nuclei at the same time.

Recent advances in accelerator technology have raised the possibility that a high energy, high current, steady beam electron accelerator could be built. The scale of this facility and its detector instrumentation require that it be a national facility available to the whole U.S. nuclear science community. A national facility producing electrons with energies in the GeV range will be able to explore that unknown transition region between elementary particle and nuclear phenomena. The problems in this area, as remarked upon in the section on nuclear theory, will be one of the main themes in the nuclear physics of the 1980's. The electromagnetic probe has the ability to contribute essential data to tell this story.

CHAPTER 5: LIGHT IONS

This component of the nuclear science program refers to the use of the nuclear projectiles with mass numbers less than or equal to that of the helium nucleus, that is the neutron and proton, the isotopes of hydrogen, the deuteron and the triton (^3H), the light isotope of helium, (^3He), and the alpha particle. It , therefore, includes nucleon-nucleon scattering; reactions induced by each of these projectiles, such as elastic and inelastic scattering; the very important particle transfer reactions, in which one or more nucleons are transferred from (or to) the projectile to (or from) the target nucleus; and the radiative capture reactions, in which the incident projectile is captured and the resultant nuclear system decays by the emission of a gamma ray. The energies range from near zero for the neutrons up to approximately 1 GeV for the protons, although there are some experiments performed with incident protons of energies ranging up to 300 GeV.

Most (and if the electromagnetic probes and beta decay are added, nearly all) of our knowledge of nuclear forces, the energy levels of nuclei, nuclear structure, the formation of new radioactive species, fission, and nuclear reactions generally have been gained using light ion projectiles. To describe the discoveries obtained with these particles would be to give a major part of the history of nuclear science.

Looking back, one realizes that these accomplishments with respect to nuclear structure and reactions are remarkable. The nuclear forces involved are strong and are quantitatively not known. And even if the forces were known, one still could hardly predict, even qualitatively, the type of phenomena that might be encountered in a nuclear reaction. Indeed, to the present day, a quantitative prediction proceeding from our knowledge of nuclear forces is not available. Nevertheless, by a series of insights into the reaction mechanisms, combined with their systematic study using a variety of targets and projectiles over a range of energies, it became possible to interpret the data in terms of models of nuclear structure.

There were two aspects of the nuclear many body problem which made this feat possible. The first is the existence of simple modes of motion of the nuclear system;

the second, the existence of reactions which are especially sensitive to these modes of motion, a property sometimes referred to as specificity. This has remained to a great extent the method by which nuclear scientists have penetrated the strong interaction curtain. It was a method discovered in light ion physics.

Recent Accomplishments

This field continues to have a major impact on the progress of nuclear science. By going to new energy domains, by using polarized beams, through the invention of new kinds of detectors and through the general improvement in beam quality, new features of nuclear structure and reactions have been obtained in the recent past and new opportunities for further discoveries have been generated. We can discuss only a few of these below.

Nuclear Forces

Of course one of the principal objectives of nuclear science research has been and continues to be the quantitative description of nuclear forces and the elucidation of their origin. A second goal is the prediction of the properties of nuclear systems and reactions from the properties of these forces.

The discovery that one can determine the nature of the forces acting between particles (in this case the nucleons), by observing the consequences of a collision between them, goes back to Rutherford. Though the present day experiments are much more sophisticated, the scattering of nucleons by nucleons remains the principal method for determining nuclear forces. These forces, in contrast to the Coulomb electrostatic force which dominates atomic systems, are extraordinarily complex requiring, as a consequence, the study of the scattering over a wide range of energies and other experimental circumstances. The early experiments established their range and strength and the existence of spin dependence; that is, the dependence of the force on the orientation of the spin of the colliding nucleons. Further progress was made using polarized beams and polarized targets. As the capability of doing more complex experiments was developed and as the energy of the projectile neutron or proton was increased, there has been a steady accumulation of data and the construction of an increasingly sophisticated set of phenomenological nucleon-

nucleon interactions. There are many important lacuna in the data, particularly those relating to neutron-proton and neutron-neutron interactions. For the higher energy situations, pion production in the collision of the nucleons must be taken into account and this requires further study.

The recent surprise discovery of resonances in the scattering of protons by protons is especially exciting. These relatively long lived states of two protons were found only when the collision of polarized protons with polarized hydrogen target was measured. They are not visible in the data obtained with unpolarized projectiles or target. Their existence demonstrates the importance of the isobars of the nucleon, such as the Δ particle. These isobars are generally more massive than the nucleon. The Δ, for example, is a relatively long lived particle made up of a nucleon and a pion. The interaction between the Δ and the nucleon becomes an important feature of any description of nuclear forces. That interaction also plays an important role in the production of pions in nucleon-nucleon collisions. This discovery has stimulated much experimental and theoretical activity. A search is being made for other examples of these resonances while the theorists are engaged in incorporating them into the theory of nuclear forces and evaluating the consequences.

Beyond their intrinsic interest, these nuclear forces serve as input into the direct calculation of nuclear properties from first principles. The methods for that calculation for the case of nuclear matter (matter consisting of nucleons of constant density but infinite in extent) have been clarified so that the properties of nuclear matter can be calculated with confidence. The results obtained using a popular phenomenological potential do not agree with experiment.

The forces which exist between the nucleons and other baryons such as the lambda (Λ) and the antiproton ($\bar{p}$) are related to nuclear forces. Their study will therefore be valuable, not only because of their intrinsic importance, but also because of the light they may shed on the structure of the force between nucleons. In this connection, we note two important advances. First, it has proven possible to form nuclear systems, called hypernuclei, in which one of the particles is a Λ, the remainder nucleons. By studying the structure of the hypernuclei, one can expect to determine the force between Λ and the nucleons. Second, in the case of the $\bar{p}$, some aspects of the force can be determined from the study of antiprotonic atoms, that is, atoms in which one of the particles orbiting around the nucleus is a $\bar{p}$. A current exciting controversy concerns the existence of a nearly stable system consisting of a proton and antiproton with a mass of 1.932 GeV. The question remains as to the reality of this state and as to whether there are other identifiable states of the $\bar{p}$-nucleon system. It is anticipated that these studies will reveal important features of the short range nature of nuclear forces and thus establish a connection with the quark models of the nucleons and quantum chromodynamics which provide a theoretical prediction for the interaction between nucleons which are very close together.

Simple Modes of Motion

As we have emphasized, one of the goals of the study of nuclei is the discovery of simple modes of motion. These are very revealing properties of the nuclear many body system. It is in fact, at first glance, surprising that such simple modes do exist particularly because the forces among the nucleons are so strong. There are a number of methods that have been developed to search for these simple nuclear states of motion. One involves the search for broad resonances by bombarding a nucleus with light ions. A resonance indicates that the system formed by the light ion and the target nucleus is almost stable. The fact that the resonance is relatively broad demonstrates that the state of motion is a simple one. The first of these excitations to be discovered is the so-called giant dipole resonance (E1) in which the neutrons move oppositely to the protons. The quadrupole shape vibration (E2) was first discovered by inelastic proton scattering. Difficult experiments, carried out over the past two years, which detect the inelastically scattered particles in the direction of the incident projectile have provided convincing evidence that the breathing mode (monopole) (E0) has been discovered. In this mode the nucleus vibrates only along the radial direction. This mode is extremely important because the vibrational frequency is directly tied to the compressibility of the nucleus.

A second method used in the search for simple modes of motion has been the production of these states by the transfer of particles (neutrons or protons) to a nucleus known to be in a simple state to begin with. Indeed, the discovery of the shell model depended to a great extent upon the transfer of a single particle to a nucleus to fill a valence orbit (or the removal of a nucleon from a valence orbit). This method has been extended by the use of multiparticle transfers to produce other kinds of simple states.

It is not possible to do justice to the accomplishments in this area in this report. We shall mention a few recent examples which will perhaps suffice to transmit the flavor of the research in this area.

By inelastic scattering of high energy protons, it has been possible to excite states with relatively large angular momentum in light nuclei. These states are thought to be unusually simple in character and, of course, this conclusion is under current investigation. If this surmise is correct, it will be possible to determine an important component of the interaction between nucleons in the nucleus.

The reaction in which four particles are transferred (for example, the incident particle is a deuteron, the final one is isotope of Li, ^{6}Li) can result in the production of a relatively simple state of the residual nucleus, examples of which occur in the oxygen and calcium nuclei.

Another example occurs for heavy target nuclei. It can be described most simply in terms of the nuclear shape. A nucleus is said to be deformed if its shape is not spherical. The shape of many deformed nuclei is that of a prolate spheroid. It was discovered that as the nucleus is deformed from its ground state shape, a second region of near stability of the nucleus appears with a relatively large deformation. This extreme deformation manifests itself in a large electric quadrupole moment for the nucleus which, in turn, makes it easy for the nucleus to emit quadrupole radiation. In a set of novel and complex experiments, a German group bombarded ^{238}U with deuterons and measured the lifetime of these excited states of a super-deformed nucleus from which it is possible to deduce the size of the deformation. For ^{238}U, the ratio of the major to minor axis is 1.8. It is likely that this phenomenon is not restricted to heavy nuclei but is a general one which exists in some form throughout the periodic table.

Interaction between Simple Modes, between Simple and More Complex Modes

One of the more startling recent developments is the discovery that two very different states of nucleus can exist with almost identical energies. These differing states often correspond to very different shapes of the nucleus, thus accounting for their stability in each other's presence although differences in other nuclear attributes (spatial symmetry is not the only symmetry) can also produce similar results. Several examples of this phenomenon were found in recent years using light ions. Although these "coexisting" states are relatively pure, there is some mixing between them which is very revealing once the overlap of very different structures is involved. As mixing is better understood, it will become possible to deal with situations in which the mixing is strong, that is, the simple modes are not so pure. A simple mode can mix with the more complex modes of motion. An example which has been carefully studied is that of the capture of protons by nitrogen, the capture being accompanied by the emission of a gamma ray. By using polarized protons, it became possible to unravel the results and determine the more complex modes involved.

It bears repeating. The existence of the simple modes of motion, and the ability to describe their interaction, in the presence of the strong interactions are discoveries of first importance not only to nuclear science but also to other disciplines. The discovery of simple modes of motion is the central task common to all of many body physics.

Clusters

Multiparticle transfers which occur with high probability are thought to signal the presence of clusters. Clusters are groups of nucleons which act collectively within a nucleus and are an extreme example of multipartical correlations. Four particle transfer indicate the possible presence of alpha particle clusters in the surface of nuclei. The results of high energy experiments in which a proton "knocks out" the alpha particle cluster have not as yet successfully demonstrated the presence of these clusters.

Matter Density

An accelerator of energetic proton beams in the one GeV range is a proton microscope, whose wave length (divided by 2) is about 0.12×10^{-13} cm. It thus becomes possible to determine the nucleon density when the data obtained with high energy proton scattering is combined with that from high energy electron scattering which is sensitive to the charge distribution. The accuracy which can be achieved is inferior to that obtained from electron scattering so that one does not have nucleon density maps of the nucleus to be compared with charge density profiles. However, even at this point it is possible to detect the size of the neutron halo and make important comparisons with theory demonstrating, for example, that the simple phenomenological models for the density are inadequate and one must employ the densities developed by sophisticated dynamical theories of nuclear structure.

Reactions

The theory of reactions which has prevailed up to quite recently sharply divided reactions into two types, those for which the interaction time is short (referred to as direct) and those for which the interaction time is long (referred to as compound nuclear). In the last decade a number of experiments for which the interaction time falls between those two extremes has been found. In fact, it is the rule rather than the exception. Theories have been developed which include this in-between region, thereby providing a complete theory of nuclear reactions in which the two extreme types are obtained as limits. These are considerations which have wide applications in the many subfields of physics and chemistry which exploit the collision process.

In one class of reactions which falls into this general scheme, the incident particle loses a great deal of its energy without losing its identity. That is, it did not really seem to be absorbed into the target nucleus, yet it gave up a large amount of its energy. This effect was observed with light ion projectiles of energies the order of 100 MeV. However, because of the greater simplicity of these cases, it was possible to show by detailed calculations that the large energy loss was the result of a very hard collision with a single nucleon in the target, in which a very large portion (approximately ½) of the total energy of the incident particle is given up while it still retains its identity.

Reactions at Very High Energies

Examination of the energy, angular distributions and multiplicity (the number of particles produced) of the reaction products generated by a high energy proton (up to 300 GeV) striking a nucleus reveal a bizarre behavior. This, it is felt, is qualitatively understood as a consequence of the time dilation of special relativity which results in the decay of the excited proton, generated by the incident proton's collision with a nucleon inside the target nucleus, occurring after the proton has left the nucleus. If this interpretation is correct, there is then the possibility of observing the initial stages of a quantum mechanical process, a unique opportunity provided by the nucleus and not available, as far as it is known, by any other experimental arrangement. A quantitative theory has yet to be developed.

Opportunities

There are obviously many opportunities for significant research which are natural extensions of or continuing studies of the phenomena discussed in "Recent Accomplishments." We will just mention a few, as well as some instances of research which has become accessible because of technical advances.

In the nucleon-nucleon scattering case, data is still incomplete. Results for neutron-proton scattering at a variety of energies, and generally the spin dependence of nucleon-nucleon scattering must still be obtained. And, of course, the discovery of resonances in proton-proton scattering will stimulate a search for others. Another matter of great interest which will be resolved in the next few years is the question of charged symmetry of nuclear forces; that is , is the force of a neutron on a neutron the same as that of a proton on a proton once electromagnetic effects are taken into account? One can also expect to soon have a better understanding of nucleon-lambda and nucleon-sigma forces from the study of hypernuclei. One will also expect to know if there are other nucleon-antinucleon resonances and again there will be information forthcoming regarding their mutual forces.

All of this does and will represent a substantial challenge for the development of a comprehensive description of nuclear forces. One question which will require resolution asks for the description of nuclear forces when the nucleons are very close together. This will require a modification of the theory of nuclear forces which will take into account recent developments regarding the structure of nucleons. It will involve the introduction of quarks and their interaction via gluons as described by quantum chromodynamics. Here is also a challenge to experiment: What measurements need to be made in order to obtain information on the nature of nuclear forces when the nucleons are close together? One should, of course, add experiments involving the three and four nucleon systems. These will provide information otherwise unobtainable on the nucleon-nucleon forces and, in addition, will yield information on "many body" forces which result because of the influence of a neighboring nucleon upon the force between two other nucleons. There are several anomalies in the three and four body systems which need clarification. Fortunately, the capability of both theory and experiment have greatly improved so that the answers may be forthcoming soon.

These investigations and those we shall discuss below will benefit enormously from the increase in the intensities of polarized light ion beams which will become available in the next few years. These will make it possible to study the spin dependence of various phenomena. It is easy to see, and this is generally supported by experience, that the extra information obtained when polarization effects are studied is of great significance.

The study of the decay of giant resonances which must be performed in order to understand their structure and their origin also illustrates this point. Of course these studies will continue; the latest member of this family, the monopole giant resonance will be thoroughly investigated and the compressibility of nuclei obtained. But there are other resonances possible and there is, in addition, the question of whether or not families of giant resonances exist which are built upon excited nuclear states in each nucleus.

New experimental techniques which have been developed recently will be extraordinarily useful in this regard. Very fast picosecond (10^{-12} sec) timing permits for the first time the use of neutron projectiles in the region of several MeV and already this capability has been of great use in these studies of giant resonances. One of the most simple and informative of all nuclear reactions is one in which the incident particle is captured by the target with the energy carried off as a gamma ray. Previous to a year ago the only cases that could be studied were the highest energy gamma rays associated with capture to the lowest few states of the final nucleus. Technical advances involving the use of fast timing and the pulsed beams naturally available from cyclotrons have allowed nuclear scientists to observe lower energy   rays associated with the capture process. This new technique instantly yielded new and exciting results in that a strong transition to a few highly excited states of the final nucleus were observed. This may signal either the existence of a giant resonance built on these excited states or may be a manifestation of a new capture mechanism. This subject is very new and has generated a large number of experiments and theoretical investigations.

As we indicated, simple modes of motion are not limited to giant resonances. The study of single particle orbitals using polarized beams is one example of a study which will undoubtedly have an important impact. But there are many others. The study of states obtained when a deeply bound nucleon is removed from a nucleus by either "knock out" or by "pick up" (a reaction in which a proton striking a nucleus leaves as a deuteron) is such a case.

The properties of these simple modes of motion as well as their coupling reveal properties of the force between nucleons inside the nucleus. These forces differ from those between free nucleons because of their differing environment, that is because of the presence of other nucleons. Determining this force is, of course, very important for nuclear structure theory. But it is also another aspect of strongly interacting many body systems.

A new phenomenon which needs a thorough investigation is the production of energetic particles moving in a direction opposite to the motion of the energetic incident projectiles. Are these particles the result of a number of scatterings inside the nucleus, or is it the consequence of the scattering by a cluster of nucleons inside the nucleus?

At the higher energies, the "proton microscope" needs to be improved and its use extended to the study of the matter density associated with a given spin. And, of course, the dramatic effects which occur with ultra-relativistic protons need considerable experimental and theoretical attention. It is already clear that these investigations will be of a great fundamental importance

CHAPTER 6: HEAVY IONS

Heavy ion nuclear science is that branch of the field that uses nuclei themselves as projectiles with which to bombard other nuclei. By this technique, it is possible to study in a very general way the properties of the material of which nuclei are composed. Throughout the history of nuclear science, it has not been possible to measure the response of the nuclear material to large changes of such conditions as composition, pressure, density, temperature or rate of rotation. The development of heavy ion nuclear science in the last few years has gone a long way toward the removal of this very serious limitation so that controlled studies are now possible.

Nature has very kindly provided us with an unexpected phenomenon that has made it possible to do many new measurements. During the collision of one nucleus with another, it often happens that the two nuclei go into a temporary orbit around each other and at a very close distance — in fact they touch, forming what might be called a nuclear molecule. After a short time, the two nuclei separate again, and as they fly apart, they carry with them the information about what happened to them during their brief encounter. Thus, it is possible to study the flow or diffusion of matter and heat from one nucleus into the other and thereby to learn about the motion of the individual components and substructures of nuclear material.

In other kinds of collisions, the two nuclei coalesce or fuse into one large nucleus, just like two drops of water that are placed in contact with one another. However, in the nuclear collision, the product is often rotating very rapidly. If the rotation is too fast, the two nuclei fly apart at once. If it is a little slower, they hold together but the rotation causes the combined nucleus to distort into a variety of shapes that can be measured by observing the radiations that are emitted. By making systems that rotate at different rates, the effect of higher and higher rotations on the shape of the nuclear matter can be mapped. Indeed, quite exotic shapes can be produced, including those produced as a spinning nucleus separates or fissions into two highly deformed (aspherical) nuclei.

Nuclear material, when it is at the lowest internal temperature, is made up of neutrons and protons. The motion of these individual particles is organized into orbits. In some cases, the shape of a nucleus in the lowest energy states of a nucleus becomes permanently nonspherical. If we try to spin a nucleus at the fastest possible rate consistent with keeping its total energy as low as possible, remarkable features of nuclear behavior are revealed. Sometimes, rather than having the nucleus rotate as a whole, one or a few of the nucleons abruptly change their orientation with respect to the other nucleons. This example of the interplay between the motion of individual particles and the collective motion of the entire system is a general feature of nuclear physics.

An important task in nuclear science is to produce nuclei in which the number of neutrons is made as different as possible from the number of protons. One method involves the fusion process mentioned above. The highly excited compound nucleus evaporates or boils off neutrons, leaving a residual nucleus which is proton rich. Many new nuclei have been discovered and studied in the past few years with this method. Another method involves accelerating projectiles to very high velocities. When a high-velocity nucleus makes a violent collision with the edge of another, some of the protons and neutrons of the projectile are sheared away. If, by chance, many more protons than neutrons are removed, the remaining nucleus will have an unusually high ratio of neutrons to protons, i.e., it will be neutron rich. Such events have recently been observed, and in two short experiments no less than twenty new species were produced in which the ratio of neutrons to protons was twice as high as in "normal" nuclei. The way is now clear to study the properties of these unsuual nuclei.

These same kinds of collisions — where only the edges of the two nuclei intersect - also occur during the passage of cosmic ray particles through the vast regions of space. Those regions are not quite empty — they contain very small amounts of gas, but the distances traveled by the cosmic rays are so great that there is a substantial probability that they will collide with a nucleus of the interstellar gas. Therefore, the cosmic ray particles are progressively broken down, and what they are upon arrival at earth or at a satellite is not what they were when they left their primordial source. The study of these collisions under controlled laboratory conditions makes it possible to convert earth or satellite measurements of cosmic rays back to the primitive source. Moreover, the recent ability of nuclear science to accelerate nuclei to velocities approaching the speed of light has given cosmic ray physicists a controlled, high-intensity source of artificial cosmic rays which they use to refine and callibrate their detection systems prior to the extremely expensive launch into space. In the past, cosmic ray physics has made enormous contributions to nuclear and particle physics: Heavy ion nuclear science is now able to pay off the loan with interest.

The head-on collision of two nuclei is expected to produce their complete overlap so that the density of the nuclear material is greatly increased. Localized effects, such as sonic shock waves within the nuclear material, might produce additional sources of compression.

What will happen when the nuclear material is compressed? Some of the nuclear material produced is heated to extraordinarily high temperature. There are reasons to believe that this high temperature nuclear material formed in the first stage of the collision undergoes a rapid outward expansion with equally rapid cooling. The elementary components of the nuclear material (mainly neutrons and protons) then recombine to form more complex structures, such as nuclei of the elements of helium, lithium and others*.

But theories have also suggested that nuclear matter at high compression could undergo a change of phase, that is, form a new kind of nuclear matter. This process is similar to the change of ice into water when it is compressed. The experiments to test these theories are just starting. One immediate and important application of these studies is to the understanding of the nature of "neutron" stars, where enormous gravitational forces compress nuclear matter.

In these collisions of very fast nuclei with one another, the description of the resulting hot matter in terms of just protons and neutrons is no longer adequate. Collisions

* A rival description which so far has successfully described the available data can be given. In this theory, during the collision, neutrons and protons are knocked out of the colliding nuclei. The heavier nuclei, which form the reaction product, are then produced by evaporation from the remainder.

between those constituents produce additional particles such as pions and heavier objects. The nuclear matter is expected to be cooled by the production of these particles. Some speculations regarding the nature of this process suggest that there is a highest achievable temperature that can be reached in the collision of two nuclei. This limiting temperature will have a value that depends upon how many different kinds of particles exist in nature. At the extremely high excitations which can be produced in collisions, it is suggested that nuclear material behaves like a soup that contains a number of different constituents. The more constituents that exist in nature, the cooler will be the equilibrium temperature of the soup, so that by measuring the highest achievable temperature, it may be possible to measure the number of different particles that exist. Does highly excited nuclear matter behave this way? One of the goals of research in this area will be to find out!

An unusual phenomenon was observed in cosmic rays about 20 years ago. In rare cases, something strange happens when a cosmic ray particle (which is a very fast-moving nucleus) strikes another nucleus. Out of the collision comes a shower of particles and nuclei, some of which behave as though they are much larger than they ought to be. Events of this kind have now been observed by the use of high energy nuclei from an accelerator. There are theoretical speculations that these apparently larger nuclei are a new form of nuclear matter. If these results are borne out by further experimental and theoretical work, they will open up an entire new area for nuclear and particle physicists to explore.

Among the products formed in the violent collision of two nuclei, there are a substantial number of negatively charged pions. By studying the correlation in direction and velocity between pairs of these pions, it has been found that the effective size and apparent time evolution of the source from which they come can be measured. The methods that are used were initially developed in radio astronomy to measure the size of the evening star, Sirius. The size and time dependence of the pion source is closely related to the state of the nuclear system at the time of pion emission and thus could provide unique information on the nature of the collision and nuclear matter under extreme conditions.

We have mentioned a number of new phenomena which have been predicted for nuclear matter under extreme conditions: sonic shock waves, compression, and changes of phase. Each of these phenomena is expected to occur above a certain threshold bombarding energy (or projectile velocity). Experiments to locate these thresholds, therefore, require the acceleration of projectiles over a wide range of continuously variable velocity and, consequently, a broad base of accelerator type and capability.

To summarize, heavy ion nuclear science has made it possible to study the nuclear material in bulk by subjecting it to various stresses and measuring its response. The knowledge to be gained impacts fundamentally across an enormous spectrum of physical phenomena that range from the interactions between particles to the use of theoretical concepts from thermodynamics to the study of cosmic rays, all the way to the structure of neutron stars and the early history of the universe.

Recent Accomplishments

Heavy ions in the context of this report are accelerated nuclei. By selecting the nucleus to be accelerated, one selects the electric charge on the ion and, therefore, the strength of the electric force it exerts on the target nucleus in the course of a collision. These electric fields can, in fact, be very large if the atomic number of the ion is large. By choosing the energy of a heavy ion, one chooses the momentum of the heavy ion and, therefore, the ability to set a target nucleus spinning, or as also happens, the heavy ion fuses with the target nucleus and the whole complex rotates. The heavy ion is a composite system. This means that it will not preserve its identity if it penetrates deeply into the target nucleus. As a consequence its interactions with the target are especially sensitive to surface properties. Because it is composite, the heavy ion can readily transfer nucleons to the target nucleus, or it can fuse with the target, to produce a large variety of reaction products. Heavy ions thus form an especially versatile group of projectiles.

Nuclear Structure

When a heavy ion strikes a target nucleus off center, the system will rotate and, if they fuse to form a single nucleus, one will observe nuclei with relatively large rotational velocities. The behavior of a nucleus as it rotates more and more rapidly reflects the effect of the resultant stress on the internal structure of the nucleus. Indeed, such internal structure changes do occur and the shape of the nucleus does change. The shape may change from prolate spheroidal to oblate spheroidal, characteristic of a classical rotating fluid or it may first assume an ellipsoidal shape before becoming oblate. Finally, at sufficiently large angular velocities, the nucleus will undergo fission. The changes in nuclear shape and internal structure on the road to fission will be extremely interesting.

Closely related to this last stage in fission is the formation of "nuclear molecules." These have been reliably observed in the collision of the lighter heavy nuclei, the classic case being that of two carbon nuclei. When two carbon nuclei collide they can, at very particular energies, form long lived systems in which the carbon nuclei act to a surprisingly large extent as independent clusters attracted by the nuclear analog of a VanderWaal's force. This is an outstanding example of the simple mode of motion involving clusters. The delineation of the circumstances under which such systems can exist provides an important challenge to both theorists and experimentalists.

The understanding of nuclear structure achieved so far has rested on experimental data and theoretical developments connected with the stable and nearly stable nuclei. An important test of that understanding will be provided by the properties of nuclei far from the valley of stability (the values of the neutron and proton number for stable nuclei), that is, with unusual values of the ratio of the number of protons to the number of neutrons. Such nuclei can be formed in the collisions of heavy ions with nuclei in which a large number of nucleons are transferred either to or from the target. These will decay radioactively. But as one goes farther from the valley of stability one will eventually form nuclei which will also decay by particle emission and for very heavy nuclei by fission. The study of these nuclei is now in progress and the domain to which they are limited is being determined.

Of great interest is the possibility of islands of stability not connected with the stable valley such as that occupied by the "superheavies" which have unusually large values of the atomic and mass number.

Nuclear Reactions

Much of the recent research in heavy ion physics has been dedicated to the study of the nuclear reactions which occur when a heavy ion collides with a nucleus. This is natural since understanding the underlying mechanisms is not only important in its own right but also because it is a necessary condition for interpreting the results in terms of fundamental attributes of nuclear systems.

It has been found that in addition to processes with short interaction time, the direct reaction, and processes with long interaction time leading to fission, there was a third kind of process with an interaction time intermediate in value*. In this process, referred to as "deep inelastic scattering," most of the initial energy of the projectile is converted into internal energy of the nuclei, or in other words, the nuclei become heated by the collision. This discovery came as a surprise. Much effort, both experimental and theoretical, has been spent attempting to determine the conditions for deep inelastic scattering and the corresponding boundaries for direct and fusion processes. It is clear that the nuclei exchange nucleons, but generally at the end of the process, the system still consists of two, often altered, nuclei. In addition to exchange of particles, there is direct exchange of energy by inelastic scattering processes by means of which the nuclei are excited.

A whole battery of explanations has been devised. At the macroscopic level, one model introduces the notions of viscosity and friction in order to describe the conversion into internal energy. At another level, a diffusion type description is used in which particles, charge and energy diffuse from one system to another. At a still deeper level, a semiclassical method is used to describe the excitation. The motion of the heavy ions can, to a certain extent, be discussed using Newtonian orbit calculations. Finally, there is a method (referred to as TDHF) based on the

* The existence of intermediate reaction time processes in light ion physics should be noted.

direct integration of the time dependent equations of quantum mechanics. Of course, the method is approximate in that each nucleon is placed in an orbit and the orbits are allowed to change with time. It is, however, a natural extension of the shell model to a reaction process since the essential assumption is equivalent to assuming that each nucleon moves in an average field generated by all the other nucleons. Most of the observed phenomena appear in the TDHF calculations so that one can immediately conclude that it is qualitatively correct.

This period has also seen the beginning of experiments dealing with "relativistic" heavy ions, that is, heavy ions with energies greater than several hundred MeV/nucleon. Two types of collisions have been distinguished, the peripheral in which the two nuclei "brush" past each other, and the central where the collision is "head on." The former leads to the fragmentation of the projectile. This process is limited to small angles. In the central collision, fragments from both nuclei are formed over a much wider angular range. Peripheral fragmentation is quite well understood. In the case of the central collision, an understanding has not yet been achieved. It has become clear that examining the production of one particular fragment is insufficient; that it is essential to establish correlations among the many possible final particles, including pions as well as nucleons and nuclei. All of this presents a formidable challenge to theory. The treatment of multiparticle final states and the determination of the appropriate measures of the experimental data are both needed in order to plan experiments and relate the data to fundamental properties of nuclear systems. But beyond that, what description should be used of the interacting systems? Hydrodynamic models, relativistic gas models, and finally the models which consider the nuclei to be "bags" of nucleons interacting one by one, have all been proposed. The correlation experiments now in progress will help to distinguish between these proposals.

Opportunities

In discussing the "recent accomplishments," we have already noted further investigations which need to be carried out to clarify the nature of the phenomenon and to approach a fundamental explanation. These are certainly on the agenda for the next several years. The study of rapidly rotating nuclei will be extended to new nuclei and the threshold of fission will be approached. The dependence of the shape of the nucleus on the speed of rotation and the relation of that shape to the internal structure of the nucleus will be the goals of this research. We already see that it will provide extraordinarily sensitive tests of our understanding of nuclear structure. Another question to be answered asks if there are other examples of nearly stable states in which the interacting nuclei substantially maintain their identity beside those exhibited by the carbon-carbon and the carbon-oxygen system. The criteria which predict in which systems these states will be found, and at what energies, need to be developed and compared with experiment. A very much related problem asks how these "nuclear molecule" modes of motion couple to other modes of the system.

The study of the exotic nuclei will need to go far beyond establishing their existence. We shall need to know their spectra, their electromagnetic properties and the way in which they decay, requiring the development of new techniques for performing the necessary measurements on short lived nuclei. These, in fact, are in progress. One can expect a continued search for exotic nuclei (that is, for islands of stability outside of the stable valley) such as the super heavy nuclei. The most promising method for producing the latter seems to be deep inelastic collisions.

The study of deep inelastic collisions will continue to be very active as research will attempt to understand the process more completely, as well as its boundaries, with respect to experimental parameters such as energy, peripheral nature, nuclear species involved and so on. More detailed measurements, particularly of the light and heavy fragments, will be important. Of course, much more theoretical work is required, particularly on determining what are the favored ways for transferring energy, momentum, and mass in these collisions, and thereby relating macroscopic parameters such as viscosity, diffusion, and relaxation times to fundamental properties of the motion of nucleons in nuclei. For the relativistic heavy ions, as we have emphasized, measurements of the correlations and eventually in some cases of all the details of the many particle final state generated in these collisions are essential. In fact, the required detectors are being built and the measurments will soon be made. The appropriate theoretical treatment of these collisions is still unknown. Should one use an extension of the multiple scattering formalism or should one have recourse to a statistical mechanical model or to a hydrodynamic model? Or will more radical theoretical assumptions be required? Whatever the solution, the implications for the possibility of forming regions of high density will be of central importance.

The discussion so far has been limited to regions accessible with today's accelerators, which provide beams up to 10 MeV/nucleon and at the Bevalac up to 2.1 GeV/nucleon. Construction now under way at the Bevalac will permit experiments in this range of energies with uranium beams. However, it is clear that a need exists for additional experiment capability using heavy ions with energies extending from 10 MeV/nucleon to 200 MeV/nucleon. Accelerators under construction will partially fill this gap which is thought to be very important because a number of transitions in reaction modes are expected to occur in this energy range. One such transition should occur when the projectile velocity equals the speed of sound in nuclear matter which is estimated to be about 0.16c (6=velocity of light). The heavy ion energy should be about 12 MeV/nucleon. Above this energy, nuclear matter may undergo compression during a collision. A second transition point occurs when the velocity of the incident heavy ion is equal to the maximum velocity of a nucleon in the target nucleus, that is, at the Fermi energy at about 36 MeV/nucleon. Beyond this energy, the Pauli exclusion principle should not play such a dominant role. Another transition should occur when pion production becomes important. This should be at some energy below the threshold energy of about 260 MeV for a hydrogen target. To observe just how these transitions reveal themselves in heavy ion induced reactions, and to determine the properties of nuclear structures generated in each of these three domains is indeed exciting.

Projectile energy above 2.1 GeV/nucleon is another domain which has not been studied. As mentioned in the preceding chapter on light ions, some rather bizarre results have been obtained with ultrarelativistic protons. These need to be understood in order to make it possible to determine nontrivial heavy ion effects which may occur when the incident projectile is ultrarelativistic. Again the question can be asked: Is this a domain in which high density nuclear matter can be produced? It is highly likely that it will be necessary to take into account the quark and gluon degrees of freedom. It may, in fact, be possible to test quantum chromodynamics and to produce quark matter, that is a system consisting of many quarks not localized inside a nucleon. Parenthetically, it should be noted that many kaons will be produced, and that it may be possible to form hypernuclei containing two or more strange baryons such as the lambda. It will then be possible to determine the statistics of the Λ 's directly, a determination which has not been as yet made experimentally.

CHAPTER 7: PIONS

Nature of the Probe

During the last half century, the experimental probes used were for the most part the neutron, the proton and the light-heavy ions, gamma rays, alpha and beta particles, and high energy electrons. Pions represent an entirely new kind of probe. Pions can have a negative charge (π^-) (equal to that of the electron), an equal and opposite positive charge (π^+) or it can be neutral (π^o). These three particles have zero spin and masses which are nearly equal. Pions, like photons, can be absorbed or produced, but unlike photons, can interact strongly with nucleons. The interaction of a low energy pion with a nucleon is relatively weak, but at higher pion energies, 100-300 MeV, a pion and a nucleon can form an excited state of the nucleon referred to as the delta* (Δ) isobar. Last but not least, the pion is the carrier of the long range part of the force between nucleons. Shorter range components are carried for the most part by pairs of pions. The "glue" that binds nucleons together to form nuclei is thus made of pions. The study of the pion interaction with nucleons and nuclei, the way the pion presence manifests itself in nuclei, the probability that nucleons are occasionally 's are all of great interest. More than that they must be understood in order to obtain a deep understanding of the nucleus and nuclear dynamics.

The scattering of pions in the 100-300 MeV range is dominated by the formation of a delta by the projectile pion. But this delta is not a free delta, but a delta inside the nucleus. Its properties will be modified by its strong interaction with the nucleons, a matter of considerable importance not only for the pion scattering by nuclei but for the quantum mechanics of resonances imbedded in strongly interacting many body systems, generally. Within nuclear science, the methods employed will be useful for discussion of the behavior of other "nearly stable" systems inside the nucleus.

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*This can exist in four charge states, doubly charged (Δ^{++}), single charge (Δ^+), neutral (Δ^o) and negatively charged (Δ^-). The first consists essentially of a proton plus a positive pion, the second a mixture of a proton and a π^o and neutron and a π^+, etc.

Pion-nucleus physics has progressed rapidly during the five years following the start of research at the Los Alamos Meson Physics Facility (LAMPF). Most of the research in pion physics in the U.S. is done here, although some experiments in photoproduction of pions are being performed at the Bates Electron Linear Accelerator and some in production by protons at the Indiana Cyclotron. Pion production by high energy heavy ions is also under study at the Bevalac.

Recent Accomplishments

In a totally new field, the first task is to determine its broad general features and to obtain an understanding of them. In the pion case, this has required the study of both elastic and inelastic scattering of pions by nuclei, that is, collisions of pions with nuclei in which , in the first instance of elastic scattering, the target nuclei do not acquire any internal energy, and in the second instance of inelastic scattering, they do, and are thus left in an excited state. Results of inelastic scattering experiments have shown a strong sensitivity to the nuclear structure of the target nuclei, for example to the presence of shape deformations. Recent measurements show large nuclear structure effects in the ratio of positive pion induced inelastic scattering to negative pion induced processes. Comparison of the elastic scattering of π^+, and π^-, as well as the single charge exchange scattering in which the π^+ projectile is converted into a π^0 by the scattering are sensitive to the distribution of the neutrons in the target nucleus. Elastic scattering experiments have been performed with a variety of nuclei. In the resonance region in which the Δ can be formed, explanations of the results have been obtained in terms of the interaction of the   with the rest of the nucleus. This is an important accomplishment, though of course much still remains to be done in exploiting and extending the concepts which have been developed. The information obtained is of crucial importance to the question of the existence of pion condensates* in dense nuclear matter and to a number of problems in astrophysics, such as the cooling of stars and the physics of neutron stars.

The collisions of low energy pions, in which the pions are able to penetrate into the interior of the nucleus because of the relatively weak interaction between

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*Pion condensates refers to the possibility that large numbers of pions may be formed in sufficiently dense nuclear matter.

the pion and nucleon at these energies, have been found to be sensitive to correlations between pairs of nucleons. Evidence bearing on this conclusion is obtained also from the spectroscopy of the atoms formed by slow negative pions in which the pion is in an orbit in the Coulomb field of the atomic nucleus.

A phenomenon especially important for the nuclear interaction of low energy pions is absorption of pions. Such absorption involves a relatively large release of energy, as the entire mass of the pion is converted into kinetic energy of the absorbing nucleons. It has been verified that in the principal absorption mode a number of nucleons absorb the energy. A dependence on the probability of finding these nucleons close together is implied.

A number of experiments, which were part of the motivation for building pion facilities both here and abroad, have been shown to be feasible to the degree required for significant impact. Single charge exchange scattering reactions in which the positive (π^+) or negative (π^-) pion projectile is converted by collision with a nucleus into a neutral (π^o) pion, the target nucleus atomic number increasing by one or decreasing by one respectively. In the first case, a neutron becomes a proton; in the second, a proton becomes a neutron. The first of these can be compared to the reaction in which a projectile proton becomes a neutron after the collision. Double charge exchange in which a π^+ (or π^-) becomes π^- (or π^+) is another reaction which can now be carefully studied. In this reaction, two neutrons become protons or vice versa. This reaction will generally produce unstable nuclei with unusual values of the ratio of charge to mass number. It is hoped that the understanding of this reaction will yield information on the correlations which can exist between pairs of nucleons inside the nucleus since the reaction can proceed only if the pion interacts twice with the nucleons inside the target.

Pion production by protons (or absorption of pions with the emission of single protons) are of special interest near the threshold energy for pion production (or the absorption of slow pions). Production here depends on the cooperative behavior of the nucleons in the nucleus, that is on multiparticle correlations.

Opportunities

Two main trends will be evident in the future of pion physics. On the one hand, there will be an increased activity to capitalize on the unique properties of the pion for probing the structure of the nucleus. On the other hand, with an increased emphasis on higher energies and shorter distances, the quark structure of the hadronic states will be probed to a greater extent, and we stand to learn the limitations of the more traditional descriptions of intermediate energy physics in terms of "elementary" mesons and baryons.

Of course, a considerable fraction of research to be done in the period which lies immediately ahead will take advantage of the results most recently obtained. The sensitivity to nuclear structure exhibited in the elastic and inelastic collision of pions with nuclei will be exploited. The few results obtained regarding the double charge exchange scattering demonstrate the accessibility to experiment of an important research area. A new generation of experiments exploring the two nucleon absorption of pions has just begun. The use of polarized protons in the proton production of pions adds a new dimension and the few results obtained so far already show its importance.

One of the more interesting problems presented by the quark theory of the structure of the elementary strongly interacting particles, such as the nucleon, is the shape of the region (the "bag") in which the quarks are contained. Some theories require the Δ to be highly nonspherical. If this were so, then the Δ would be a more efficient source of electromagnetic quadrupole radiation if the Δ is accelerated. This acceleration does indeed occur during a collision between a pion and nucleon for pion energies which result in the formation of the Δ. Therefore, the effect of the shape might be visible in the properties of the electromagnetic radiation generated by the Δ.

Studies of the behavior of the nearly bound baryon and meson systems will lean heavily upon the methods developed for studying the Δ inside the nucleus. Such investigations may very well reveal new properties of these elementary particles.

A promising area for future experimental work involves searches for pionic and isobaric components in nuclear wave functions. The character of the electromagnetic radiation produced when π^- are annihilated may be sensitive to the former while pion-nucleon coincidences reveal the presence of Δ's, to be seen in a knockout process. Experiments are being considered, the intent of which are to search for "precursors" of the unusual state of matter referred to as pion condensation. Such a phase of coherent pion admixtures in the ground state is expected to occur in neutron star matter at densities of two to three times that of normal nuclear interiors.

The electromagnetic production of pions by photons and electrons is and will continue to be under investigation. It promises to be interesting because the pion is produced within the nuclear volume. In the case where the photon energy is such as to excite a Δ, the Δ will be made inside the nucleus. Information on how it propagates inside the nucleus will be more accessible than when the pion is introduced from the outside, that is, as a projectile. In that case the Δ formation occurs mostly in the surface of the nucleus. Comparison of this evidence on the Δ with that obtained from other production processes such as those induced by protons and by heavy ions should be revealing.

With enhanced pion beam intensities, we could study a new type of weak interaction physics. Experiments would become possible which could measure for the first time the weak interaction component of pion-nucleon scattering, a quantity of fundamental importance for the theory of weak interactions.

CHAPTER 8: KAONS AND ANTIPROTONS

Introduction

The use of kaons and antiprotons as projectiles colliding with nuclei offer important new ways of studying nuclei and nuclear forces.

The kaon, unlike the more familiar projectiles, possesses the additional attribute, "strangeness," a quantity which is conserved in strong interactions. A kaon, upon interacting with a nucleus, can deposit a unit of strangeness in the nucleus by changing a neutron or a proton into a strange baryon, such as the lambda (Λ) or the sigma (Σ). These strange baryons have greater mass than the nucleons; they have a single unit of strangeness and they decay to the nucleons via the weak interactions, that is by a form of β decay. The nucleus which is formed when a neutron, for example, is replaced by a Λ, is called a hypernucleus. Hypernuclei, like ordinary nuclei, will exist in well defined states with discrete energies and electromagnetic properties. The properties of these states will depend upon the nature of the interaction of the Λ with a nucleon and in how the host nucleus reacts to the presence of the Λ. Studying hypernuclei should thus provide information on the behavior of the host nucleus being probed by the Λ. It should provide information on the interaction of a nucleon with a Λ and Σ . Although the meson exchange theory of nuclear forces is highly developed for the nucleon-nucleon system (NN), very little is known about the corresponding ΛN or ΣN forces. These can be treated theoretically on the same footing as the NN forces. The underlying theory presumes a very close relationship between NN, ΛN, and Σ N interactions. Nuclear reactions involving strange particles should enable us to test the consistency of that theory, eventually modifying our ideas on the nucleon-nucleon interaction.

The field of kaon-nuclear physics is still in its infancy. Pioneering experiments in Europe and the U.S. have provided very stimulating glimpses of the nature of strange nuclei, but the most exciting prospects lie ahead. More intense beams of kaons are required before the potential of this field can be realized.

Antiprotons ($\bar{p}$) have recently become available for nuclear studies. The antiproton is a particle with exactly the same mass as the proton but with opposite electric charge. It bears the same relation to the proton as the electron does to the positron. When the positron and electron collide, they can annihilate into photons. On the other hand, they can form a nearly stable system known as positronium. The nucleon-antinucleon system can also annihilate into pions. It can also form a nearly stable system. One is thought to exist at 1.932 GeV but there may be others.

More generally there are antineutrons ($\bar{n}$) which together with the $\bar{p}$ are referred to as the antinucleon ($\bar{N}$). Because of this close connection between the nucleon N and the antinucleon $\bar{N}$, the nucleon-antinucleon ($N\bar{N}$) interaction is intimately related to the interaction between two nucleons (NN). The ($N\bar{N}$) interaction results from the exchange of the same kinds of mesons, the pion and others, as are responsible for the NN interaction. The study of the collision of antinucleons with nucleons will yield information on the $N\bar{N}$ interaction and its dependence on meson exchange, and thus help to complete our understanding of the nuclear force problem.

The meson exchange picture provides one level of understanding of the interaction between nucleons and antinucleons, primarily applicable to the medium and long range parts of the force. When nucleons and antinucleons are close together, one must consider their detailed structure. Particles such as nucleons are thought to be composed of fundamental constituents called quarks contained within a region about 10^{-13} cm in radius and referred as a "bag." The nucleon consists of three quarks (QQQ) and the antinucleon from three antiquarks ($\bar{Q}\bar{Q}\bar{Q}$). The mesons such as the pion and kaon consist of a ($Q\bar{Q}$) structure. When the nucleon and antinucleon come into close contact, the three quarks plus three antiquarks can fuse into a single "bag" containing ($QQQ\bar{Q}\bar{Q}\bar{Q}$), and various reaction processes can be initiated. For instance, a $Q\bar{Q}$ pair can annihilate, leaving the fused system as $QQ\bar{Q}\bar{Q}$. Modern quark models are able to predict the masses and quantum numbers of such $QQ\bar{Q}\bar{Q}$ composite mesons, called "baryonium." These new particles are more complicated in structure than the more familiar mesons such as the pion ($Q\bar{Q}$), but they represent a prediction of the quark model. It is obviously of great importance to verify the existence of "baryonium" and to determine its properties. Thus, the objectives of experiments involving the collisions between antinucleons to be provided by an appropriate accelerator facility and nucleons in the form of hydrogen and deuterium include determining the NN interaction, nearly stable $N\bar{N}$ systems, and the observation of reactions which lead to baryonium, which cannot be described in terms of nucleons and antinucleons, but which can be described in terms of quarks as $(QQ\bar{Q}\bar{Q})$.

Recent Accomplishments and Opportunities

The last few years have seen the production of a number of hypernuclei using the reaction in which the incident projectile is negative kaon (K^-) which through collision with a nucleus is converted into a negative pion (π^-). This is accompanied by the conversion of one of the nucleons in the nucleus into a lambda (Λ). The reaction proceeds efficiently because within a rather broad range of kaon energies, the reaction is recoilless, that is, the momentum of the hypernucleus is nearly zero. This research is still in its infancy. Although a number of the energy levels in some hypernuclei have been seen, the measurements are not yet sufficiently extensive or accurate to completely determine the nature of these energy levels, to be certain that none have been missed and to look for their existence in a wider group of nuclei. These measurements are only possible if more intense beams and better resolution become available.

The research described above refers to hypernuclei with single Λ's in the host nucleus. The production of doubly strange hypernuclei is considerably more difficult. Several possibilities have been suggested including the reaction in which a K^- is converted into a K^+, or in the multiple kaon production in a high energy heavy ion collision. The production of such hypernuclei would permit direct verification of the fermion character of the Λ's.

Very recently, the discovery of a remarkably stable hypernucleus in which the strange baryon is a sigma (Σ) has been made. This was entirely unexpected and requires further investigation.

Only one "stable" state of $\bar{p}p$, at 1932 GeV is thought to have been observed, although several others are suspected. A broad ranging research program concerned, not only with the existence of nearly stable states, but also with studying the collision of $\overline{p}$ with p in the form of hydrogen over a wide range in energies is clearly indicated for the field. This program would require the development of a powerful source of antiprotons such as the one being developed at CERN.

CHAPTER 9: NUCLEAR SCIENCE RELATED RESEARCH AND APPLICATIONS

Nuclear science interfaces with almost every branch of physics; it has had a pervasive influence on all science and technology. As the frontiers of nuclear science expand, fruitful contributions continue unabated to such diverse fields as astronomy, archeaology, chemistry, medicine and geology and, within physics, to materials science, atomic physics and condensed matter physics.

Stars shine from nuclear energy as one element is transmuted into another. The understanding of stellar objects and the evolution of the universe is dependent on our understanding of the nucleus. How does our sun shine? The essential answer depends on our detailed knowledge of how the sun burns hydrogen to form helium, and basic puzzles still remain. How was the Crab Nebula formed, with its pulsar (neutron star) core surrounded by an exploding nebular remnant? How has the universe synthesized the elements to produce the abundances we see in meteorites, in the earth, in the sun and in other stars? How do we explain the evolution of stars and galaxies since the primeval fireball? The answers to such questions as these necessarily require detailed and wide-ranging nuclear data, much of it not yet determined, and the application of theoretical considerations which are at the very frontier of current developments in nuclear theory.

The result has been the pursuit in many nuclear laboratories of what we designate here as Nuclear Science Related Research and Applications. Nuclear science related research is defined in the Nuclear Science Advisory Committee Charter as "closely related research conducted with the same equipment and facilities and funded via the same channels." The total DOE/NSF funding in FY 1979 was $4.6M at 27 institutions and involved at least part time activity on the part of one hundred faculty-equivalent investigators. Nuclear science applications are supported by a great number of governmental and industrial agencies. The FY 1979 funding by the Nuclear Science Section, Division of Physics, NSF and by the Divisions of Nuclear Physics and Nuclear Sciences, DOE was $6.5M, making a total of $11.1M support during FY 1979 in the total area under consideration here .

A representative but not inclusive list of the activities in nuclear science related research and applications supported by the offices in the DOE and NSF mentioned above includes:

1) Nuclear Astrophysics and Cosmochemistry
2) Accelerator Radiochronology
3) Accelerator Related Atomic and Molecular Physics including Hyperfine Interactions
4) Accelerator Related Solid State Physics including SR (muon spin rotation)
5) New Applications of Nuclear Data, Instrumentation and Accelerators

We discuss these areas briefly in what follows.

Nuclear Astrophysics and Cosmochemistry

Nuclear Astrophysics and Cosmochemistry cover the overlapping areas in which nuclear physicists and chemists contribute to cosmology, astronomy (lunar, planetary, stellar, galactic and extragalactic) and to the study of meteorites and the cosmic radiation.

Experimental nuclear physics produces the empirical data necessary to determine the rates of nuclear energy generation and nucleosynthesis under astrophysical and cosmological circumstances. It produces data necessary to calculate the equation of state, nuclear partition functions and weak interaction rates for pair emission, electron capture, neutrino transport, neutrino energy loss, etc., in nuclear matter at extremes of density and temperature. It produces the data necessary to extrapolate elemental and isotopic abundances observed in the cosmic radiation to the abundances in the sources of this radiation. It has had considerable influence on the development of detection techniques for extraterrestrial gamma radiation and neutrinos and for depth profiling in extraterrestrial materials. Theoretical nuclear physics is essential to the application of experimental nuclear data to astrophysics, especially in the extrapolation of low energy cross section measurements to even lower stellar energies, and in deducing reaction rates involving short lived radioactive nuclei and the excited states of stable nuclei. Theoretical nuclear physics integrates the empirical data and specifies the properties of nuclear matter at extremes of density and temperature under both hydrostatic and hydrodynamic circumstances.

There have been a number of highlights in experimental nuclear astrophysics during the past five years. Direct capture yields have been used to determine proton reduced widths of states near thresholds in a number of proton induced reactions in the CNO-cycle. This permits a determination of the resonant contributions of these states at stellar energies. Extremely accurate measurements of the nuclear parameters which determine the rate of the $3\alpha \rightarrow {}^{12}C$ reaction in helium burning in red giant stars have been made so that this rate is now one of the most accurately known in nuclear astrophysics. On the other hand, careful low energy measurements on ${}^{12}C(\alpha,\gamma){}^{16}O$ still leave a very uncertain extrapolation to helium burning energies and thus a real challenge remains — experimentally and theoretically — in determining the nuclear data necessary to specify the ${}^{12}C/{}^{16}O$ ratio produced in helium burning.

Much of the recent effort in experimental and theoretical nuclear astrophysics is directed toward the prototype problem in supernova astronomy — how was the Crab Nebula formed, with its condensed neutron star/pulsar surrounded by an exploding nebular remnant? In the implosion-explosion models for supernovae, core collapse is followed by relatively slow infall of the mantle until bounce on the hard core reverses the infall. At the high temperatures induced by the resulting outward traveling shock wave, the silicon group nuclei in the inner mantle can ignite explosively, perhaps triggered by the deposition of momentum and energy by neutrinos from the neutronizing core. Explosive nucleosynthesis occurs on a time scale of the order of seconds. This is much too short for many of the nuclear processes to reach equilibrium in forward versus reverse reaction rates. Thus, reaction rates, not equilibrium considerations, are important in calculating the abundances produced in explosive nucleosynthesis. The specific direction experimental efforts will take in the future will be guided by calculations of the elemental and isotopic abundances produced during the quasistatic presupernova stages and the explosive supernova stages of stellar evolution.

In the collapse problem, considerable progress has come about from the realization that the entropy per nucleon remains small during the entire collapse. At subnuclear densities, nuclei partially dissolve into alpha particles and neutrons, but are reconstituted at higher densities and are preserved right up to nuclear matter densities beyond which nucleons are squeezed out of the nuclei. Neutronization occurs through electron capture on nuclei rather than on the less abundant free protons. Neutrino trapping occurs at approximately one per cent of nuclear matter densities and the subsequent collapse is adiabatic with an index of slightly less than 4/3 up to nuclear matter densities. At this point, the equation of state suddenly stiffens with the adiabatic index going up to $\sim 5/2$ with bounce at about 3 times nuclear matter density. There is still much to be done in making this picture more precise with better nuclear input involving neutral current weak interactions and URCA processes among other things. The greatest challenge lies in specifying the strength of the shock wave which follows the bounce and answering the question whether the shock wave, in conjunction with neutrino transport or rotation, can dismantle the star and eject nuclear species previously synthesized explosively into the interstellar medium. Nucleosynthesis in supernovae and all other aspects of these fascinating astronomical events will continue to be a challenge throughout much of the 1980's.

Turning to cosmochemistry, there have been a number of exciting new developments in the past decade of which we first discuss isotopic anomalies in the Allende meteorite. The fall of this carbonaceous chondrite made available for careful isotopic scrutiny large amounts of material which is thought to be the most primitive in the solar system. Enhancements in ^{26}Mg abundances which correlate with the Al/Mg ratio in Allende inclusions indicate the in situ decay of ^{26}Al ($\bar{\tau} = 1.1 \times 10^6$ yr) and show that the early solar nebula was incompletely mixed, and contained debris which was ejected from a stellar source at most a few million years prior to the formation of the solar system. This has led to a revival of an old idea that a supernova triggered the formation of the solar system.

It has also been established that the isotopic composition of many elements (O,Ne, Mg, Si, Ca, Kr, Sr, Xe, Ba, Nd, Sm) in some meteoritic materials is distinctly different from that in terrestrial samples. There is every reason to believe that continuing study of nucleosynthetic processes and meteoritic isotopic anomalies will give us better understanding of solar system formation and direct insight into element processing and reprocessing during the evolution from birth to death of massive stars whose short lifetime immediately preceded the formation of the now middle aged solar system.

The radiochemical $^{37}Cl/^{37}Ar$ technique has been used for over two decades in the search for solar neutrinos, but only recently has a result other than an upper limit been obtained. This new result is $2.2 \pm 0.4 \times 10^{-36}$ neutrino captures per second per ^{37} Cl target in the 100,000 gallon perchlorethylene detector located one mile deep in the Homestake Gold Mine at Lead, South Dakota. Because the detector is omnidirectional, it can only be argued on general grounds that the neutrinos are from the sun.

Even so, this determination, with its small standard deviation, raises serious problems since the expected flux from the standard solar model is two to three times greater. The uncertainty implied in the "two to three times greater" arises directly from the fact that the only solar neutrinos detectable by the $^{37}Cl/^{37}Ar$ technique are principally those from the decays of ^{7}Be and ^{8}B. The ^{7}Be and ^{8}B contributions to the capture rate are very model dependent in the sense of varying rapidly with varying temperature at the center of the sun which is intrinsically model dependent.

The uncertainties in the model dependent capture rate for the $^{37}Cl/^{37}Ar$ technique have spurred attempts to develop techniques which have detection thresholds below the energy of the model independent pp-neutrinos from the primary $H(p,e^{+}\nu)D$ reaction in the conversion of hydrogen into helium in the pp-chain of reactions. Two such techniques look very promising, one involving $^{71}Ga/^{71}Ge$ (radiochemical) and the other, $^{115}In/^{115}Sn$ (electronic). The $^{71}Ga/^{71}Ge$ technique has a known sensitivity calculable from the rate of beta decay of the ground state of ^{71}Ge and thus is capable of an absolute determination of the capture rate of the pp-neutrinos from the sun. The $^{115}In/^{115}Sn$ technique will not be able to do this (unless calibrated using megacurie sources of neutrinos, e.g., ^{65}Zn) because it involves neutrino capture into an excited state of ^{115}Sn which gamma decays. However, it employs electronic detectors capable of measuring the energy spectrum of the electron ejected in $^{115}In\,(\nu,e)^{115}Sn^{*}$ and thus of the incident solar neutrinos. The two techniques are needed in conjunction to test the basic premise of solar model calculations that the sun shines on nuclear energy generated by hydrogen fusion via the pp-chain.

The $^{71}Ga/^{71}Ge$ technique has successfully passed a number of small scale tests. A modular extractor facility for 1.5 metric tons of gallium is now under construction. Eventually, 50 tons of gallium will be required to obtain a predicted rate of one capture per day. The extractor facility is designed to process the 50 tons in one day — short, compared to the 11 day half-life of ^{71}Ge. The current cost of gallium is approximately \$0.5M per ton, indicating a minimum cost of \$25M for the experiment. The $^{115}In/^{115}Sn$ technique has also passed small scale tests, and a proposal for a substantially scaled-up test is in preparation. An order of magnitude estimate for a full scale experiment is \$10M.

Accelerator Radiochronology

The use of accelerators as ultrasensitive mass spectrometers is one of the most exciting new developments in nuclear science. The sensitivity of radioisotope dating is improved considerably by counting atoms rather than detection of radiation. The size of the sample can be reduced and the age that can be measured can be pushed back by many half-lives with the new accelerator technique.

The measurement of cosmogenic radioiostopes can provide information in many scientific areas. ^{14}C with a half-life of 5730 years can date archeaological and geological carbonaceous samples on a 50 thousand year time scale and can provide information on cosmic ray and climatic variation on a 10 thousand year time scale. The advantages of using a tandem accelerator as an ultrasensitive mass spectrometer are the use of negative ions from the source, molecular dissociation at the terminal, and sufficient energy for Z identification at the detector. Recent results on ages have been obtained with carbon samples of about 1 milligram.

The isotope ^{36}Cl with a half-life of 0.31 million years can be used to measure the age of old ground water, ice and meteorites on a million year time scale. The measurement of ^{10}Be in natural samples such as ice and ocean cores, as well as the ratios of ^{10}Be to other radioisotopes in such samples, can provide important information about geochronology on a ten million year time scale as well as in weathering and sedimentation rates relating to paleoclimatology, about reversals in the earth's magnetic field, about the formation of manganese nodules, and on the constancy of the cosmic ray flux incident on the earth.

^{26}Al, with a half-life of 0.72 million years, is of geochronological importance on a few million year time scale. Previously, ^{26}Al was measured by detecting the gamma rays following its beta decay to ^{26}Mg; recently, this isotope has also been measured by the accelerator technique. Other important cosmogenic radioisotopes are ^{53}Mn and ^{129}I with half-lives of 3.7 and 17 million years, respectively. Again, they are important for geochronology on an even more extended time scale as well as for other studies.

Accelerator Related Atomic and Molecular Physics Including Hyperfine Interactions

In this section, we summarize briefly some of the atomic and molecular science which is being carried out at nuclear accelerator facilities, and which is closely related in spirit and methods to the nuclear research currently or previously carried out on the same accelerators. This area includes NSF/DOE-funded topics as varied as the study of ion-atom collisions to learn the dynamic character of Coulomb fields, the development of particle induced x ray emission (PIXE) as a means of elemental analysis, and the interaction of charged particles with solids to study channeling and blocking.

Recent studies of ion-atom collisions have emphasized the use of heavy ions. Studies of inner shell ionization in such interactions are providing fundamental information about the Coulomb ionization mechanisms and about electron capture processes. Beam foil spectroscopy with heavy projectiles has provided ways of testing relativistic, many body calculations of atomic structure with great precision. From nearly symmetric heavy ion collisions, many new phenomena about transient quasimolecular systems have been observed. One of the leading topics of current interest is the overcritical fields that are expected to be formed in close collisions of heavy atoms, such as U on U.

There is almost no empirical data on the structure of molecular ions because they are difficult to concentrate for conventional spectroscopic analysis. Molecular ion beams such as OH^+, CH_4^+ and heavier molecules, when impinging on solid or gas targets, dissociate and separate in a manner determined by the Coulomb repulsion of the fragments. By studying the angular and energy distributions of these fragments, singly or in coincidence, one measures the original molecular ion structure, binding energies and details of charged particle motion while inside solids.

The PIXE method is widely used in elemental analysis in a number of areas; e.g., air and water for environmental control. Recent research has emphasized the development of highly localized charged particle beams, leading to a new vocabulary with words such as nuclear microscopy. Other analytical methods using charged particle beams have also been developed that depend on resonance reactions such as ${}^{1}H({}^{19}F,\alpha\gamma){}^{16}O$ and ${}^{1}H({}^{15}N,\alpha\gamma){}^{12}C$ to determine the spatial concentration of hydrogen in various materials. Laser methods of analysis have been made so sensitive that single atoms can be detected; thus low yield products of a nuclear reaction can be identified and studied.

In the case of atomic collisions in solids, the channeling of charged particles in single crystals has been studied for some time, leading to new information about impurity locations, surface phenomena, radiation damage, interatomic potentials and electron densities in crystals, and to the development of the crystal blocking lifetime technique for the time range 10^{-16} to 10^{-18} sec.

Hyperfine interactions between nuclear moments and the fields produced by the electronic environment of either the free ion, or the solid in which the nucleus might be imbedded, have been studied for many years. However, recent technological developments, such as the extension of pulsed beam techniques to heavy ions, the ability to produce a variety of single crystal targets, as well as the possibilities of varying the target temperatures from the cryogenic range to very high temperatures, have vastly extended the range of magnetic and electric hyperfine interactions that could be studied. The discovery of very strong magnetic interactions acting on swift ions traversing ferromagnets has opened a completely new area of research, which allows not only the determinations of nuclear magnetic moments of very short lived nuclear states, but also provides a unique laboratory to study the ion solid or ion surface electronic interactions.

In the next few years, as new heavy ion accelerators come on stream, increasing attention is expected to be focused on the atomic physics one can do with higher energy heavy ions, because of the high states of excitation reached when they interact with atoms, the dynamic processes induced by virtue of their high velocities, and the high charge states formed during the penetration of thin foils or gases. For example, at 35 MeV/nucleon, hydrogen-like Zn ions can be produced for Lamb-shift studies.

Another study likely to be pursued with vigor seeks to determine the conditions necessary for occurrence of molecular phenomena in heavy ion collisions. For example, a particularly interesting case is the manner in which K vacancies are shared in an ion atom collision. Another interesting topic is the radiative decay process in quasimolecular systems; this is a prerequisite for understanding the background observed in attempts to produce overcritical fields (i.e., $Z\alpha > 1$).

Accelerator Related Solid State Physics Including

The investigations of condensed matter using nuclear accelerators are difficult to codify for long range planning, in part because the applications are diverse and often appear serendipitously with little forewarning of which phenomena will be useful, and in part because the proven techniques spin away from the nuclear facilities to dedicated instruments. An obvious example is ion implantation for creating junctions in semiconductor material which was wholly research oriented only 10 years ago and is now the preferred method in the manufacturing of large scale integrated circuits and other semiconductor devices.

The unique ability of swift nuclear projectiles to produce nuclear reactions has been important in a few solid state applications, most notably the depth profiling of minor concentrations of light elements (particularly hydrogen) in the outer layers of materials. Of far greater utility have been those properties of high specific ionization with only rare large angle scattering which have found broad applications in Rutherford backscattering for depth profiling and for studies of crystalline properties, as well as proton induced x ray emission for trace element analysis, especially with microbeams to obtain spatial distributions. Muon spin resonance represents the application of the intrinsic properties of the nuclear probe particle itself; e.g., the stopped positive muons appear to behave like light protons when inside materials. And, the accelerator and ion source techniques themselves are finding applications in solid state physics: Tandems and cyclotrons are being adapted as highly sensitive mass spectrometers — at least a million times more sensitive than the secondary ion mass spectrometer (SIMS) — and this advance, now proving so useful to geophysics, will no doubt be adopted soon by the materials science investigators interested in trace elements; field emission sources are producing focused beams of high luminosity with exciting promise in ion beam lithography and surface physics.

Trace concentrations of hydrogen in metals, semiconductors, and insulators are not easily measured by most analytic techniques, but can be readily quantified with the use of heavy ions through an inverse reaction leading to a unique gamma ray. When the reaction involves a sharp resonance, such as the $^{15}N + {}^{1}H$ ^{12}C + ^{4}He + 4.43 MeV gamma ray, which as a 6 keV width at the resonant energy of 6.385 MeV, it is possible to measure the hydrogen concentration down to depths of 3 or 4 microns below the surface with a depth resolution of 0.0005 microns at concentration levels of less than a part per thousand.

Rutherford backscattering (RBS) is now routinely used by the solid state community to measure the depth profile of elements. The energy spectrum of backward scattered alpha particles results from the kinematic energy loss in the Rutherford collision, plus the stopping power energy losses as the alpha particle traverses the sample before and after the backscattering. Thus, RBS is a sensitive measure (less than 100 A resolution) of the depth of the struck nucleus, as well as a determinant of its mass. RBS cross sections are large enough so that microbeams can be used effectively, and it is now practical to measure depth profiles with a spatial resolution of a few microns.

When scattering is combined with crystal orientation so as to determine the yield as a function of the angle between the beam and the crystal axes, the result is a unique method for determining the integrity of the crystalline structure as a function of depth and the lattice positions of near surface elements, and has allowed the extraction of interatomic potentials and electron densities in crystals. RBS with channeling is still a research laboratory technique, but it is already recognized as a needed tool for the study of solid state devices such as solar cells and infrared detectors. The effectiveness of these devices depends critically on the integrity of the crystalline structure, and RBS plus channeling is gaining acceptance as the preferred method of characterization.

Proton induced x ray emission (PIXE) is now an established method for measuring trace elements at levels of one part per million of the matrix atoms. The characteristic x rays are produced with minimal background due to bremsstrahlung and the sensitivity of PIXE to trace elements is generally several orders of magnitude higher than that obtainable with electrons. But the real power of the proton beams is realized when they are focused to micron size and scanned over the sample to make measurements as a function of position. A one micron beam of MeV protons maintains its resolution over most of its depth of penetration; a one micron beam of 50 keV electrons, used in a scanning electron microprobe, balloons to almost 20 microns diameter. Thus, a scanning proton (or other light ion) microprobe (SPM) beam can yield two dimensional maps of trace elements in thick samples by detecting characteristic x ray; three dimensional profiles of major elements can be obtained by means of Rutherford backscattering, and similar profiles can be made of certain light elements through the use of nuclear reactions. Almost every technique used in the scanning electron microprobe — a vital and long established tool for solid state physics — can be profitably adapted to the SPM.

The ongoing development of the tandem accelerator as a highly sensitive mass spectrometer, described in the radiochronology section of this report, has great potential in solid state physics, particularly when the tandem is equipped with a sputter ion source with a spatial resolution of the order of a micron or less. Such an instrument would be orders of magnitude more sensitive than the secondary ion mass spectrometer (SIMS) which is an established tool in the field. The sensitivity of the tandem scanning mass spectrometer is such that it should be able, for the first time, to observe the elemental composition in the grain boundaries of polycrystalline metals and semiconductors, a subject of great importance to materials science.

Accelerator related solid state physics is expected to grow more rapidly in the coming decade than in the last. The microelectonics industry is already heavily ion beam related with a continuing demand for projectile beams of higher current and higher energy. New diagnostic tools, such as ion beam induced current measurements for determining the location of defects, will be developed for this fast growing technology. The development of microbeams is still in its infancy and expected advances into the submicron regime will lead to numerous applications in solid state research, as well as in the fabrication and diagnostics of semiconductive devices.

Muon Spin Resonance. Polarized positive muons stop quickly in matter, thermalize, precess in the local magnetic field, and decay with an electron signature of the final muon spin direction. SR has already proven to be an important probe of local magnetic fields: The measurement of the hyperfine field on the muon in nickel was critical to the understanding of the local magnetic fields; in dilute magnetic alloys, the existence of a spin freezing type of order was discovered. Studies of the diffusion of the thermal muons are revealing the presence of microscopic impurity clusters in metals. The study of muonium, formed in semiconductors, is revealing the nature of the hydrogenic interaction in silicon and germanium. The simplicity of the probe, which reveals such detailed information of its local surroundings, gives high promise that it will become the "hydrogen atom" of solids, revealing new information about magnetism, crystalline impurities and defects, as well as a number of dynamic effects such as diffusion and spin relaxation.

New Applications of Nuclear Data Instrumentation and Accelerators

In this section, we present capsule descriptions of some new applications of nuclear physics data, instrumentation, and accelerators. It is not meant to be complete — some of the examples have already been given — but it illustrates the breadth of these applications in medicine and energy.

Medicine

Nuclear Medicine. Nuclear tracer techniques in living organisms have grown from a rare technique several decades ago to a common medical routine today. It has been stated that 6 to 10 million nuclear medicine procedures per year are given in the United States alone. A major U.S. industry is based on producing the pharmaceuticals necessary for these tests. Typically, the routine utilizes a drug which has certain tissue seeking properties and which has been prepared with a radioactive tracer, which allows its position within the body to be examined utilizing an imaging nuclear camera. Uptake rates and distributions can be analyzed to discriminate between healthy and diseased body functions or organs. As an example, ^{131}I is a radioactive isotope emitting a 0.36MeV gamma with a halflife of eight days. Iodine has a special affinity for the thyroid gland, and can be used in detailed thyroid function studies. $^{99}Tc^{m}$, a six hour isotope milked from a Mo generator, can be produced at a hospital and combined with various compounds for affinity to several organx in the body. Brain scans are typically run with a $^{99}Tc^{m}$-based tracer and have proven to be extremely useful in diagnosing certain brain diseases.

Cancer Radiotherapy. The treatment of cancer with radiation is an increasingly important modality in cancer management in the United States. In recent years, some previously fatal cancers, such as Hodgkin's disease, have been treated with cure rates over 90% with radiation therapy techniques developed utilizing accelerator generated radiation fields. A major advance in this field has been the increase in energy of electron beams used to generate x ray fields in order to achieve deeper penetration into the body, and 20 to 30 MeV linear accelerators are now routinely used for therapeutic purposes. These machines are direct descendants of the nuclear physics accelerators in use in many nuclear labs around the world. In fact, medicine uses a far larger number of electron linacs than does nuclear research. Over 1000 electron linacs are in use world wide for cancer therapy. Recently, it has been shown that radiations in conjunction with chemotherapy and other cancer therapy techniques can be extremely effective for certain types of tumors, and even more intensive utilization of electron machines is indicated for the future.

Just within the past few years, a new interest in more exotic radiations has become apparent. This has partly stemmed from the realization that gamma fields do not work extremely well on certain tumors, and that heavy particle radiation (neutrons, pions, heavy ions) have many functions which may make them more effective for these tumors. These heavy particle radiations may be biologically more effective, and also may allow a more advantageous dose distribution. Active clinical trials are underway at present using neutrons beams of mean energy up to 30 MeV, and of pion beams capable of penetrating anywhere within the body. Heavy ion based trials are just now starting seriously. If these radiations live up to the promise expected, we can expect a major application of nuclear physics developed accelerators in medical practice, with significantly enhanced cure prognosis for many tumors poorly treated with conventional techniques today.

ENERGY

Elemental Analysis. The use of nuclear physics techniques in developing energy technologies pervades almost all aspects of the problem. There is the obvious example of "nuclear energy," both fission and fusion, but the impact of nuclear physics on energy does not stop there. In fact, it is through use of nuclear physics techniques to characterize materials properties (such as composition, structure and durability) that nuclear science has one of its greatest impacts on energy technology. For example, portable nuclear accelerators are regularly lowered down oil wells to assay the oil content (*vs.* water) and rock composition. The important contribution of heavy ion simulation of neutron damage for reactor materials is well known. Nuclear reaction analysis is used to predict the long term capabilities of glasses designed to consolidate radioactive reactor wastes. Nuclear scattering is becoming the routine method for characterizing solar cell material.

Conclusions and Recommendations

Nuclear science related research and applications have developed historically as nuclear physicists and chemists found opportunities to make innovative applications of some aspects of their research in other fields of science and technology. These thrusts beyond the confines of nuclear science *per se* have been wisely supported by the Nuclear Science Section of the Division of Physics of the NSF and by the Divisions of Nuclear Physics and Nuclear Sciences of the AEC/ERDA/DOE. Where necessary, these Divisions of the NSF and the DOE continue almost total funding of certain aspects of nuclear science related research and applications. Where possible, these Divisions have actively sought out and made arrangements for partial or total funding from other parts of their respective agencies. We conclude that the result has been a happy balance in which Nuclear Science nurtures or weans its offspring. We recommend that long range planning in nuclear science related research and applications must seek to maintain this balance.

It is well nigh impossible to predict what will be the next thrust in nuclear science related research and applications or where it will arise or how much it will cost. By how much it will cost, we refer to the initial effort diverted from nuclear science per se but with little or no specific funding and eventually to the additional cost which must be borne under nuclear science funding until transfer to other sources can be effected. Although we have outlined in the previous pages a number of exciting areas in nuclear science related research and applications, it must be anticipated that new targets of opportunity will arise as these currently recognized areas mature and become the responsibility of the appropriate scientific disciplines, or of interdisciplinary programs in the agencies.

We will restrict our funding recommendations to the activities we have designated as nuclear science related research. The future funding of applications, especially in medicine and energy, is extremely difficult to estimate without a full scale analysis of future developments in these fields. We have indicated previously that the FY 1979 support for nuclear science related research was $4.6M or approximately 4% of the total FY1979 operating budget for Nuclear Science and Nuclear Physics in the NSF and the DOE. We do not consider this percentage to be excessive in view of the payoff from nuclear science related research and the feedback into the general support of nuclear science. We anticipate that this percentage may slightly increase over the next decade, and we recommend that long range planning in nuclear science anticipate that the funding of nuclear science related research will increase to 5% of the total nuclear science budget by 1986. We recommend that at the same time the Nuclear Science Section of the Division of Physics of the NSF and the Divisions of Nuclear Physics and Nuclear Science sof the DOE make every effort to transfer the burden of support to the appropriate parts of their respective agencies and urgently support the establishment of mechanisms for special or interdisciplinary funding in their respective agencies.

There are special problems involved in the support of major activities in nuclear science related research, for example in the funding of the $^{71}Ga/^{71}Ge$ and $^{115}In/^{115}Sn$

searches for the basic pp-neutrinos from the sun. The Nuclear Science Advisory Committee addressed the problem at its Boulder, Colorado meeting June 11 and 12, 1978. At that time, it concluded that "It is thus imperative to find cost sharing mechanisms by which the total cost of a neutrino program is not financed primarily out of nuclear science budgets." We endorse this conclusion.

PART II

CHAPTER 1: GENERAL CONSIDERATIONS

Introduction

It is useful to begin with a brief review of the funding pattern for nuclear science. We shall follow with a more detailed description of present day facilities, and finally with a discussion of the global constraints and interrelationships which govern long range planning. Figure (1) shows the total operating budget for basic nuclear research from 1964 to the present provided by the two funding agencies, the NSF and the DOE (formerly ERDA and AEC) in 1979 dollars. The deflators used are given in Table (I) which gives the breakdown of the operating funds into categories used in the Friedlander report. Figure (2) provides a chart of the expenditure by the DOE/ERDA/AEC for capital equipment, construction, and accelerator and reactor improvements and modifications (ARIM). The details are provided by Table (IA). One notes the bulge in the late sixties and early seventies, of which a major component was the construction of the meson physics facility at Los Alamos (LAMPF).

1. Operating support declined from 1968 to 1974 by about 10%. Since then, it has risen so that by 1979 it was within a few percent of the 1968 value. However, the FY 1980 budget shows a reduction from the 1979 value. During this period, a number of large new facilities requiring large operating budgets for effective utilization (LAMPF, Bates, SuperHILAC, Bevalac, Indiana University Cyclotron) came into operation. Accelerators requiring substantial R&D funding are being developed at Illinois, Stanford, SUNY at Stony Brook, and the Argonne National Laboratory*.
2. The unfortunate wide swings in the funding for construction are shown by Figure (2). From the peak in FY 1970, these funds fell sharply to zero

*The funds in this case were obtained in large part by reprogramming within the ANL budgets.

FIGURE 1

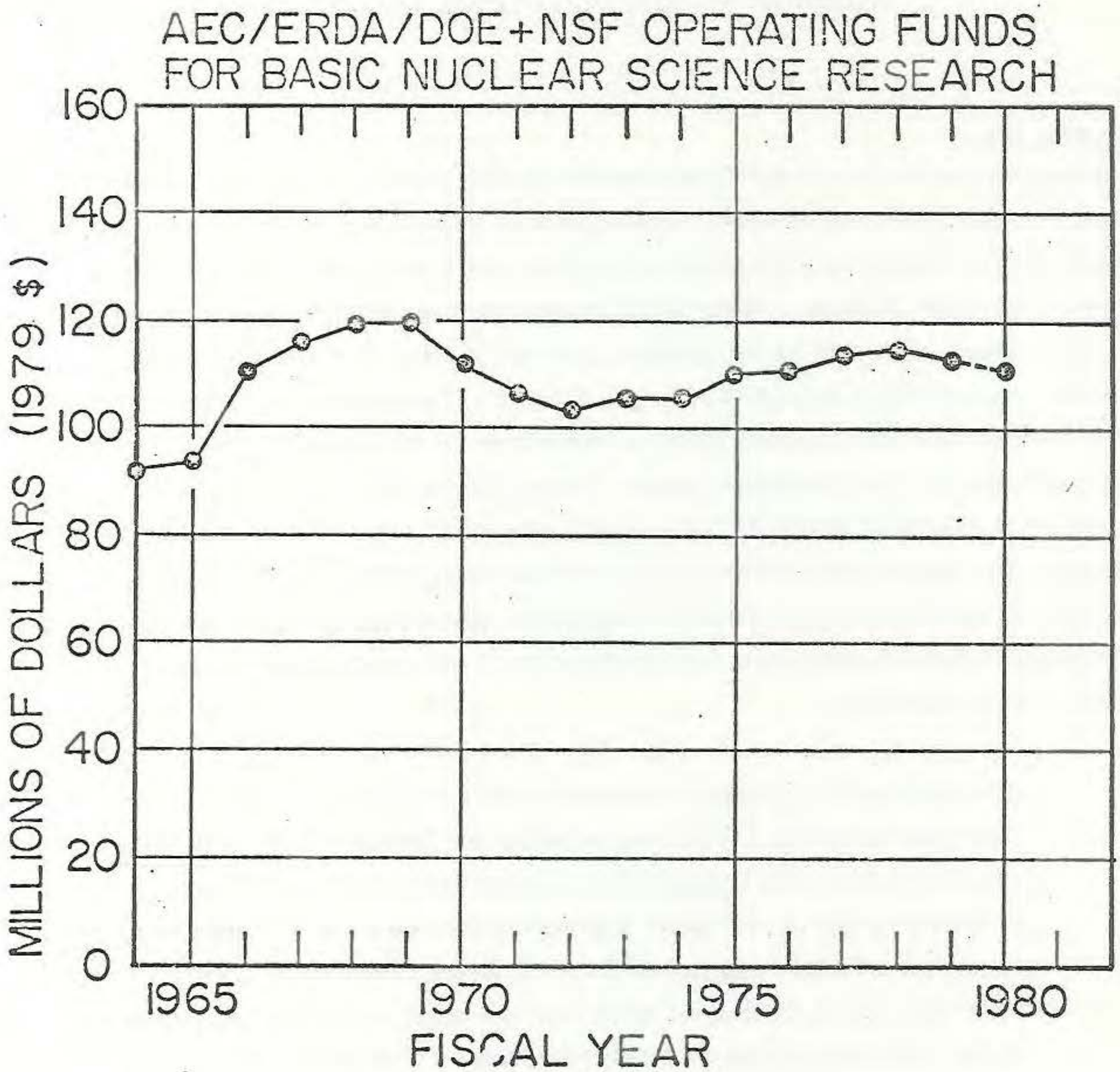

AEC/ERDA/DOE+NSF OPERATING FUNDS
FOR BASIC NUCLEAR SCIENCE RESEARCH
MILLIONS OF DOLLARS (1979 $)
160
140
120
100
80
60
40
20
0
1965
1970
1975
1980
FISCAL YEAR

TABLE I: AEC/ERDA/DOE and NSF Operating Funds for Basic Nuclear Science Research

	FY74	FY75	FY76	FY77	FY78	FY79	FY80 (EST.)
AEC/ERDA/DOE[a,b]							
MENS	19.0	23.9	27.6	30.7	32.9	37.4	40.6
HINS	16.2	18.6	21.0	25.1	28.1	29.7	32.8
LENS	17.5	17.5	15.9	14.3	14.9	15.9	17.6
NTh	3.1	3.4	4.0	4.8	5.2	6.1	5.9
	55.8	63.4	68.5	74.9	81.1	89.1	96.9
(1979$)	84.3	86.3	87.0	88.5	89.5	89.1	(88.2)
NSF[c]							
NP	8.6	9.2	9.6	11.3	12.2	11.6	(12.0)
IE	4.7	7.1	7.8	8.9	9.2	10.7	(11.3)
NTh	0.9	1.0	1.0	1.2	1.4	1.6	(1.8)
	14.2	17.3	18.4	21.4	22.8	23.9	(25.1)
(1979$)	21.5	23.5	23.4	25.3	25.2	23.9	(22.8)
DOE + NSF	70.0	80.7	86.9	96.3	103.9	113.0	(122.0)
Inflation Factor[d]	1.511	1.361	1.271	1.182	1.104	1.0	(0.91)
DOE + NSF (1979$)	105.8	109.8	110.4	113.8	114.7	113.0	(111.0)

NTh = Nuclear Theory
MENS = Medium Energy Nuclear Sceince
HINS = Heavy Ion Nuclear Sciene
LENS = Low Energy Nuclear Science
NP = Nuclear Physics
IE = Intermediate Energy

in 1974 and have been rising slowly since that time. Long range planning should help to smooth out these oscillations in funding.

3. The allocation for capital equipment purchased has also oscillated over this period. In FY 1980, it has had a slight upswing to about 8% of the operating budget.

The unhappy consequences of this financial history have been discussed and documented in the Friedlander report, and for a group of university based research facilities, by the 1979 report of the National Science Foundation Subcommittee to Review NSF Supported Nuclear Science Laboratories. The latter report points particularly to the substantial erosion of the capability of many university sited facilities with concomitant deleterious impact on graduate education in physics. We shall not repeat their discussion here.

Notes to TABLE I.

a) In addition to the funds listed here, AEC/ERDA/DOE also supplies substantial support in their Nuclear Science Budget for the areas of Heavy Element Research (primarily a study of the electronic, magnetic and chemical properties of heavy elements of the lanthanide and actinide elements), Electromagnetic Isotope Separation, Special Isotope Preparation and Safeguards.

As an example, for FY 1974-FY 1979 support for these areas is as follows:

	FY74	FY75	FY76	FY77	FY78	FY79	FY80
HER	1.2	1.4	1.8	2.2	2.7	3.2	3.5
EIS	1.9	2.1	1.3	1.2	1.1	1.2	1.3
SIP	5.5	4.9	5.8	6.0	6.3	7.0	7.6
SG	0.0	0.0	0.1	0.0	0.0	0.0	0.0
	8.6	8.4	9.0	9.4	10.1	11.4	12.4
('79$)	13.0	11.4	11.4	11.1	11.2	11.4	(11.3)

b) In addition to the operating funds listed here, AEC/ERDA/DOE also supports Basic Nuclear Science Research with Capital Equipment and Construction Funds. These additional funds are listed in Table I (A) beginning in FY 1974.

During the period FY 1966 through FY 1980, the total AEC/ERDA/DOE Capital Equipment and Construction Funds for Basic Nuclear Science Research have averaged \$24.1M (1979 \$) per year (Construction = \$13.3M; ARIM = \$1.3M; and Capital Equipment = \$9.5M).

c) Included within these NSF figures are funds for "Permanent Equipment" which include facility construction and improvements as well as purchases and construction of new permanent equipment and instrumentation.

d) Extracted from the Consumer Price Index from the Bureau of Labor Statistics, assuming FY 1979 = 1.000.

FIGURE 2

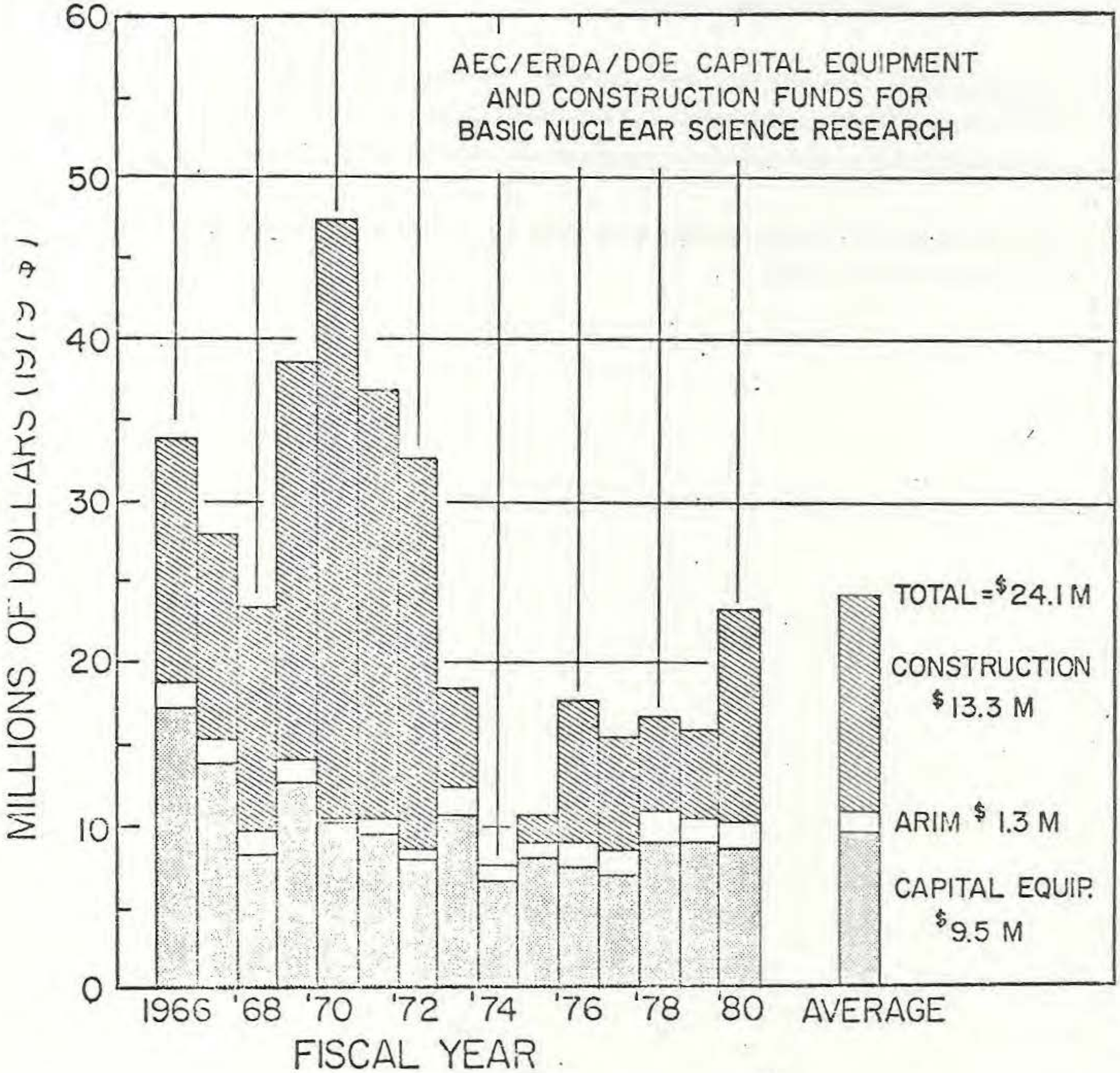

AEC/ERDA/DOE CAPITAL EQUIPMENT
AND CONSTRUCTION FUNDS FOR
BASIC NUCLEAR SCIENCE RESEARCH
MILLIONS OF DOLLARS (1979 $)
60
50
40
30
20
10
0
1966
'68
'70
'72
'74
'76
'78
'80
AVERAGE
FISCAL YEAR
TOTAL = $24.1 M
CONSTRUCTION
$13.3 M
ARIM $1.3 M
CAPITAL EQUIP.
$9.5 M

TABLE I(A): AEC/ERDA/DOE CAPITAL EQUIPMENT AND CONSTRUCTION FUNDS FOR BASIC NUCLEAR SCIENCE RESEARCH

	FY74	FY75	FY76	TQ	FY77	FY78	FY79	FY80
Capital Equipment	4.3	5.8	5.7	1.3	5.7	7.8	8.8	9.3
Accelerator and Reactor Improvements and Modifications	0.6	0.7	1.2	0.3	1.3	1.9	1.5	1.6
Construction:								
ORNL HHIRF		00.4	5.4	2.1	4.7	3.4	2.0	
LBL SuperHILAC Modification		0.8	1.4	0.3	0.3			
Bates Target Room Expansion					0.9	1.8	2.3	
SuperHILAC/Bevalac Uranium Upgrade							1.0	4.0
Bates Recirculator								1.8
LAMPF Staging Area								2.4
MSU II								6.0
TOTAL	4.9	7.7	13.7	4.0	12.9	14.9	15.6	25.1
INFLATION FACTOR	1.511	1.361	1.271	1.227	1.182	1.104	1.0	(0.91)
TOTALS	7.4	10.5	17.4	4.9	15.2	16.4	15.6	22.8

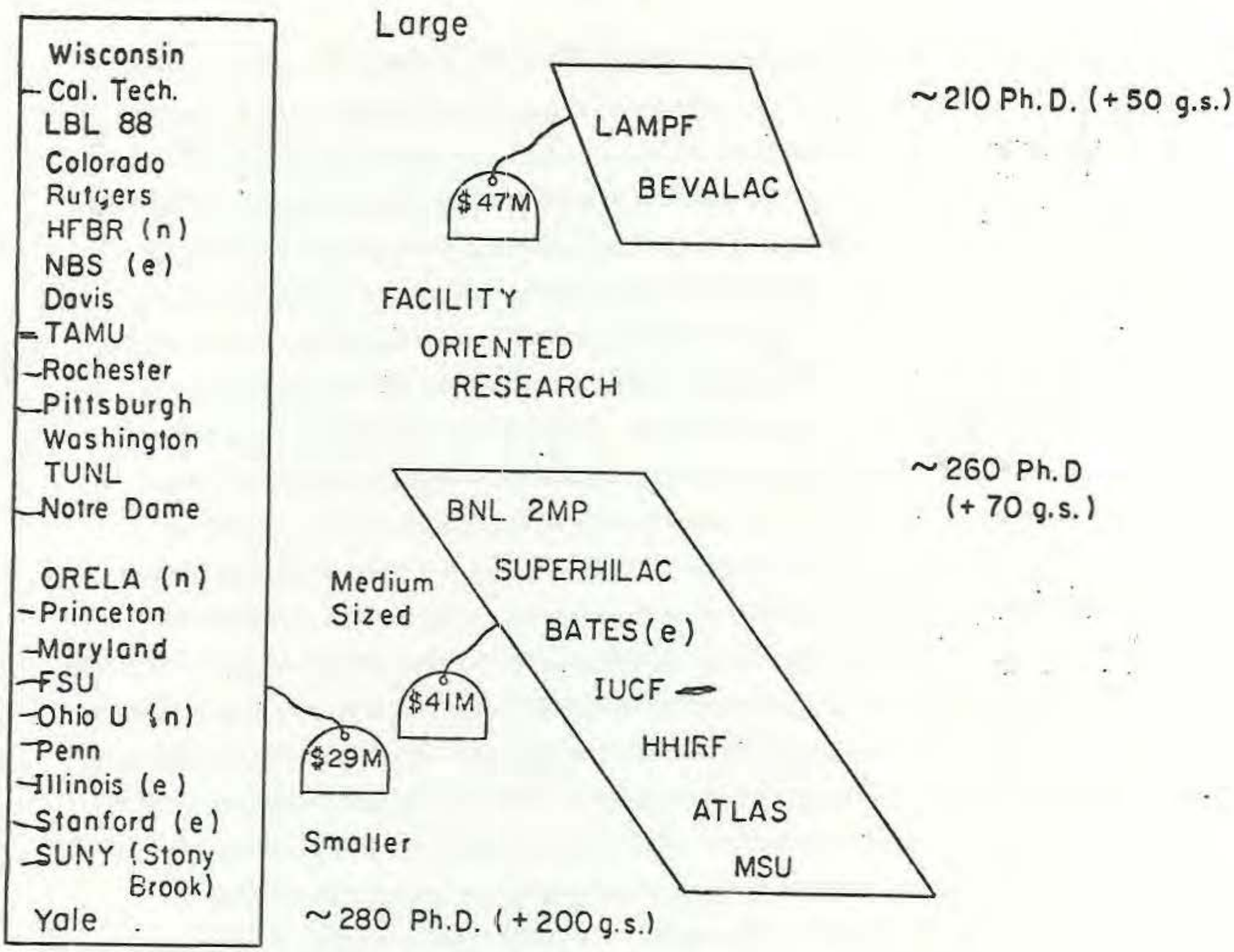
A census of the manpower involved in nuclear science has been conducted by the Manpower Subcommittee which issued a report entitled "The 1978 Census of Basic Nuclear Scientists in the USA." This subcommittee identified some 1700 individuals engaged in nuclear science activities. Of them, approximately 1300 are Ph.D. scientists (or have equivalent experience). The remainder are graduate students working toward their Ph.D.'s. It is more difficult to break down these total figures into the categories under consideration by the various working groups. We shall be content here to provide very rough values. We estimate that about 210 SMY are devoted to heavy ion physics and about 250 SMY to research involving light ions and neutrons. Pion physics research involves about 100 SMY while electromagnetic interactions research accounts for another 90. Both weak interactions and (K,p) physics involve a considerably smaller fraction of the community, running to roughly 5% each or about 40 SMY each. The (K,p) effort is funded only in part by the NSF/DOE nuclear program. Radioactivity studies account for 100 SMY, and 120 SMY are involved in accelerator design and research. Finally, the nuclear theory effort is estimated to be about 280 SMY. These numbers do not include graduate students which total roughly 400.

A summary of the recent history of facility support is given in Table IA.

At the time of this report, the experimental usage of accelerators in terms of the SMY of Ph.D. physicists is roughly evenly divided among the group of 25 of the smaller facilities with relatively little (<25%) outside use, the group of 7 moderate sized user facilities, and the two large facilities. Figure 3 gives an overview of this usage distribution. The smaller facilities are mostly home based, the moderate sized ones are evenly divided between national laboratories and universities, while the large facilities are sited at national laboratories.

The cost per SMY to use a facility in each of these three groups varies widely within each group. It is still useful to state what the average cost is but the resultant number can be very different from the cost for a particular facility. With this caveat in mind, the numbers are roughly about \$70K/SMY for the smaller facilities, about \$140K/SMY for the medium sized ones, and about \$210K/SMY for the large. One should bear in mind that these costs represent only those funded by the Federal agencies and do not include funding by universities, state agencies or other sources.

Figure 3



The attached figures indicate the Federal funding for each group of facilities in 1979 dollars and does not include other sources of funding.

Except for those labelled (n) for neutrons or (e) for electrons, the facilities listed provide light and/or heavy ion beams.

Abbreviations:

- LBL 88 = 88" cyclotron at the Lawrence Berkeley Laboratory
- HFBR = high flux reactor at the Brookhaven National Laboratory
- NBS = National Bureau of Standards
- TAMU = Texas A & M University
- TUNL = Tri-University Nuclear Laboratory
- ORELA = Oak Ridge Electron Linear Accelerator
- FSU = Florida State University
- BNL2MP = Two coupled Emperor tandem accelerators at Brookhaven National Laboratory
- Superhilac = a linear accelerator for heavy ions at the Lawrence Berkeley Laboratory
- Bates = a linear accelerator for electrons at the Massachusetts Institute of Technology
- IUCF = Indiana University Cyclotron Facility
- HHIRF = Holifield Heavy Ion Research Facility at the Oak Ridge National Laboratory
- Atlas = a linear accelerator for heavy ions at Argonne National Laboratory
- MSU = Michigan State University

The mix of facilities shown in Figure 3 mirrors the requirements of nuclear science research in its collective attack on a family of scientific problems using a variety of probes and techniques to elucidate differing aspects of questions of current interest. The smaller facilities are used for a wide variety of experiments of current interest extending from the study of weak interactions and symmetry laws to the investigations of the structure and the simple modes of motion of complex nuclei. Light and heavy ions, neutrons and electron projectiles are employed. Two facilities included in this group provide moderately high energy heavy ion beams and are concerned with both structure and dynamics. The medium sized group involves generally more powerful facilities, providing beams with higher energy and with excellent beam quality. Heavy ion beams produced by five of these are used to study both nuclear dynamics and nuclear structure. One is a relatively high energy electron accelerator which is employed principally to study nuclear structure as revealed by static and transition charge densities and to some extent nuclear dynamics as revealed by electron and gamma-ray induced reactions. Finally, one is a relatively high energy proton accelerator which is used to study nuclear dynamics and structure, using a large variety of proton induced reactions. The two largest facilities include the Bevalac, which is mostly concerned with nuclear dynamics and possible relationships to the properties of nuclear matter, when energetic heavy ions ranging up to energies of 2 GeV/A interact with nuclei. The other large facility is LAMPF, which produces energetic protons and secondary beams of pions in three overlapping energy ranges, muons both stopped and in flight, and high energy neutrons and neutrinos. A wide range of problems in nuclear science is being studied with this considerable variety of beams. Their interpretation in many cases is not possible without information provided by the electron accelerators and by the nuclear structure studies with light and heavy ion beams.

Each facility must justify its support in terms of the unique capabilities it may have; capabilities which, when exploited by an effective group, can lead to definitive and significant results. It is, of course, not possible to prove that the present mix is ideal or if it were that it would remain so. The panel does feel that, at present, it is reasonably well matched to the full range of important questions in nuclear science. Changing the mix in a substantial way would lead to the loss of the ability to study the significant problems of nuclear science.

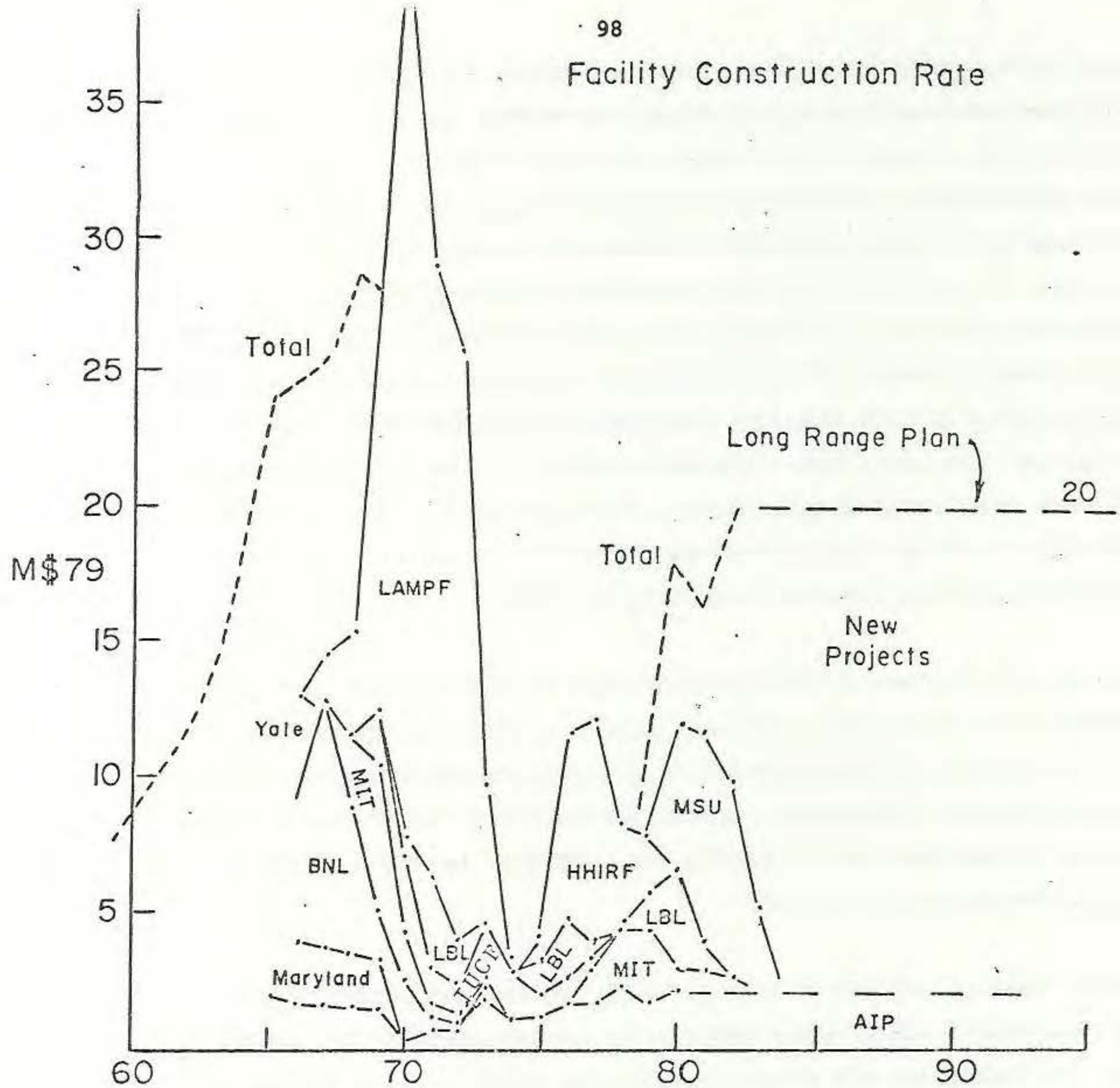
Change in these capabilities will be required in response to the new and increasingly more profound questions generated by progress in nuclear science. It is particularly exciting to see the dramatic improvements which have become feasible because of recent and innovative technological developments and improvements which will make it possible for nuclear scientists to address the burning scientific questions of the future. The application of superconducting technology to circular and linear accelerators has given large increases in duty factor for electron beams and in energy for heavy ion beams. Promising ideas for exotic sources of highly charged ions, beam storage for time structure manipulation, and electron cooling for improved beam brightness may make future advances possible. We can look forward with confidence to nuclear scientists developing other such opportunities to push back experimental limitations by selective improvements to the diverse collection of both the small and large facilities required by our field.

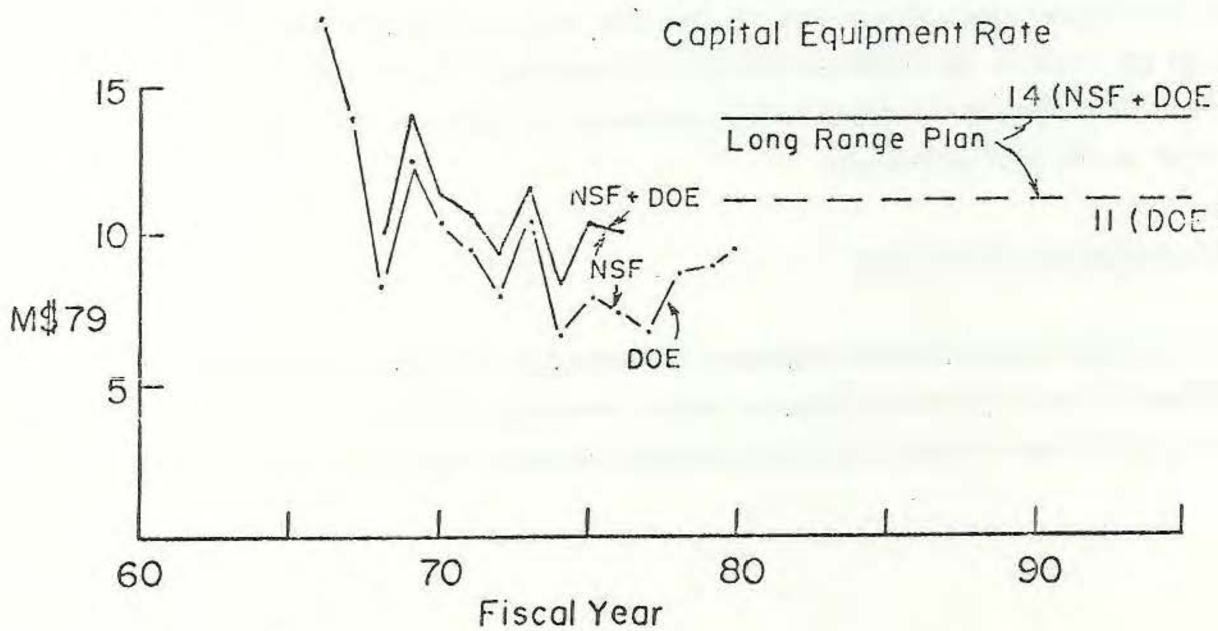
Figure 4 shows the history of facility expenditures for the presently operating accelerators in nuclear science. Information prior to 1966 is somewhat less precise. A few of the larger projects are identified. All costs are converted to 1979 dollars. We have commented on this history earlier. Discrepancies from Figure 2 reflect differences between the time the facility was authorized and the period over which the actual expenditures were made.

An orderly evolution requires, as well, provision for resources needed by nuclear scientists in order to exploit these facilities for the production of high quality science. The Committee will remain sensitive, not only to developments which bear upon the improvement of accelerators, but also to the development and possibilities in the fields of detector systems and data handling. Figure 4 shows the history of capital equipment funding which represents the response of the DOE and the NSF to this need in the past.

Interrelationships and Constraints

In devising a long range plan which addresses the important scientific questions, attention must be paid to the allocation of scarce resources. In this section, we examine some of the key fiscal issues that underlie facility utilization and obsolescence.


Facility Construction Rate
35
30
25
20
15
10
5
M$79
Total
LAMPF
Yale
MIT
BNL
LBL
LUCF
Maryland
HHIRF
LBL
MIT
LBL
MSU
Total
New Projects
Long Range Plan
20
AIP
60
70
80
90


Capital Equipment Rate
15
10
5
M$79
NSF + DOE
NSF
DOE
14 (NSF + DOE)
Long Range Plan
11 (DOE)
60
70
80
90
Fiscal Year

There are many other issues which need to be considered as well and these will be the subjects of study in the future. To the extent that we can establish the general character of the interrelationships among various factors governing the development of nuclear science and the constraints which these must satisfy, it becomes possible to provide necessary conditions on a long range plan which will help maximize the effectiveness of the U.S. program in nuclear science.

We begin the discussion by examining the utilization of a facility, which we take to be the relation between its operating cost and the number of users served by the facility. There is, in general, a threshold level of support below which operation becomes impractical because the technical staff and critical skills needed to maintain the facility in reliable working order is lost. The threshold varies considerably with the complexity of the accelerator. Above threshold, the usage in general rises relatively steeply as the additional support covers power costs, extra personnel for 24 hour operation, and so forth. As the level of continuous operation is approached, further advances in utilization are made by provision for emergency repairs (e.g., by overtime, spare parts inventory) to minimize time lost to breakdown, and by reducing time lost between experiments (e.g., duplicating some electronic components so that lengthy setups can be made in parallel). Eventually a saturation level is reached in which extra support is not justified by the gain in utilization.

We can characterize the slope of the curve with a dimensionless "leverage" factor. If a 5% increase in facility operation support leads to a 20% increase in the number served, the leverage factor would be 4. In actual practice, the leverage factor for some medium sized user facilities which are now operating below the saturation level because of restricted funding is about 3.

For a collection of N similar facilities, it is easy to show that optimum operation corresponds to a critical point at the knee of the curve just below saturation, where the leverage factor is unity. Operating all of the facilities at higher support levels is less effective than increasing N. Operating well below the critical point, on the other hand, is less effective than reducing N and reprogramming the released support to increase utilization of the remainder. The critical point is thus an equilibrium point for the number of similar accelerators to satisfy a given demand. The instability associated with attempting to operate at a lower total support with fixed N is well known to the field. Under these circumstances, small variations in support can become magnified in terms of perceived productivity with the consequence that N may be reduced, that is some accelerators may be shut down, moving the system thereby toward the optimum operation.

Utilization, as measured by the number of users served, is not the primary component determining the scientific effectiveness of a facility. In particular, as we have repeatedly emphasized, it is essential for the success of nuclear science research to maintain the necessary diversity in capability. It is thus worthwhile to continue operations below the critical point for optimum utilization if the research at the facility is making a unique contribution to nuclear science.

More effective use may be made of the capital investment in, and of the operating support of, a facility, the larger the "multiplicity," defined as the average number of significant experiments performed in parallel. Parasitic users at low rates, or division of the beam which may lengthen completion time for each experiment, must be prorated in calculating the multiplicity. From the point of view of the economy of the whole field, each component responsible for the multiplicity must be judged by the importance of the experiments it makes possible, and in comparison with other facilities which perform similar functions. Uniqueness is again of prime importance. One should bear in mind the fact that such multiple use carries with it substantial extra operating expenses primarily because of the strong requirements on accelerator reliability, in addition to the need for liaison staff, travel funds, etc., common to user facility operation. The highest multiplicity is found at LAMPF where the entire program for nuclear science has a multiplicity of 6 or more (excluding applied programs and prorating channels of intermittent use) while the pion program by itself has a multiplicity of 3 or 4.

Smaller facilities with largely home based usage tend to have fairly low thresholds, and the maximum number of users is primarily set by the size of the local group. This may be extended, albeit at some expense, through collaboration most often with scientists nearby. Conversion into a "user" mode of operation does, however, require a substantial increase in funding, in part because of the need for increased accelerator reliability and availability.

The managers of facilities operating below the critical point for optimal utilization invariably attempt to approach that point more closely by keeping the number of users at the level appropriate for greater funding, that is by increasing the leverage ratio. This can be done if funds for research instrumentation, for the purchase of capital equipment, for student support and for maintenance are reduced. Such a policy is clearly destructive because in the long run the capability of the researchers to utilize facility disappears. Several of these user facilities are under-utilized, with the accelerators operating a fraction of the fiscal year. The correction of these inefficiencies at both small and large facilities was a primary motive behind the Friedlander Recommendation A.

Time Dependence

As nuclear science moves to answer more profound and consequently often very new questions, the capability of existing facilities generally becomes less relevant unless substantial improvements, "upgrades," are made. At the same time, entirely new facilities will also be required. The rate at which upgrades should be made and new facilities added is a most important issue for long range planning. That rate depends critically upon the response to another question which asks whether the present investment in terms of people and facilities is of the correct order of magnitude. As is abundantly clear from the discussion of utilization made just above, it is the opinion of the panel that a more efficient operation of the national program, with the consequent enhancement of its scientific effectiveness, would require an increase in the funding level. A "minimal" program would, at the very least, maintain the present strength and effectiveness of nuclear science. As we shall see, it is then possible to devise a long range plan which provides the capability needed to perform the important experiments and carry out the theoretical studies of the future. Roughly (it is not possible to be more precise), such a minimal program would require, inter alia, keeping the capital investment in nuclear facilities at its current level; though, as stated earlier, the nature of these facilities would change with time, following the needs of the science. Taking a constant capital investment as a guideline does, as we shall see, determine the rate of construction funding. Expansion with a larger investment would enhance the national scientific capability, while contraction to a smaller one would be destructive. In this report, we shall reluctantly take the conservative approach of maintaining our present scientific effectiveness and strength, which we shall refer to as the "constant scientific strength" program.

As we shall see, the rate of facility construction under these circumstances, is determined by the useful lifetime of a facility in the absence of substantial upgrading. That lifetime is on the average certainly less than 20 years. Under the "constant scientific strength" approach, it would be wasteful to introduce new facilities and upgrades at a rate faster than the rate at which an average facility loses its effectiveness, which we shall refer to as the obsolescence rate. Such a course of action would result in the premature retirement of facilities, under the constant scientific strength assumption. On the other hand, since the prospects for outstanding advances, as discussed earlier in this report, are extremely good, it would be equally unfortunate to introduce new facilities at a rate much smaller than the obsolescence rate. Such a course would result in a substantial reduction in scientific effectiveness.

Thus the rate for the introduction of new facilities in the field should be approximately equal to the rate with which a facility loses its effectiveness. The capital investment in facilities is at present about $500M in 1979 dollars. Taking an average facility lifetime of 20 years, one obtains $25M/year as the rate. The constant scientific strength budget would thus require about an equal expenditure of $25M/year for construction.

Manpower

Creative and dedicated personnel form, of course, the most important component of an enterprise such as the one envisaged by the long range plan presented in this report. In this regard, the Committee is concerned with the low rate at which able young people are entering the field of science. This problem is not unique to nuclear science. It is a problem which is common to all branches of physics, although the situation is considered to be most severe for the case of nuclear science. The compression of the nuclear science program at universities, through the reduction of support and the closing of facilities, is undoubtedly one of the major factors behind the precipitous decline in the Ph.D. production in our field. This report does not present any ameliorative strategy beside the traditional one of providing an exciting program focussed on uniquely important scientific problems which should be attractive to young scientists and graduate students. In what way one can add to this approach is a subject of debate by the entire physics community and the funding agencies. It is a problem to which the Nuclear Science Advisory Committee is sensitive. Indeed, it recommended unanimously last spring to the DOE and the NSF that a subcommittee be set up to consider the role of universities in nuclear science. It is anticipated that this subcommittee will be formed and will make its recommendations during the coming year. The parent committee will, on the basis of the subcommittee report, consider what actions are desirable to enhance the quality of the scientific program. They will need to be consistent with those which are adopted in behalf of the physics community as a whole.

CHAPTER 2: LONG RANGE PLAN

The long range plan, to be presented below, aggressively pursues initiatives which promise important scientific advances, permitting U.S. scientists to continue to make major discoveries of unique importance for the understanding of nuclear structure and dynamics. Such a plan will generate excitement among both experimentalists and theorists; this comes with the ability to perform decisive experiments and the opportunity to uncover new phenomena. It should be attractive to high quality graduate students and young scientists who respond to the opportunity to be part of the effort in a science with significant research problems having a broad impact.

New technical developments may make possible dramatic improvements in facilities presently in operation and the construction of new facilities to investigate problems fundamental to nuclear science but not accessible with present techniques. We refer here to the need to explore the possible applications of superconductivity, to new approaches to sources of heavy ions and polarized particles, to the use of electron cooling. New probes, new uses of established probes, and greatly improved precision are the consequences of the application of these new techniques. The long range plan must make provision for the research and development required to take advantage of these opportunities.

As we have emphasized, the attack on the fundamental problems of nuclear science requires a balanced program in which the various subfields contribute collectively to the firm establishment and elucidation of a nuclear phenomenon and to its relationship to, and possible modification of, what are thought to be the underlying mechanisms governing nuclear structure and dynamics. This, in particular, requires a mix of facilities, and the construction and upgrading in the next decade of facilities of the small, moderate and giant sized types, so as to take advantage of the differing types of opportunities for scientific advances.

The panel felt that the current mix of facilities is reasonably well matched to the range of questions inspired by the aforementioned fundamental problems. Certainly, the rapid transition of the past decade to the user modes should not be continued, as the scientific requirements of the plan for the next five years can be met only with a substantial complement of the smaller facilities. The long range plan to be presented in this report will, therefore, not involve large perturbations of the current distribution of resources among the various subfields.

As discussed in Chapter I, Part II, under the "constant scientific strength" program which will develop the minimum capability needed to perform the important experiments of the future, the rate of construction funding should be roughly $25M/year. In the long range plan submitted in this report, we shall use the somewhat smaller figure of $20M/year. This sum will by no means permit the construction of all the new and promising facilities brought forth by the working groups in each of the subfields. For a balanced program, this annual expenditure on construction would imply upgrading and/or construction of about one facility of the smaller type each year. These facilities are currently largely devoted to light and heavy ion, electron, and neutron research. About three or four years would separate the construction of facilities of moderate size. These currently provide moderate energy light and heavy ions and energetic electron beams. Each decade would see the construction of a large facility. Provision for these has not been made in the budget. They would require special add on funds. Those presently in existence provide high energy ($\sim$1GeV) proton beams and attendant secondary beams of neutrons and "exotic" particles such as muons, pions and neutrinos (LAMPF); and heavy ion beams with energies ranging from moderately high to relativistic (Super-HILAC-Bevalac). The new or upgraded facilities might permit the use of new probes, or they might permit measurements in a new energy range or with qualitatively greater precision.

It is to be emphasized that this rate of construction is meaningful because there are high priority scientific needs for facilities of each of these types. It is the panel's estimate, based on known construction initiatives and on its own considerations regarding new directions in nuclear science, that the proposed rate is reasonable, certainly for the next five years and probably for the next decade. However, surprises are likely so that the long range plan must remain flexible so as to allow adjustments for unexpected developments.

Special attention has to be given to major projects for the construction of new facilities which fall into the "moderate" or "large" categories. These are expensive, not only to construct but also to operate, so that care must be explicitly taken to prevent a destructive impact on other essential components of the nuclear science effort. It is no longer possible or desirable to fund the incremental cost of the operation and funding of capital equipment for such a new facility by shutting down several small installations. Such a procedure would destroy important needed capabilities. The remaining option is the reduction of support for a major facility. A major facility shutdown to provide for a new one has been the method adopted by particle physicists. The advantages and disadvantages of such trade offs need to be carefully evaluated for each case.

Moderate size accelerators, such as the proposed high energy CW electron accelerator, can be (and have been) included in the budget presented below. This is not possible for the very large accelerators of the "large" type, which are estimated to have construction costs exceeding $100M. Their construction, if one attempts to fit them into a budget allocating about $20M/year for construction, would take too many years for completion during which no other construction could take place, thus destroying the essential overall balance of the nuclear science program. Moreover, the operating costs of such a facility, together with equipment and user costs, will be too large to be accommodated within the present funding levels without destroying the base which is needed for the meaningful interpretation of the research conducted at such a large facility. Such very expensive projects must be justified separately as required by important national goals, requiring special construction allocations, and must be provided with substantial operating costs additional to those which might be released by the shutdown of a major accelerator as described above.

The construction of a "large" facility requires an increase in the operating and capital equipment funding level for nuclear science. The Nuclear Science Advisory Committee should recommend such construction if, and only if, it is highly probable that such add on funding will be provided by the funding agencies. Recent history does not make us optimistic that such recommendations will be followed unless the strongest possible support for add on funding is expressed by all concerned. Accelerators currently under discussion (which are thought to be in the "large" class) include one for ultrarelativistic heavy ions and one for high intensity kaons and antiprotons. Better information on the cost and on the scientific utilization offered by these initiatives will be available after the completion of the R&D studies of these devices.

The long range plan thus moves the field forward by taking full advantage of clear opportunitites for scientific advance, while preparing for new opportunities in the more distant future through R&D. The plan is fiscally responsible, assuming that tradeoffs will be made — tradeoffs which are especially necessary if major projects are to be funded.

A corollary to the above discussion is the consequence that smaller "home based" facilities which have been upgraded or constructed in the recent past (or will be upgraded or contructed in the future) must be open for use by other scientists, most likely from nearby institutions. The nature of the arrangements will vary, but they should be clearly stated and should favor the performance of the most meritorious experiments, regardless of their origin, as judged by a group containing both local and outside users. Such a user mode requires increased funding

The increases in operating costs and capital equipment funding projected by the budget to be presented below are designed to achieve constant scientific effectiveness of the nuclear science program in the U.S. Such a plan will maintain the U.S. position at the scientific frontiers of nuclear science, but will make only partial use of capabilities that U.S. nuclear science potentially possesses. Optimum use of these capabilities is the goal of Recommendation A of the Friedlander panel. The Nuclear Science Advisory Committee strongly supported that recommendation as expressed by Chairman W. A. Fowler who, in a letter dated April 14, 1978, reminded the agencies of the serious effects of the current low level of operating funds, instrument and user group support and capital equipment budget.

CHAPTER 3: PROGRAMS

In this section we wish to provide a quick review of the programs recommended by the working group for each subfield. The scientific justification is contained in Part I and will not be repeated here*.

1. Nuclear Theory

Nuclear theory , of course, contributes to each of the preceding subfields in providing a framework for the interpretation of the data, by developing a quantitative understanding of phenomena, often in terms of simple models, and by suggesting further avenues of investigation. In addition to these tasks, which are often shared interactively with the experimentalists, nuclear theory attempts the synthesis of these results, establishing the correlations among them to obtain a single unified explanation. One familiar example is the attempt to understand nuclear structure and dynamics in terms of the forces between the constituent neutrons, protons, mesons and more recently quarks; that is, to solve the many body problem.

In the area of nuclear dynamics, it has been clear for some time that it is necessary to generalize the familiar concepts of direct and compound nuclear reactions through the use of multistep direct and multistep compound reactions, the steps corresponding to the various ways the reaction can proceed from a given initial to a given final state. Cascade calculations in which one follows the reaction classically, collision by collision, is an example. Another method makes use of coupled channels, that describe the coupling among the various possible final and intermediate states which can occur. Both of these methods become quite complex computationally as the projectile energy increases and, indeed, they often provide more detail about the reactions than necessary. This has led to the development of a statistical theory of these reactions in which averaged cross sections

*Full reports have been prepared by the various (but not all) working groups. Copies may be provided at the discretion of the group chairmen with the understanding that the reports do not have the endorsement of the full Nuclear Science Advisory Committee.

are calculated. In another procedure, one attempts to describe the phenomena which occur in terms of a hydrodynamic description, or of an appropriate Fokker-Planck equation employing obviously macroscopic variables. The range of validity of these macroscopic equations needs to be determined. From another point of view, this subject can be viewed as nonequilibrium statistical mechanics of a system involving a relatively small number of strongly interacting particles.

Attempts have been made to describe nuclear reactions from a microscopic point of view, that is starting with the observed nuclear force and developing the consequences. Procedures using the methods of nuclear matter calculations have been applied, as well as the time dependent Hartree-Fock method, with very interesting and tantalizing results. These methods involve very large and complex calculations.

Another problem in nuclear dynamics, which will become more and more important as the energy and complexity of the projectiles increase, is the characterization of a multiparticle final state together with practical methods of calculating "final state interactions" among these particles, and finally with a reaction description which takes them properly into account.

Nuclear structure calculations are based (for the most part) on the interacting shell model using orbitals in both spherical and deformed force fields. The ability to carry out these calculations is limited to the case of a few valence nucleons. When the number of valence particles increases, the number of possible states increases very rapidly and shell model calculations are not of much value. Statistical methods can be used, or models based on various kinds of symmetry which pick out the important states may be valuable. The discovery of important classes of states which bear simple relations to each other is a fundamental problem of many body physics. It is, of course, clearly connected with the experiments described earlier which attempt to observe these simple states.

Nuclear theory stands at the threshold of new era. In the past, we worked with nucleons as fundamental constituents, describing their interaction in terms of the exchange of mesons of various kinds, obtaining a description of nuclear forces valid at substantial separation of the interacting nucleons. This method cannot be readily extended to a shorter distance where the quark structure of matter interacting through the exchange of gluons becomes important. The nuclear theorist is faced with the challenge of including the underlying quark structure into the description of nucleon forces, particularly at short range, and more generally to develop the effect of the quark-gluon degrees of freedom on nuclear properties.

The working group on nuclear theory reminds us of the recommendations of the Friedlander report. The problems alluded to in that report have not been resolved (indeed, if anything they have been exacerbated) and the recommendations have not been implemented. The working group recommends a yearly increase in funding for nuclear theory at the rate of $0.6M per year for the five year period so that the total increase in the base would be $3M.

The working group also points out that nuclear theory in the U.S. is hampered considerably by the lack of good computing capability required by modern theory.

It recommends, therefore, funding to provide computing capability which would remedy this situation. Two options have been proposed. For each of these the cost would be between $10-15M and the operating costs would run about $3M/year.

2. Weak Interactions

Experiments in this area are concerned with the violation of various conservation laws by the weak interactions. Experiments of importance include the measurement of the electric dipole moment of the neutron, parity violation in radiative neutron capture by protons, and the scattering of polarized electrons and protons by nuclei. The character of the weak interactions, as exemplified by the conserved vector current hypothesis

(CVC), and the partially conserved axial vector current hypothesis (PCAC), can be studied in β-decay of nuclei, and muon capture. More complete space-time, isospin and spin dependence can be obtained by studying reactions induced by neutrinos. Important limits can be set on gauge theories by studies of rare decay modes, such as neutrinoless muon decay. Once understood, these reactions can be used to study nuclear structure. The working group recommended detector development (for example, a 4π NaI crystal ball, large volume scintillators and Cerenkov counters) at a cost averaging about $0.35M/year and a neutrino horn to be built at LAMPF to serve as a neutrino source, with a construction cost of $2M. A more intense neutrino facility having one hundred times present intensity would probably cost at least $50M. Such a neutrino source could be one of the secondary beams in a K, p, π "factory" for example, but it would require a duty factor less than 10^{-3}.

3. Electromagnetic Interaction

This area is concerned with the use of electrons and gamma rays to study nuclear structure and nuclear processes. Charge, current and magnetization densities of nuclei can be obtained and the presence of meson currents and charge detected by elastic electron scattering. Transition densities are measured in inelastic scattering. All these results can be compared directly with theory. The excitation of especially simple modes of motion of nuclei, such as giant resonances by electromagnetic probes, can be used to determine the quantum numbers of these states, their electromagnetic properties, and their modes of decay. The nature of these "simple" states, and the reason for their existence, forms one of the fundamental problems of nuclear science. Studies of reactions in which the incident electron or gamma ray may "knock out" a nucleon inside the nucleus, (e,e'p) or (e,e'n), or knock out more complex units such as deuterons (e,e'd) or alpha particles (e,e'α) have indicated their possible usefulness for the understanding of nuclei. Production of mesons of various kinds, such as pions and kaons, permit the study of the behavior of particle resonances, such as the delta or the Y* inside nuclei. Investigations at very high energies may be useful for the study of quark structure inside nuclei, to be compared with the quark structure of free nucleons.

The thrust in this area, which will provide the means for making coincidence experiments, for the production of mesons, etc., is toward higher energy and high duty factor electron accelerators. The energy doubler at the MIT Bates Linear Accelerator, taking the electron energy up to 750 MeV, has been included in the FY 1980 Presidential Budget. Several R&D efforts, with the goal of constructing 100% duty factor accelerators in the medium energy range, are now under way. Superconducting structures, as well as room temperature possibilities, are under study. Successful conclusion of these studies would further indicate how a CW accelerator , producing electrons in the GeV range, could best be built. Such beams, together with good resolution and large solid angle detectors, would permit the coincidence experiments required to carry many of the investigations mentioned above to a point where they become relevant for the interesting questions at the frontiers of nuclear science.

At the present time, the R&D for the superconducting accelerators is funded. The R&D for a room temperature accelerator is now being proposed at a cost of some $6M to be spent over essentially a five year period. An energy doubler is being constructed at Bates at a cost of $1.8M, as well as the construction of a pion spectrometer, to be followed by a proton spectrometer. The R&D projects for the 100% duty factor accelerators could lead to proposals for several accelerators in the 350 MeV to 700 MeV range. Additional operating costs of these, together with increase in the cost of Bates operations would produce an average increase of close to $3M/year. over the FY 1979 base of $11M/year.

4. Light Ions and Neutrons

This comprises a vast area of investigation in which contributions are made to all the scientific questions posed by the Friedlander panel. It will not be possible to do justice to it in this brief summary.

(a) Nucleon-Nucleon Forces

These are of fundamental importance. Recent discovery of resonances in the proton-proton system indicates the importance of baryon resonances (also indicated by pion production in nucleon-nucleon collisions) as well as the experimental importance of using polarized beams. Much experimental work at a wide range in energies remains to be done, especially involving neutron beams. The character and magnitude of charge asymmetry in nuclear forces has not yet been fixed. The theory of the short range nature of forces is still open and may directly involve the quark constituents of the nucleons.

(b) Light Ions

Most of present day information regarding nuclear structure comes from these studies which include inelastic scattering as well as particle transfer. An important goal of this research area is the isolation and study of special categories of states whose special attributes reflect important properties of the nuclear many body system and of nuclear interactions inside nuclei. Examples include the giant resonances of which the isoscalar quadrupole (E2) and the monopole (E0) are the most recent ones uncovered. The presence of other types of giant resonances, as well as the presence of giant resonances built on excited states, are under investigation. The discovery that states of very different deformation can have quite similar energies is another example. The identification of multiparticle hole states using particle transfer reactions, in particular deeplying particle hole states by pickup reactions, permits the study of another special category of states. Once these special categories of states are identified, under what circumstances can they interact and perturb each other? The study of the charge exchange reaction in which the incident proton becomes a neutron, and elastic and inelastic proton and neutron scattering, can give important information on the spin and isospin character of nucleon-nucleon forces inside nuclei. The difference of these forces from those of free nucleons is of great interest since it reflects the effect of the nuclear medium. Related to this is the ability to study the high momentum components of nuclear wave functions using reactions, such as pion production by protons (proton incident, pion only emerging) or back angle production of nucleons by fast incident protons, in which large momentum changes occur. The excitation of high spin states by high energy proton beams with anomalously high cross sections, the investigation of correlations by means of "knock out" reaction, such as proton incident with proton plus deuteron or proton plus alpha particle emerging, are examples of studies with high energy protons. Elastic scattering of these energetic protons is particularly important, for it yields the matter density distribution and, possibly in the future, spin densities as well.

(c) Neutrons

Neutrons, being uncharged, are particularly useful for the study of low energy reactions. Recent advances in neutron time-of-flight spectroscopy, as well as in the gamma ray spectroscopy following neutron capture, permit precision studies of nuclear levels. Recent examples are the location of the magnetic dipole (M1) strength in both ^{208}Pb and ^{207}Pb at low energies, the existence of neutron excited doorway states, the measurement of neutron widths which, when compared to proton widths of analog states, can be related to their isospin impurity, fission experiments using polarized neutrons and polarized target nuclei and many others. In addition, neutron reactions which were used to establish the statistical theory of nuclear reactions, in which many degrees of freedom are excited, can also be used to extend that model into a domain where only a few degrees of freedom are excited. This area of investigation forms an important part of the study of non equilibrium statistical processes as they occur in nuclei.

Recommendations for this area by the working group include, as first priority, a growth in the operating level at the rate of 3% per annum leading to a budget increase of $5M per year at the end of the five year period. Accelerators are undertilized. Capital equipment and instrumentation at many of the laboratories have eroded. The upgrading and replacement of obsolete computer facilities, the development and installation of new ion sources, particularly those producing polarized beams, and those producing high charge states for heavy ion accelerators, and the development and installation of new spectrometer systems and detectors are recommended. The upgrading of three accelerators, generally by raising the ion energy, improving precision and some heavy ion capability, at the average cost of $7M, was recommended. In addition, the construction of an accelerator using a storage ring to control the time structure of the beam, and possibly electron cooling to obtain good intensity and energy resolution, was recommended. Such a facility as a booster upgrade to an existing facility is estimated to cost about $10M.

5. Heavy Ions

As in the case of the preceding section, this comprises a vast area of research. It will be possible only to indicate the breadth and impact of past and present investigations. Because of the large momenta of heavy ion projectiles, and their large charge and mass number, it becomes possible, using heavy ion induced reactions, to study nuclear systems under extreme conditions that occur because of extraordinarily large values of the nuclear spin, unusual values of the ratio of neutrons and protons, and behavior of nuclei in the presence of very strong electromagnetic fields. Collisions between heavy ions and nuclei will produce regions of higher density and higher temperature. Each of these permits the investigation of nuclear systems at some distance from the stable valley nuclei. New phenomena have been uncovered, such as the progression in the shape of nuclei as their spin increases, providing new and important tests of our understanding of nuclear structure and requiring descriptions of the nuclear equation of state for nuclear matter in new domains of temperature and density. An enormous variety of reaction phenomena can be studied by changing the nuclear species and by increasing the energy of the incident ion past such benchmarks as the Fermi energy, the velocity of sound in nuclei, energies at which the pion degrees of freedom become important, energies at which relativistic effects play a dominant role, energies at which other mesons such as kaons must be considered, and finally energies at which possibly quarks and quantum chromodynamics must be explicitly considered. The interplay of compound nucleus formation, deep inelastic scattering, (a surprising new process in which most of the incident kinetic energy is converted into internal energy), and the direct reactions (including, especially, particle transfer), promise a qualitative advance in our understanding of reaction mechanisms and, more broadly, into the nonequilibrium statistical mechanics of many body systems involving a relatively small number of strongly interacting particles. New forms of intermediate structure, involving new kinds of nuclear systems and simple modes of motion, have been discovered. Fundamental issues, like the applicability of macroscopic descriptions of nuclei such as "nuclear quantal hydrodynamics," are attacked. At the higher energies, final states involving many particles become important. Techniques for their characterization must be developed, as well as for the extraction from the data of significant properties of the nuclear system involved. It is not yet clear what these properties are. Are they temperature and density? At relativistic energies, the effect of time dilation and the Lorentz contraction are very important. But when and how will the quark structure and quantum chromodynamics manifest themselves? Is there another state of nuclear matter, for which ". . . .a quark rather than a nucleon description . . . ." of the constituents of nuclear matter is most appropriate? Much has been omitted in this discussion; however, the variety of phenomena and the opportunities offered by having a variety of projectiles with differing charge, mass, and energy, and a variety of target nuclei, should be apparent.

The working group identified a number of needs in order to take full advantage of these opportunities. Proper utilization of existing facilities and those being constructed and those recommended by the Facilities Subcommittee would require an increase in operating funds totalling $4.7M by 1984. Increases in beam energies, for example by adding "after burners" to existing facilities, would produce a significant increase in scientific capability. It would permit exploration in the interesting energy range extending from 20 MeV/A. The working group recommended, as first priority, the upgrading of three such facilities at the cost of $21M over the next six years. Facility improvement in terms of ion sources providing high charge states, polarized heavy ions or exotic particle species are particularly important. Modest upgrading of beam characteristics and accelerator performance generally are included in this list, which is estimated to require an expenditure of about $2M per year for the next five years. Instrumentation improvements would require replacement of outmoded "digital hardware" at the cost of $4M, and the development of detectors especially designed for multiparticle final states. A new venture, that of producing ultrarelativistic heavy ions in the energy range of 20 GeV/nucleon for fixed targets or 800 GeV/nucleon equivalent energy for colliding beams, is described. R&D for this concept is proposed and would total about $10M. The construction plus experimental equipment are estimated to cost about $130M.

6. Pions

An intensive effort in pion physics is a new aspect of the program in nuclear science, the experiments to be discussed below having been performed during the past few years. It is clear from these that pion induced reactions are sensitive to the details of nuclear structure. For example, survey experiments of pion single charge exchange experiments in which a positive pion (π^+) is changed to a neutral one (π°) have seen strong analog state transitions throughout the periodic table. This ability to probe isotopic effects using pion probes is also evident in the large variation in the ratio of the cross section for inelastic scattering by π^+ to that by π^-. Positive pion production by protons differs considerably from π^- production. Each is sensitive to the nature of the final state of the residual nucleus and to the state of polarization of the proton. On the other hand, there is considerable evidence from measurements in the resonance region (energies near those where the pion and free nucleon resonate to form a Δ) to show that it is possible to determine the properties of the Δ inside the nuclear medium. The effect on its properties will depend upon the state of the host nucleus, so that it may eventually be possible to use the Δ as a probe of nuclear structure. Since nuclear forces are to some extent produced by exchange of pions, the question as to the nature of pionic matter inside nuclei naturally arises. Experiments on the two photon annihilation of $^-$ captured by nuclei (the reaction is $\pi^+ + \pi^- \rightarrow 2\gamma$) may be informative in this regard. The question of pion condensation has not been settled by laboratory experiments, although astrophysical phenomena suggest its existence.

Double charge exchange reactions ($\pi^{\pm} \rightarrow \pi^{\mp}$) to individual final states of nuclei have been observed. This reaction should be able to excite "double analog states" in which the isospin differs from that of the target by two units. Exotic nuclei off the stable valley can be formed in this way. The probability for the process should depend on the correlations between the nucleons in the nucleus. It is, however, not straightforward to extract this important nuclear information from the data. Correlations also play a role in the absorption of an incident pion by two nucleons (π,2p). The importance of energy dependence of the pion nucleon interaction for the pion nucleus interaction should be noted. In the Δ resonance region, one expects that the pion nucleus interaction would be very sensitive to the surface properties of nuclei, while at lower energies volume properties are more important.

These experiments demonstrate the potential of the pion as a probe of nuclear structure. They demonstrate, as well, the existence of the Δ inside nuclear matter. Many additional experiments are still needed in order to fully exploit these possibilities. In the future, it is expected that studies revealing the extent to which the nucleus consists not only of neutrons and protons but of isobars (like the Δ), as well, will be carried out.

The study of the interaction of the pion with free nucleons is of importance, not only for the description of the pion nucleus interactions, but also for the theory of nuclear forces. Elastic and charge exchange scattering by protons, as well as pion production by pions, form the basis of our understanding of the pion nucleon interaction. In this connection, more experiments are needed, particularly with polarized nucleon targets. One also hopes to probe the quark structure of the   to see, for example, if it is deformed.

The working group in this area recommended the construction of a new low energy pion/muon channel at LAMPF at a cost of $3M. New equipment included a pion spectrometer costing $0.6M. Larger possible projects include a new experimental area at LAMPF with several pion channels and increasing the primary proton current to 2 mA. The cost would be about $20M. A storage ring to increase the LAMPF duty factor to 100% and thus make coincidence experiments possible would cost $25M. Finally, the construction of a high intensity kaon antiproton accelerator, which would also be an intense source of high energy pions, is listed. The cost of such a facility would put it into the "large" class. This last facility was also recommended by the working group on kaons and antiprotons.

7. Kaons and Antiprotons

The past two years have shown a sharp increase in interest in nuclear physics problems that can be attacked using kaons and antiprotons as probes. In the case of kaons (K), it has been shown that hypernuclei consisting of neutrons, protons and the strange lambda baryon ( ) can be formed in a reaction in which an incident negative kaon interacts with a neutron in the target nucleus to form a positive pion and a Λ nearly at rest. By examining the energy spectrum of the pions, one can determine the state of the hypernucleus. Only a few experiments have been done and the full potentialities of this reaction have not yet been ascertained. But it is apparent that a whole new set of nuclei may be available for study.

These investigations can yield some understanding of the interaction between the Λ and a nucleon, its spatial as well as its spin dependence. A difference between the interaction of a Λ with a proton and a Λ with a neutron, charge symmetry breaking, has been observed. Such information is of great value to the theory of the interactions of the fundamental particles, in this case of baryons. The possible formation of hypernuclei in which the nucleus contains a strange particle would add to this opportunity as would the formation of double hypernuclei, that is nuclei containing two Λ's. The first of these could be produced in a $K^- \rightarrow \pi^{\pm}$ reaction. The second utilizes the $K^- \rightarrow K^+$ reaction and is much more difficult to study. Another possibility to be investigated would be the formation of bound states consisting of a nucleon and a strange baryon which could be studied using deuterons as the target nucleus.

From the point of view of nuclear structure, the presence of the Λ inside a nucleus provides us with a unique probe. The Λ has a mass of the same order as that of a nucleon, interacts strongly with a nucleon, but since it is not a nucleon does not satisfy the Pauli exclusion principle with respect to the nucleons. It can, therefore, occupy states which would not be allowed for nucleons and, therefore, act as a more effective probe than either a neutron or proton. One would observe the effect of such a probe by determining how it modifies the properties of the host nucleus. These modifications should be reflected in the properties of the hypernuclear states.

Hypernuclei will decay to ordinary nuclei through the weak interactions. Some of the possible processes involved are unusual, so that the study of the weak decay of hypernuclei could add importantly to our understanding of the weak interactions.

The interaction of the negative kaon (K^-) with a nucleus shows resonances referred to as a Y*. Studies of K^- elastic and inelastic scattering and atoms formed with the K^- (kaonic atoms) should determine how the properties of the Y* are changed by the host nuclear medium and vice versa. On the other hand, the K^+ interacts weakly with nucleons; no resonances are formed and so it can penetrate much more readily into the nuclear interior. Thus, the exploration of nuclear structure with K^+ induced reactions would complement information obtained with strongly absorbed probes.

The major interest in p interactions has so far been in observing possible resonances and bound states of the nucleon antinucleon (NN) system. The existence of these is suggested by theories based upon models describing nuclear forces. So far, one such resonance at 1932 MeV has been strongly suggested, and there are indications of the possible presence of several others. The observation of both the masses and widths of such states would be undoubtedly of great importance for the understanding of nuclear forces, particularly their short range character which is presently poorly understood. The presence of another kind of resonance, consisting of two quarks coupled to two antiquarks, has been predicted. These are thought to be strongly coupled to the NN system and so should be observed as resonances in NN scattering. These are all very exciting possibilities.

Experiments induced by kaons and antiprotons are presently strongly limited by lack of intensity, so that accelerator modifications to increase the flux of these particles is the first priority of the working group in this area. Toward this end, they suggest the construction of a high performance beam line and spectrometer system for kaons at the AGS accelerator at Brookhaven National Laboratory. Such a device would cost about $7M to build. To exploit this facility, user support of about $2M/year would be required. They also suggest an antiproton storage ring with beam cooling to be installed, for example, at Brookhaven or Fermi National Accelerator Laboratory to develop an increase of antiproton flux by two orders of magnitude. Such a source is being built at CERN. The operating cost of such a facility is estimated to be about $3M/year in user support. These operating costs for both the kaon and antiproton facility do not include any prorated costs of the AGS or FNAL operation.

Finally, the eventual construction of a high current kaon antiproton accelerator facility is suggested. It would probably be a fast cycling synchrotron with a linac injector, together with an antiproton storage ring with beam cooling. Such a facility, including the cost of the experimental areas and ancillary equipment, might be as much as $150M. It would have multiple beam and multiple target capabilities.

8. Nuclear Science Related Research and Applications

Nuclear science interfaces with almost every branch of physics; it has had a pervasive influence on all science and technology. As the frontiers of nuclear science expand, fruitful contributions continue unabated to such diverse fields as astronomy, archaeology, chemistry, medicine and geology and, within physics, to materials science, atomic and condensed matter physics. Similarly, the impact of nuclear science on industry and medicine is widespread. Medical, materials, electronics, computing, and energy technologies make extensive use of methods and instruments originating in nuclear science research. The applied use of new discoveries in nuclear science develops in a remarkably short time. We cannot, in the little space available, give a complete account of the influence of nuclear science.

As far as nuclear science related research is concerned, we shall limit ourselves to examples of such research funded by the DOE/NSF for FY 1979 and included in the nuclear science budget. In the case of applications, we shall limit the discussion to a few examples. This should not obscure the fact that the dividends to society arising from its investment in nuclear science and nuclear scientists continue to be extraordinary.

A representative, but not inclusive, list of the activities in nuclear science related research that are mentioned in this report include nuclear astrophysics and cosmochemistry, accelerator radiochronology, accelerator related atomic and molecular physics including hyperfine structure, accelerator related solid state physic,including muon spin resonance, (μSR) and a few new applications of nuclear data, instrumentation, and accelerators.

The understanding of stellar evolution and the production of the elements by nucleosynthesis depend critically on the empirical data and the quantitative theory of nuclear reactions and the equation of state of nuclear matter. Both strong and weak interactions are involved in important ways. The formation of pulsars and neutron stars, the mechanism underlying supernovae explosions are examples of stellar phenomena of recent interest in which nuclear phenomena play an essential role. The process of energy production in the sun is being investigated by measurement of the neutrino flux arriving at the earth and coming from the sun. At the present time, the measured flux is 1/2 to 1/3 the predicted value, so that new experiments which will test the process more incisively are proposed. Nuclear astrophysics has stimulated a number of nuclear physics studies and has at times provided data otherwise unavailable. The existence of neutron stars and the relation of their rate of cooling to the existence of pion condensates are examples.

Accelerator radiochronology refers to the use of heavy ion accelerators as ultrasensitive mass spectrometers permitting the determination of the presence of long lived radioisotopes, even with very small samples. By measuring the presence of different isotopes, time scales have been extended from the 50,000 year time scale provided by the familiar ^{14}C dating technique to time scales of the order of a few million years.

Accelerator related atomic and molecular physics, including hyperfine interactions, involve a wide variety of activities. Beam foil spectroscopy is a familiar example. Using heavy ion projectiles, one can test the relativistic many body calculations of atomic structure and make studies of the Lamb shift in high Z stripped atoms. The close collisions of very heavy ions can give rise to very strong electrostatic fields, testing thereby quantum electrodynamics in a new domain. Imbedding a free ion in a medium, and observing the effect of the local electromagnetic fields on the orientation of the spin of the ion permit the determination of these fields. These measurements have already made an appreciable impact on the understanding of condensed matter. New techniques recently developed promise to extend vastly the range of magnetic and electric hyperfine structure that can be studied.

Muon spin rotation provides a method for measuring the hyperfine field acting on a muon by measuring the direction of the electron produced when the muon decays. The detection of muonium (the atom formed by a negative muon and proton) can be used to reveal the presence of hydrogen. The simplicity of this probe, which provides such detailed information regarding its local environment, gives high promise of its future use to investigate properties of condensed matter.

In accelerator related solid state physics, nuclear projectiles are used to study the concentration of light elements (particularly hydrogen) near the surface through the nuclear reactions they induce. Rutherford back scattering of alpha particles is now routinely used to study the depth profile of the elements in a sample providing a sensitive measure of the mass and depth of the struck nucleus. Good spatial resolution is also possible. Scattering can also be used to provide a diagnostic tool to determine the integrity of crystal structure. This technique is being used for the study of solar cells and infrared detectors. A third method exploits proton induced x ray emission (PIXE) to determine the presence of trace elements at levels of one part per million of the matrix atoms. When these proton beams are focused to micron size, these determinations of trace elements can be made as a function of position. These three techniques — nuclear reactions, Rutherford back scatterings and PIXE — suffice to give a complete characterization of the spatial distribution of a wide variety of trace elements. Beams of nuclear projectiles have been used, as well, to study the interatomic forces present in solids and to understand the mechanisms of radiation damage.

There have been many spinoffs from basic nuclear science with applications in industry and medicine. Ion implantation used in the manufacture of large integrated circuits, the development of a diagnostic tool for solar cells, the use of nuclear science techniques for characterizing materials and, indeed for fabricating new alloys not accessible by other means, and a wide range of techniques for profiling the presence of trace elements add to the more familiar contributions to computer and energy technologies which continue to occur. The use of radioactive isotopes in the diagnosis and, on occasion, in the treatment of disease, or in the study of various processes which occur within an organism, continues to expand. Electron accelerators providing x ray sources are used for the treatment of malignancies. Over 1000 electron linear accelerators, direct descendants of nuclear physics accelerators, are in use world wide for cancer therapy. Within the last few years, the use of neutrons, pions and heavy ions in the treatment of tumors has been under study.

The working group in this area recommends the continuation of funding for nuclear science related research and applications by the nuclear science program. It is, of course, not possible to predict what the new targets of opportunity will be, but it must be anticipated that they will arise. At the present time, 4% of the FY 1979 budget is devoted to nuclear science related research (not including applications). The working group recommends that it be raised to 5% of the total nuclear science budget in 1986. Other special recommendations are given in Part I, Chapter 9.

CHAPTER 4: ESTABLISHING PRIORITIES

It is essential to consider priorities among the various programs presented to the panel.

We must begin with the concept that nuclear science is multifaceted, that the subfields are mutually supportive. The criteria used to establish prorities are thus, in many instances, of comparable importance.

In order to focus the discussion, the members of the panel judged the programs and projects according to a number of criteria.

The first set of ratings was directed toward the subfield programs, attempting to obtain a profile for each. The items are listed below with comments wherever necessary.

1. Scientific impact: Rate the intrinsic importance of the scientific program. Are the scientific issues it will address important and have they been sharply formulated? Has it been shown convincingly that the program will have a significant impact on these issues or is it only indicated by "glittering" generalities?
2. Probability for important fundamental advances.
3. Impact on other subfields of nuclear science: Is the subfield being rated important for progress in other subfields?
4. People (Quality).
5. People (Number): Does the panel feel that the interest of the nuclear community in the subfield is sufficiently strong so that the number of individuals now participating and expected to participate will be adequate to carry out the scientific program proposed?
6. Applications: What is the probability for the development of important applications of technological and scientific importance?
7. Attractiveness to young people: Will the program be attractive to graduate students and to postdoctoral researchers?

8. Attractiveness to other sciences: Will the program be attractive to physicists in other subdisciplines and to other scientists?
9. Funding (Operations): Should the operating funds be increased?
10. Funding (Capital Equipment): Should the funds for capital equipment be increased?

The programs which were rated with respect to these ten categories were (a) weak interactions, (b) electromagnetic interactions, (c) light ions, low energy, (d) light ions, high energy, (e) nucleon-nucleon, (f) neutrons, (g) heavy ions, energy less than 20 MeV/n, (h) heavy ions with energies between 20 MeV/n and 200 MeV/n, (i) relativistic heavy ions, (j) pions, (k) kaons, (l) antiprotons, (m) nuclear theory and (n) nuclear science related research and applications.

The second set of ratings concerned priorities among the various construction and accelerator research and development proposals made by the working groups. The criteria employed included:

1. Scientific merit: This title refers not only to the scientific importance of the facility but also to the plan for the exploitation of the facility, paying attention to the interpretability of the projected experiments.
2. Technical feasibility: Will the construction involve the development of new technolgy with respect to "hardware" and systems or is it a state of the art project?
3. Cost effectiveness: Does the nature of the results to be obtained and the anticipated productivity of the facility justify its cost? The cost includes both the cost of construction and the cost of operation. New facilities are generally more costly to operate and will thus require a reallocation of resources and manpower. This implies some reduction in activities now being carried on. Does the capability provided by the proposed facility make this "trade off" worthwhile?
4. Attractiveness to young investigators: Does the proposed facility present exciting new possibilities which will make it attractive? Will it be of the type which will present young investigators with opportunities for initiative and growth?

These priority issues, with respect to the subfields and to facilities and R&D, were voted on by the fourteen Nuclear Science Advisory Committee members attending the meeting, plus the three chairmen of the working groups who are not members of the full Committee. The straw ballots on these subjects were extensively discussed and resulted in a much improved understanding of the nature of the problem involved in long range planning, of the significance and relevance of the individual questions, and of the extent to which the Committee was equipped to answer them using the information at hand. After these discussions, the priority recommendations included in the final report were developed in a separate series of open ballots.

The results of these discussions are encapsulated in a priority listing of the facilities, a number of recommendations, and finally a long range plan and corresponding budget projections. In all these considerations, it was clearly understood that the recommendations concerning facilities are fairly general at this time, since no presentations of specific proposals were made before the Committee. Cost estimates are quite approximate. It is anticipated that specific construction recommendations will be made by the Committee in each fiscal year in response to detailed proposals entering the competition within the overall plan presented here or an appropriate modification of it. It should be emphasized that the plan presented includes only about one third of the facility construction which is expected to be proposed, so that in each fiscal year the successful projects will emerge from a very severe competitive evaluation.

The facilities which were all given the highest priority included the construction of a neutrino horn at LAMPF which would make possible the study of coherent neutrino scattering by nuclei, reactions induced by neutrinos such as the neutral current disintegration of the deuteron, a kaon line for the study of K-nuclear interactions and hypernuclei, a 100% duty cycle electron accelerator of intermediate energy (500 MeV) which can be used for coincidence studies of electron induced reactions, an upgrade of an accelerator capable of accelerating light and heavy ions and the upgrade of an accelerator for heavy ions. A second level of priority was assigned to a high energy (energy not yet specified) CW electron accelerator, a high energy light ion upgrade using a storage ring plus electron cooling which promises to provide both higher energy and improved energy resolution, and a dedicated computing facility for theorists. The priority of these three projects is influenced by the need for prior "Research and Development" or further development of the concepts involved prior to a firm recommendation. An upgrade of a low energy pion-muon beam line and further upgrades of heavy ion and light ion facilities were assigned a third level of priority.

Research and development of facilities and equipment are essential for the future. The R&D for the high energy CW electron accelerator mentioned above was assigned a very high priority; a somewhat lower one for the R&D for a high current, high energy proton accelerator and antiproton storage ring leading to an intense kaon and antiproton beam together with pion beams having considerably higher energy than now available at the projected intensities. R&D was also recommended for a facility providing beams of heavy ions at ultrarelativistic energies per nucleon. It is essential in all these cases that the R&D is not confined only to accelerator and other technical developments. A serious investigation into the scientific case for the projected facility must be mounted as well, since technical feasibility alone will not suffice. Scientific feasibility, that is the demonstration that one will be able to obtain results, is equally essential. It is to be exhibited through the design of specific experiments, which are shown to be feasible, together with the description of the analyses to be used to obtain new information not otherwise available.

The recommendation of R&D in no way commits the Committee to a recommendation of the resulting projected facility. This is to be considered when a specific proposal for construction is made in which both scientific and technical feasibility is demonstrated.

In view of the fact that the R&D expenditures are , in some cases, of the same order of magnitude as facility construction costs, the panel recommends very strongly that the Committee be informed by the agencies of such large R&D proposals, so that it can comment upon them. In these cases especially, it must be clear that the large investment in R&D does not guarantee the approval of construction.

An absolutely vital aspect is the balance among the subfields of the discipline which reflects the characteristic use of diverse approaches to study nuclear phenomena.

While it is recognized that there must be shifts in emphasis from time to time, careful study should be made of proposed large or medium sized facility construction to understand if its eventual operating budget will have an adverse impact. The construction should not be undertaken unless a clear plan of action is developed that shows that the required balance in capability can be retained.

Note that only one CW electron accelerator in the 500 MeV energy range is given high priority. This is an important recommendation since proposals for several such accelerators are in various stages of preparation.

Among the suggestions for new facilities are some very large and costly ones. These, as were discussed above (see Chapter 2, Part II), need a separate evaluation because of the difficulties which will be encountered in funding both their construction and operation.

It is useful to record the very strong support of the panel for the needs of nuclear theory and weak interactions. This is reflected in the facility priorities by the presence of a neutrino horn in the construction schedule and sizable outlays for detector development, and, in the budget, by substantial increased funding for theorists.

The discussion on item 3, (Impact on other fields of nuclear science), revealed the clear recognition by the panel of the mutually supportive relationship of the different subfields.

The panel is confident that the chances for fundamental discoveries to be made through the study of nuclear science are high. It feels that the programs of research are very exciting so that a sufficient number of high quality people, and particularly high quality young people, will find them attractive and so provide the manpower needed for their implementation and execution, assuming the requisite funding.

CHAPTER 5: BUDGET

On the basis of the general discussion in Chapter 1 and Chapter 2, and of the decisions taken by the panel as described in Chapters 3 and 4, it is possible to outline a budget for operations, capital equipment and construction, as well as a construction schedule for the next five years. Priorities are reflected in this schedule, which is arranged so that the first priority items in general are to be authorized early while second priority items occur later.

Before we proceed to describe the results, it should be pointed out that the schedule proposed below should not be considered as rigid. It will be necessary to revise the details of both the budget and construction schedule each fiscal year after a review of the specific proposals which are submitted for consideration at that time. Revision is required because of the possible impact of scientific and technological advances which make different goals important and accessible. Revision may be necessary, because the yearly allocations in the Federal budget finally adopted by the President and Congress will differ from those recommended in this report. As a consequence of all these aspects of budget formulation and acceptance, it may be necessary to revise some of the priorities, especially the detailed ones established for facilities and the scheduling of their construction. First priority items will remain firm, although the program may be expanded by proposals of comparable high quality in terms of scientific merit and technical feasibility.

Facilities

Table II shows the Committee's plan for facility construction projects for the next decade. The upper section of the table reviews the anticipated obligation plan for projects previously approved or recommended. The lower section contains two groups of new projects or major upgradings of existing facilities of moderate size, one project of substantially greater magnitude beginning about the middle of the decade, and finally a less well defined group of projects of moderate size to be authorized toward the end of the decade. This general pattern is based upon the broad considerations discussed in Chapter 1 and Chapter 2. The list was selected and priority ordered from a much larger set of planned or anticipated projects on the basis of the present assessment of scientific importance, technical feasibility, cost effectiveness, and probable attractiveness to the younger generation of nuclear scientists as described in Chapter 3.

Starting dates are no earlier than the year in which the project might be ready and many have been delayed to obtain a constant level of facility construction which should be of the order of $20M/year as discussed in Chapter 1.

In addition to the projects listed under the "Prior" heading of Table II, one should also mention the upgrading at LAMPF to a 1 mA average proton current and the construction of a storage ring for neutrino production, the completion of a 25 MV electrostatic accelerator (HHIRF-Phase I) at Oak Ridge, the development at both University of Illinois and Stanford University of superconducting accelerators for medium energy CW electron beams in the 200-300 MeV region, the construction at California Institute of Technology of a low energy high current accelerator and finally an initial upgrading of the tandem at Florida State University funded by the State of Florida.

The listing in the table is intended as a guideline to an annual preparation of recommendations based on detailed proposals, and one would anticipate some departure from the strict priority ordering based on the merit of individual proposals as assessed at the time they are made. The field is evolving rapidly and one would also anticipate new ideas to displace some elements of the present list, especially later in the decade.

For some of the smaller facility upgrades for which detailed cost estimates are not available, an average figure of $7M is used which represents an average over a number of proposals for FY 1980 and FY 1981 reviewed by the Facility Subcommittee.

Capital Equipment

The Friedlander Panel, the Bromley-NSF Subcommittee, and our Instrumentation Subcommittee have all recommended substantial increases in funding for capital equipment. We support those recommendations and urge that significant increases

TABLE II

NUCLEAR SCIENCE FACILITY CONSTRUCTION PLAN

	FISCAL YEAR	80	81	82	83	84	85	86	87	88	89
PRIOR	Bevalac Uranium	$4M	1								
	Michigan State Phase 2	6	8	8	5						
	Bates Energy Doubler and Pion Spectrometer	3									
	LAMPF Staging Area	2.4									
	Stony Brook, Caltech	2	1								
	Argonne Atlas		6								
NEW	Neutrino Horn LAMPF			2							
	Light-Heavy Upgrade 1			7							
	Heavy Ion Upgrade				7						
	Kaon channel				7						
	CW electron accel. (medium energy) Illinois/Stanford			3							
	Nuclear theory computer					12					
	High Energy Light Ion upg.						10				
	Light or Heavy Ion upg. 2					7					
	High Energy CW Electron Accel. 1-2 GeV						10	20	20		
	Upgrade									7	
	Upgrade									7	
	User Facility									5	13
	Upgrade										7
	TOTAL	17.4	16	20	19	19	20	20	20	19	20

be made in the capital equipment budgets at the DOE and the NSF. For example, at the DOE, where capital equipment appears as a separately identified budget item, we recommend an increase from the present level of \$9M/year to \$11M/year, with a similar increase and separate identification at the NSF. These increases will go to cover the items discussed in detail in the reports of the Bromley-NSF Subcommittee and our Instrumentation Subcommittee, including (1) upgrading and replacing obsolescent computer facilities at a number of accelerator laboratories, (2) the development and installation of new ion sources producing positive ions in higher charge states, for more intense polarized beams, for more efficient negative heavy ion production, etc., (3) the development and installation of new spectrometer systems and detectors, etc. Item (1) was recommended by our Instrumentation Subcommittee as its highest priority at a cost of \$6M. Items (2) and (3) represent expansions of existing development programs at universities and national labs, as well as increases in the availability of funding for the installation and utilization of such ion sources, spectrometers and detectors in other laboratories. Specific examples of projects in these areas include the ion source development programs at the University of Pennsylvania, the University of Wisconsin and Lawrence Berkeley Laboratory, the installation of an upgraded split pole spectrometer at Yale, the new pion spectrometer at Bates, the ultrasensitive mass spectrometer system at Rochester, etc.

The Committee's plan for the component of the capital equipment and construction funds to be provided by the DOE is shown in Figure 5. The totals for both agencies are shown in Figure 4, assuming that the NSF contribution to capital equipment funding will be about \$3M in 1986.

Operating Budget

Table III gives the breakdown into subfields of the funding for operations in FY 1979. The budgets for FY 1980 have not, as of this moment, been fixed. It will be assumed in what follows that the allocations in FY 1980 will be the same as those in FY 1979, in FY 1979 dollars. For successive years up to 1986, the operating budgets in Table IV for constant scientific effectiveness were estimated as follows: Funds were added to operate new facilities projected in Table II, as well as R&D

for a high energy CW electron accelerator, and for a possible ultrarelativistic heavy ion or intense K,p, accelerator, and finally for projects which are in the process of construction and will be completed in this period. Otherwise,the operating funds were kept constant. The operating costs associated with the CW high energy electron accelerator were not included, since it would not be completed by 1986. It is anticipated that the additional operating costs for this facility would be absorbed

TABLE III

NSF AND DOE OPERATING FUNDS FOR NUCLEAR SCIENCE

FOR FY 1979 (1979$)

	NSF	DOE	TOTAL
Weak Interaction	1.7	3.8	5.5
Electromagnetic Interaction	3.7	6.9	10.6
Light Ions and Neutrons	7.4	19.9	27.3
Heavy Ions	6.5	29.6	36.1
Pions	0.6	12.9	13.2
Kaons and p's	0.2	0.9	1.4
Theory	1.6	6.2	7.8
Nuclear Science Related Research	2.1	2.4	4.5
Applications	0.1	6.5	6.6
	23.9	89.1	113.0

i

in part by the subfield by reducing the operating funds at other installations. The only subfield showing a major increase is that of nuclear theory. This is, in part, a consequence of the recommended expansion of the number of nuclear theorists at a rate governed by an increase in funding $0.5M per year for the five year period. The other component of the increase comes from the operating funds associated with a computer system dedicated to theory. The detailed nature of this system has yet to be considered by the Committee so that the amount of this increase is approximate. The net effect of these considerations for the operating budget is shown in Figure 6. The distribution among various subfields is shown in Table V. Except for relative increases in nuclear theory and K, p categories, the distribution is essentially unchanged. The overall change corresponds to an increase of 3%/year in the operating budget over the five year period.

An overall summary of the allocations is shown in Table VI. Operating funds form about 80% of the total, construction about 12% and capital equipment funding over 7% in both FY 1980 and FY 1986.

TABLE IV

	79/80	81	82	83	84	85	86
WI	5.5	5.5	5.5	5.5	5.8	5.8	5.8
EM	10.6	12.1	12.1	13.7	14.7	13.2	13.2
Light	27.3	27.3	27.3	27.3	27.8	27.8	28.8
Heavy	36.1	36.1	37.1	37.1	39.1	39.6	40.1
π	13.2	13.2	13.7	13.7	13.7	13.7	13.7
K, p	1.4	1.6	2.3	2.5	4.0	4.0	4.0
Th.	7.8	8.3	8.8	12.3	12.8	13.3	13.8
NSR^2+A	11.1	11.4	11.7	12.0	12.3	12.6	13.0
TOTAL	113.0	115.5	118.5	124.1	130.2	130.0	132.4

WI = Weak Interaction

EM = Electromagnetic Interaction

Th = Theory

NSR^2+A = Nuclear science related research plus applications

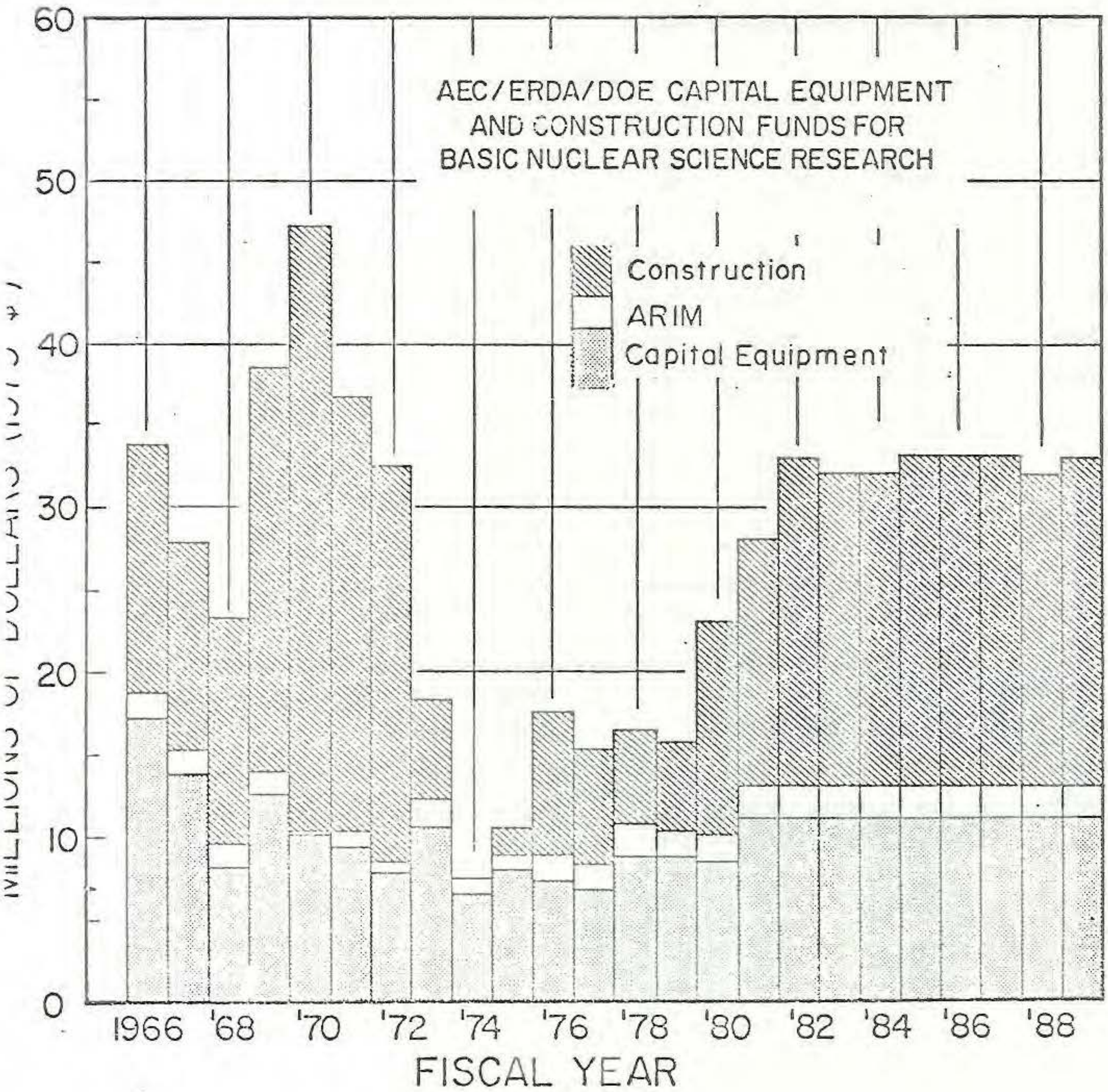
Light = Light Ions and Neutrons

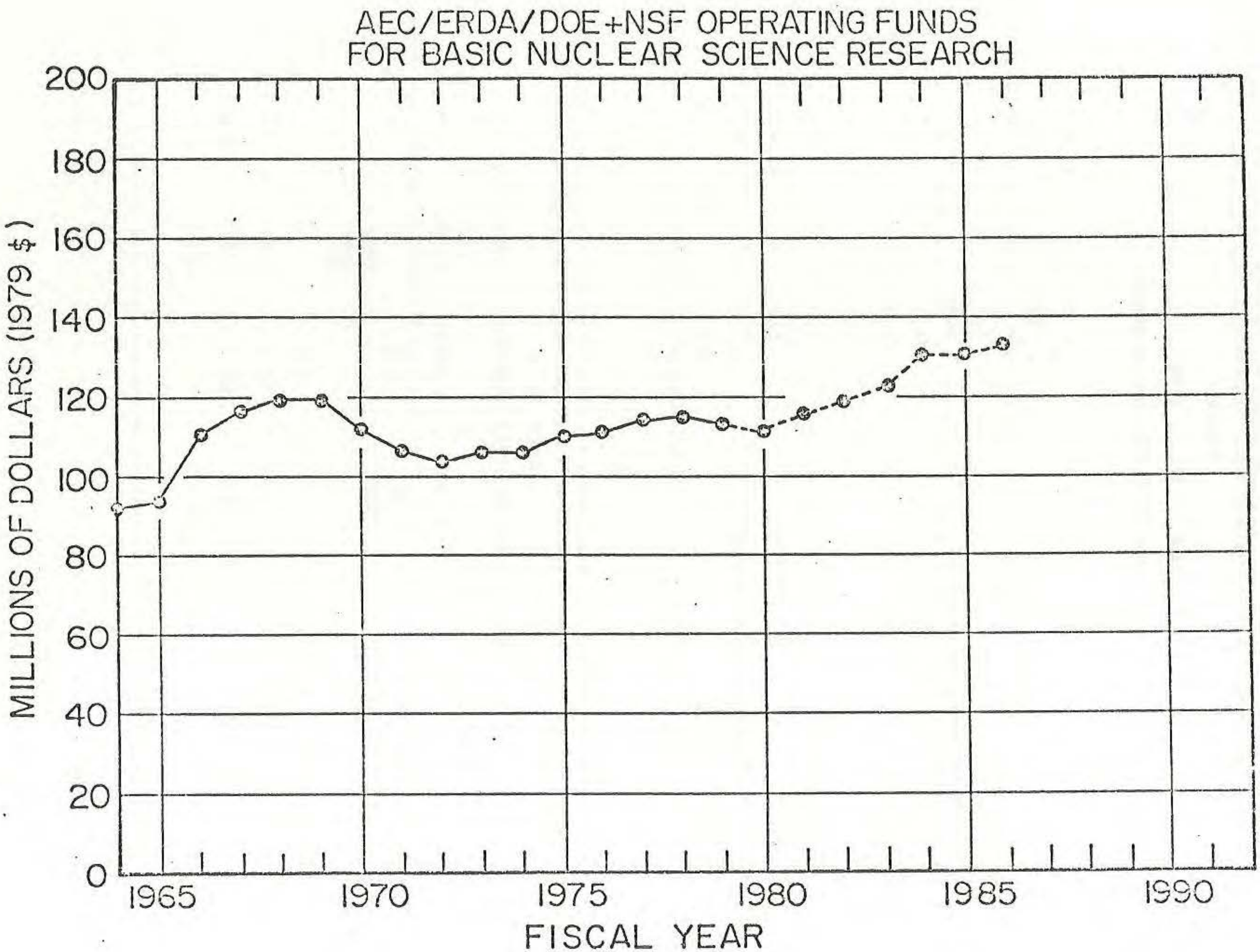
Heavy = Heavy Ions

π = Pions

K,p = Kaons and Antiprotons

FIGURE 5


AEC/ERDA/DOE CAPITAL EQUIPMENT
AND CONSTRUCTION FUNDS FOR
BASIC NUCLEAR SCIENCE RESEARCH
Construction
ARIM
Capital Equipment
60
50
40
30
20
10
0
1966
'68
'70
'72
'74
'76
'78
'80
'82
'84
'86
'88
FISCAL YEAR



AEC/ERDA/DOE+NSF OPERATING FUNDS
FOR BASIC NUCLEAR SCIENCE RESEARCH
MILLIONS OF DOLLARS (1979 $)
200
180
160
140
120
100
80
60
40
20
0
1965
1970
1975
1980
1985
1990
FISCAL YEAR

TABLE V

NSF AND DOE OPERATING FUNDING DISTRIBUTION

FOR 1979 AND 1986 COMPARED

	% Total 1979	% Total 1986
Weak Interaction	4.9	4.4
Electromagnetic Interaction	9.4	10.0
Light Ions and Neutrons	24.2	21.8
Heavy Ions	31.9	30.3
Pions	11.7	10.3
Kaons and p	1.2	3.0
Theory	6.9	10.4
Nuclar Sciecne Related Research and Applications	9.8	9.8

TABLE VI

NUCLEAR SCIENCE ADVISORY COMMITTEE 5 YEAR PLAN

	FY 80	% Total	Plan FY 86	% Total
Capital Equipment and Instrumentation	10M (DOE)	7.1	14 (DOE + NSF)	8.2
Accelerator Improvement	1.6	1.1	3	1.8
Facility Construction	17.4	11.5	20	11.7
Operating Funds	113.0	80.3	132.4	78.3
TOTAL	141.0		169.4	

APPENDIX A

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D.C. 20550

MAY 14 1979

Professor Herman Feshbach
Department of Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Herman:

This letter is to request that the DOE/NSF Nuclear Science Advisory Committee conduct a study on scientific opportunities and priorities in U.S. nuclear research for the next decade and submit a report on this subject to the Department of Energy and the National Science Foundation by September 1, 1979.

We request that in your report you discuss highlights of nuclear research during the past few years, areas of nuclear research which are expected to be opened up by facilities recently brought into operation or under construction, and scientific needs and opportunities which you can identify and which may justify new facilities or programs in future years. We expect that you will draw on the information developed and consider the recommendations made in recent studies such as the NAS study on the "Future of Nuclear Science" and the ERDA/NSF Panel report on "The Role of Electron Accelerators in U.S. Medium Energy Nuclear Science," but that your report will provide a new overall assessment of the field of nuclear research.

It is important that in this study you consider also the nuclear research programs and plans, as known, of other countries. Obviously, manpower and funding constraints limit the United States from being foremost in all areas of nuclear research. Which areas should the U.S. seek to be pre-eminent in, competitive in, or abandon? What would constitute a strong and balanced program for the U.S.?

We recognize that some funding guidelines are necessary for developing a realistic long range plan. One scenario, of course, would be that of a level funding plan but allowing for redistribution of funds within the program. Another funding scenario could be that of modest growth through the next decade. Above all, we need to know what plan is required to insure vitality to the field over the next decade. What does it take to keep the field intellectually exciting, to attract high quality young scientists, to be able to respond promptly to exciting opportunities?

The attraction of outstanding young scientists to the field of nuclear research has been an important recent issue. We feel that special attention should be given to this issue. Is there an adequate influx of young nuclear scientists to the field to meet the needs of the program levels which are implied by your program recommendations? Are the employment opportunities being offered adequate to ensure retention of a sufficient number of high quality graduates within the nuclear research program? Are there specific actions that the funding agencies might take to respond to perceived needs in this area?

There has also been extended discussion recently as to the level of support for instrumentation, capital equipment and technical manpower. We would like the study to address these items.

In your report, you should make general recommendations concerning existing programs and new possibilities rather than review specific projects or proposals. Detailed reviews of specific proposals or current projects would be handled separately.

We believe that this report will have a profound impact on the future of nuclear research in the United States. We cannot impress on you too strongly that whether or not nuclear research is viewed as a viable field by higher level governmental officials will likely be influenced through a reading of this report. Therefore, we urge that the report not be written to convince people within the field, if the case can be made, but to convince science administrators and scientists in other fields that nuclear research is deserving of the federal support levels recommended.

Undoubtedly, the study and preparation of the report will require a large sacrifice on the part of a number of scientists. We appreciate all the effort that will go into this work and we look forward to your advice on these matters.

Sincerely yours,

James E. Leiss
Department of Energy

Marcel Bardon
National Science Foundation

Copy to:
Professor W. A. Fowler
California Institute of Technology