LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

ORNL/M--157

ORNL/M--157

DE86 010007

FUTURE DIRECTIONS
in
INTERMEDIATE ENERGY HEAVY ION PHYSICS
A PROPOSED EXPANSION OF THE HOLIFIELD FACILITY

January 1986

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Date Published: February 1986

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**Cover: The Site of the Holifield Heavy Ion Research Facility with
Proposed Expansion**

The three synchrotron rings of the proposed accelerator facility are drawn to scale in the highlighted area on the cover. The large, 15-Tm, ring encompasses the 10-Tm ring, at the right, and the 4-Tm ring near the center. Existing buildings of the ORNL Physics Division Complex and, at the right, of the Joint Institute for Heavy Ion Research are illustrated beyond the rings. The buildings at the left house the Holifield Facility (the tandem is located in the tower) and offices and laboratories. The small building in the center contains additional offices. Not illustrated are two buildings which are part of the proposed expansion. One building, to be located within the 15-Tm ring, will house the 4-Tm ring and the power supplies for the synchrotrons. A second building located at the right of the 15-Tm ring will be a large, high bay, structure which will serve as an experimental research area.

A site plan for this area is shown in Chapter V in Fig. V.A.1.

Cover design by Vickie Corner

TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENTS	v
I. INTRODUCTION AND SUMMARY	I-1
II. PHYSICS MOTIVATION	
II.A. Physics Overview	II-1
II.B. Nuclear Models for Physics with Intermediate- Energy Heavy-Ion Beams	II-9
II.C. Heavy-Ion Dynamics and Nuclear Matter.....	II-17
II.D. Nuclear Spectroscopy	II-75
II.E. Interdisciplinary Studies and Atomic Physics	II-125
III. THE PROPOSAL FOR OAK RIDGE AS A SITE	
III.A. Overview	III-1
III.B. A Tradition of Heavy-Ion Research — The Early Years	III-2
III.C. Transition to a Users Community	III-6
III.D. The Holifield Facility	III-8
III.E. A Tradition of Equipment Development	III-10
III.F. State and University Roles	III-12
IV. ACCELERATOR SYSTEM	
IV.A. Required Beam Properties	IV-1
IV.B. System Description	IV-7
IV.C. General Synchrotron Considerations	IV-15
IV.D. Injection	IV-18
IV.E. Synchrotron Ring Parameters	IV-26
IV.F. Ring Magnets	IV-50
IV.G. RF Accelerating/Decelerating Systems	IV-55
IV.H. Vacuum System	IV-75
IV.I. Electron Cooling System Requirements	IV-104
IV.J. Stochastic Cooling System Requirements	IV-116
V. FACILITIES	
V.A. Site	V-1
V.B. Buildings	V-3
V.C. Beam Transport	V-10
V.D. Shielding	V-12
V.E. Experimental Facilities Overview	V-19
VI. COST ESTIMATE AND CONSTRUCTION SCHEDULE	VI-1
APPENDIX	A-1

ACKNOWLEDGMENTS

This proposal is based upon suggestions from many members of the ORNL Physics Division Research Staff as well as from numerous outside scientists. The proposal contents have been greatly influenced by the input we received during a Workshop on Intermediate Energy Heavy Ion Physics held in Oak Ridge, September 23-25, 1985. The physics ideas set forth in the invited talks and discussions were instrumental in setting the final parameters for the proposed accelerator. We are very grateful for the suggestions of all our colleagues who have provided input but are too numerous to recognize explicitly. We are also most grateful to those scientists who provided critical review — H. C. Britt (LANL), K. A. Erb (ORNL), J. H. Hamilton (Vanderbilt University), S. E. Koonin (California Institute of Technology), G. A. Leander (ORAU), L. L. Riedinger (University of Tennessee), P. J. Siemens (Texas A&M University), and P. H. Stelson (ORNL). Their efforts have helped create a better and more thorough document.

Members of the Physics Division staff who took responsibility for the writing and editing of major sections of the proposal were:

F. E. Bertrand, Editor
J. B. McGrory, Associate Editor
R. L. Robinson, Associate Editor
J. B. Ball
J. R. Beene
C. E. Bemis, Jr.
D. J. Horen
N. R. Johnson
I. Y. Lee
J. A. Martin
D. K. Olsen
F. Plasil
D. Shapira
G. R. Young

We particularly thank those staff members (non-ORNL affiliation shown in parentheses) who contributed written material for inclusion in this proposal: R. L. Auble, T. C. Ames, C. Baktash, A. B. Balantekin, M. Beckerman (JIHIR), C. Bottcher, B. L. Burks, R. Y. Cusson (Duke University), K. A. Erb, C. W. Glover, J. Gomez del Campo, M. W. Guidry (University of Tennessee), F. K. McGowan, W. T. Milner, F. E. Obenshain, G. K. Satchler, S. P. Sorensen (University of Tennessee), M. R. Strayer, K. S. Toth, C. P. Vane, and C. Y. Wong.

We also wish to recognize others who contributed through engineering and cost estimating: K. D. Cook and B. R. Pietrzak, Martin Marietta Engineering Division, buildings and utilities; S. W. Mosko, Physics Division, magnet power supplies, and rf systems; J. W. Johnson, Physics Division, vacuum systems.

Finally, the proposal could not have been prepared without the talent and hard work of C. R. Wallace, R. T. Webber, A. S. Tate, R. L. Ferguson, A. B. Livingston, and R. W. Miles.

I. INTRODUCTION AND SUMMARY

I. INTRODUCTION AND SUMMARY

This document presents a proposal for a major accelerator addition to the Holifield Heavy Ion Research Facility at Oak Ridge. The expanded facility will provide ion beams of mass 1 to 238 with a combination of energy, intensity, momentum resolution, and beam quality that will not be available at any other facility in North America. Although configured primarily on the basis of heavy-ion performance requirements, the accelerators will provide beams that offer a broad diversity of opportunities for new research in medium-energy light-ion physics, photonuclear physics, nuclear structure physics, atomic physics, and astrophysics. We and our colleagues believe that the scientific program described herein will be central to a major portion of the scientific endeavor in accelerator-based physics over the next two decades.

Heavy-ion physics is a relatively young subfield of nuclear physics, having begun with the development of low-energy heavy-ion accelerators in the late 1960's. As has been the case for the older subfield of light-ion nuclear physics, the trend has been to evolve toward studies utilizing higher energy accelerated projectiles.

The field of heavy-ion physics addresses the fundamental question of the behavior of nuclear matter. The accelerated heavy ion is itself a piece of nuclear matter that, when used to bombard a heavy target nucleus, provides a laboratory in which fundamental properties of nuclear matter can be studied. A truly versatile accelerator facility can change the conditions of the collision so that different measurements can be made to elucidate various properties of nuclear matter.

Furthermore, the sophistication of nuclear particle detection devices available today make possible the observation of extremely rare but particularly revealing nuclear interaction processes, but only to the extent that the beam intensity and beam quality from the accelerator are able to match the technology of the detector and computer analysis systems. The facility proposed in this document addresses directly the need for a heavy-ion accelerator that is designed to match the requirements of the research program presented in this proposal.

An understanding of the properties and dynamics of nuclear matter is fundamental to an understanding of our universe. The cosmological processes that created our universe, and that are continuing to influence stellar evolution, are based upon the behavior of nuclear matter under extreme conditions. Can such conditions be initiated in controlled ways in the laboratory? Can nuclear matter be created at densities several times that of "normal" matter? Can we raise the temperature of nuclear matter orders of magnitude above that of the quiescent state? If we succeed in these endeavors, will we find that nuclear matter undergoes changes of phase? Does it degenerate into a plasma of fundamental constituents? Can we experimentally establish enough of the properties of nuclear matter to be able to write a mathematical expression for the nuclear matter equation of state?

While these questions lie at the heart of the nuclear physics that will be explored with the proposed facility, the facility also provides a versatility that offers new and exciting research possibilities for several subfields of physics.

- **HEAVY-ION PHYSICS** ---- The facility will provide beams of heavy ions of mass through uranium at energies above 500 Mev/nucleon, in all cases, and energies as high as 1500 Mev/nucleon for lighter ions. The high beam intensity, low emittance, and excellent energy resolution that will be available from the proposed accelerators far surpass that available from any existing accelerator for heavy ions in this energy range. It is the combination of these outstanding beam properties that will permit such a thorough physics program as is described in this proposal to be carried out.
- **LIGHT-ION PHYSICS** ---- The proposed accelerator will supply beams of light ions (e.g., deuterons, helium-3, helium-4, lithium) at energies up to 1500 Mev/nucleon. Furthermore, these beams can be delivered at a momentum resolution of 10^{-4} and with exceptional beam quality provided by a second ring to cool the beam. The proposed facility will provide the traditional medium-energy physics community with a capability for reaction studies with composite light particles that cannot be met by any existing or planned accelerator in North America.
- **NUCLEAR STRUCTURE PHYSICS** ---- The energy of the heavy-ion beams from the proposed facility and the intensity of those beams will be high enough to permit the production of exotic, radioactive, secondary beams. Furthermore, these secondary beams may be stored, decelerated and cooled, and used to initiate their own reactions. This capability will permit studies of nuclei not accessible with more conventional techniques. It will also make possible studies of reactions, of particular importance to astrophysical models, that are not accessible by other means.

- PHOTONUCLEAR PHYSICS ---- The extremely large cross section for Coulomb excitation by the high-energy heavy ions from this facility will lead to virtual photon excitation of the nuclear giant dipole resonance that will serve as the basis for a vigorous program in photonuclear physics. The large excitation yields for both isoscalar and isovector resonances will permit detailed studies of decay properties of giant resonances that cannot be done with other techniques.
- ATOMIC PHYSICS ---- The proposed facility will have the ability to provide ions of elements throughout the periodic table with charge states ranging from one to that of the totally stripped ion. Other features important to atomic physics experiments are the ability to cool the beam to very low temperatures, to supply extremely high quality beams, and to decelerate these beams for studies at low laboratory velocities.

The nuclear physics questions to be addressed by this facility cover the transitional region between that described by conventional non-relativistic treatments and the region where relativistic considerations may dominate. Thus, understanding the physics of nuclear reactions involving beams from the proposed facility will almost certainly demand the development of an in-depth understanding of the fully relativistic many-body problem. Among those areas of physics which are highlighted in this proposal are the following:

- A primary thrust of the program on the proposed facility will be to map out the "nuclear equation of state," the bulk properties of nuclear matter at high densities (several times that of normal

nuclear matter) and at temperatures greater than 100 MeV. The range of nuclear matter conditions accessible with this facility crosses many possible phase boundaries. The studies to pursue these ideas will be guided strongly by the pioneering work done at the Bevalac facility at Lawrence Berkeley Laboratory. This work has contributed much in the areas of reaction dynamics and equation-of-state studies to provide the impetus for the next generation of experiments. Only with the high-energy, intense, high quality beams possible with the proposed facility can the intricate correlation experiments that will be required to map out the quantitative features of the "stressed nuclear matter" be carried out.

- Fully stripped ions of nuclei over the entire mass and charge range of stable nuclei will be available with the proposed facility. With these ions, extremely precise tests of quantum electrodynamics can be performed.
- High energy projectiles of high Z will be the source of unprecedentedly intense and clean spectra of virtual photons, so much so as possibly to redefine the field of photonuclear absorption physics. The Coulomb excitation cross sections expected with these beams are extraordinarily large and will provide the means for opening new vistas on the study of giant resonances at high excitations, particularly for isovector states.
- A new frontier of the nuclear topography for exotic isotopes far from beta-stability will be reached in reactions induced by both primary and secondary beams from this facility.

- Experiments conducted on the proposed facility will provide input central to outstanding questions about astrophysical properties of the core matter of neutron stars, of matter in the bounce-off region of supernova, and on neutron capture cross sections for radioactive species which are crucial to a complete understanding of nucleosynthesis.

In this document we present a discussion of the physics that can be studied with heavy ions accelerated to intermediate energies (~ 1 GeV/nucleon), and we propose a major addition to the Holifield Heavy Ion Research Facility, which will provide the means to accomplish such studies.

The basic elements of the proposed facility are three synchrotron rings: a 4-Tm fast-cycling booster ring, a 15-Tm main accelerator ring, and a 10-Tm storage/cooler ring. The existing 25 MV tandem accelerator of the Holifield Facility will provide the initial stage of acceleration for the ion beams. Operating in a macropulsed mode, this accelerator serves as an ideal injector for a wide variety of ions over the full range of the periodic table. The 4-Tm booster ring is designed to accept the ion beam produced by the tandem accelerator and prepare it for injection into the 15-Tm main accelerator ring. The combination of 4-Tm and 15-Tm synchrotrons was chosen to provide the heaviest mass ions with energies in excess of 500 MeV/nucleon at intensities of at least 10^9 particles per second. This same combination provides low mass ions with energies to 1500 MeV/nucleon at intensities over 10^{11} particles per second.

The 10-Tm storage/cooler ring serves a number of purposes. A major function of this ring is to accept the short pulses of beam from the 15-Tm booster and store them for slow extraction, thus providing near 100% duty factor beams. Special equipment in this ring will provide the ability to "cool" the circulating beam to produce beams of extremely high "brightness" and excellent energy definition. The "cooling" of the accelerated ions represents an exciting technical challenge in the design of this facility.

Much of the physics discussed in this proposal will call for experiments that share two requirements of the ion beams: good intensity and good quality. The proposed facility is designed to meet these requirements and to deliver an unprecedented variety of ion species over a very wide range of available energies. The maximum ion-energy performance is shown in Fig. I.1 and compared with other existing and planned facilities. As the figure shows, this energy is similar to that obtained from the present Bevalac facility (Lawrence Berkeley Laboratory), from the upgrade now in progress at Saturne (Saclay, France), and from the SIS-18 accelerator to be built at GSI (Darmstadt, Germany). However, a very crucial comparison is that neither the Bevalac nor Saturne/Mimas will have the beam intensity and beam quality necessary for effective exploitation of the research interests described in this proposal. This point is illustrated in Fig. I.2. From an analysis of beam requirements presented in Section IV.A, one measure of beam quality for the desired performance of an intermediate-energy heavy-ion facility, expressed as the ratio of intensity to emittance, is indicated by the hatched area in the figure. The proposed facility has

Fig. I.1. Comparison of the ion-energy performance of the proposed facility with other facilities either operating or under construction.

Fig. I.2. A comparison of desired performance capabilities with average characteristics of existing facilities.

been configured with beam characteristics to meet these performance goals, while existing facilities fall short by orders of magnitude. Only the facility proposed here and the SIS-18 facility in Germany will allow for an aggressive research effort in intermediate energy heavy-ion physics.

The geographical relationship of the proposed rings to the existing Holifield Facility is illustrated in the sketch on the cover of this report and shown more explicitly in figures included in Chapter V. The present estimate of construction costs for this facility (in FY 1986 dollars with 20% engineering and 25% contingency added) are:

4-Tm booster synchrotron	6.4M\$
15-Tm main synchrotron ring	24.4M\$
10-Tm storage/cooler ring	18.1M\$
Beam transport system	8.2M\$
Buildings, site work, etc.	11.3M\$

Thus, the total estimated cost for the facility is 68.4M\$. Although a detailed estimate has not been developed for new experimental devices, costs of the initial complement of these are estimated at about 10M\$. Annual operating costs for the facility are estimated at 11M\$.

In the body of the proposal which follows, Chapter II is a discussion of the physics motivation for the facility and, in addition to nuclear physics, includes topics in atomic and interdisciplinary areas. Chapter III presents some remarks on the merits of Oak Ridge as a site for this facility and places this proposal in some historical

perspective. Chapter IV is devoted to a description of the accelerators. Chapter V discusses other aspects of the project, including buildings and experimental facilities. Finally, the estimated cost and proposed construction schedule are presented in Chapter VI.

II. PHYSICS MOTIVATION

	<u>Page</u>
II.A. PHYSICS OVERVIEW	II-1
II.A.1. References	II-8
II.B. NUCLEAR MODELS FOR PHYSICS WITH INTERMEDIATE-ENERGY HEAVY-ION BEAMS	II-9
II.B.1. References	II-16
II.C. HEAVY-ION DYNAMICS AND NUCLEAR MATTER	II-17
II.C.1. Evidence for Nuclear Matter Compression in High-Energy Heavy-Ion Collisions	II-20
II.C.2. Pion Production and the Nuclear Equation of State	II-27
II.C.3. Subthreshold Kaon Production and the Equation of State	II-32
II.C.4. Particle-Particle Correlations	II-38
II.C.5. Liquid-Gas Phase Transitions	II-42
II.C.6. Cold Deconfinement	II-50
II.C.7. Heavy-Ion Reaction Dynamics	II-54
II.C.8. Studies of the Properties of Nucleon Excited States in Intermediate-Energy, Heavy-Ion Collisions	II-59
II.C.9. The Giant Dipole Resonance Under Extreme Conditions	II-61
II.C.10. Relation to Total Reaction Cross Section	II-65
II.C.11. References	II-68

	<u>Page</u>
II.D. NUCLEAR SPECTROSCOPY	II-75
II.D.1. Coulomb Excitation of Giant Resonances and the Virtual Photon Field	II-77
II.D.2. Giant Resonance Decay	II-81
II.D.3. Isoscalar Giant Resonances — Singles Measurements	II-83
II.D.4. Isovector Resonances — Singles Measurements	II-88
II.D.5. Charge-Exchange Reactions	II-92
II.D.5.1. Single Charge Exchange	II-94
II.D.5.2. Double Charge Exchange	II-100
II.D.6. Baryonic Resonances	II-102
II.D.7. Transfer Reactions	II-104
II.D.7.1. "Spectral Function" Determination	II-104
II.D.7.2. Inverse (p,2p) Reactions	II-105
II.D.8. γ , β , and Particle Spectroscopy of Nuclei Far from Stability	II-107
II.D.8.1. Very Neutron-Rich Nuclei	II-109
II.D.8.2. Use of Secondary Beams to Produce Exotic Nuclei	II-113
II.D.8.3. g-Factor Measurements Utilizing Energetic Beams	II-118
II.D.9. References	II-120

	<u>Page</u>
II.E. INTERDISCIPLINARY STUDIES AND ATOMIC PHYSICS	II-125
II.E.1. Strong Coulomb Field Quantum Electrodynamics ($Z > 80$)	II-128
II.E.2. Hyperfine Interactions in High-Z, 1-Electron Ions	II-133
II.E.3. Atomic Collision Physics at Ion Energies up to 1 GeV/nucleon	II-138
II.E.3.1. Specific Areas of Atomic Collision Research	II-142
II.E.4. Condensed Crystalline Beams: the "Wigner Solid"	II-154
II.E.5. Production of Elementary Particles in Strong Fields	II-156
II.E.6. Resonant Atomic and Nuclear Coherent Excitations of Channeled Ions	II-162
II.E.7. The Storage Ring as a Recoil Ion Source for Low-Energy, Highly-Ionized Ions	II-164
II.E.8. Astrophysical Plasma Simulation	II-168
II.E.8.1. Atomic Physics Aspects of Astrophysical Plasmas	II-168
II.E.8.2. Nuclear Physics Aspects: Determination of Neutron Capture Cross Sections Using the Inverse (d,p) Reaction and Radioactive Beams	II-169
II.E.9. Selected Applications of High-Energy Heavy Ions	II-174
II.E.9.1. Nuclear Tracks	II-174
II.E.9.2. Testing of Integrated Circuits	II-175
II.E.10. References	II-177

II-1

II.A. PHYSICS OVERVIEW

The outstanding characteristic of the research program that would develop on the proposed accelerator facility is diversity. Much of the program would involve physics dominated by meson-exchange forces, the traditional regime of nuclear physics. A significant part of the program would involve Coulomb-force dominated physics. Finally, very speculatively, the physics may enter a regime where the quark and gluon degrees of freedom are significant.

The richness of the variety of phenomena that might be studied is indicated by the postulated [Si84] nuclear phase diagrams shown in Fig. II.A.1. The state of nuclear matter is specified there by the baryon density and the temperature of the matter, the two axes in the figure. Consider first variations in the baryon density at a fixed, low temperature. At high baryon density, cold matter is composed of a gas of quarks interacting through gluon exchange. As the density decreases, the quarks cluster into hadrons. At some intermediate density, this hadronic matter has a liquid crystal structure, where the "ordering" field is created by the pionic fields. At somewhat lower densities, the pairing force is dominant, and superfluid hadronic matter is formed. Normal nuclear matter hadronic density is 0.17 fm^{-3} . At very low densities, α -clustering occurs, and eventually at ultra-low densities a Bose condensate of α -particles is formed, governed by the Coulomb force. At high nuclear temperatures and very low densities, the "matter" consists of a plasma of quarks, anti-quarks and gluons. As the temperature decreases, hadrons form and, as the temperature continues to decrease,

Fig. II.A.1. Postulated [Si8^d] phase diagram for nuclear matter.

deuterons and alpha particles form until, finally, at super-cool temperatures, an α -condensate is formed. At intermediate temperatures and densities, various mixed phases of nuclear matter can occur.

With beams produced by the proposed accelerator, theoretical calculations indicate that nuclear matter can be formed at densities up to 4-5 times normal nuclear densities [Ma84]. Nuclei can also be heated to very high temperatures, 100 MeV or more [Nz84]. When hot compressed matter is formed in collisions with beams from the proposed facility, it is expected that there will be a time during which the nuclear matter expands to a density below that of normal nuclear matter. Thus, through experimental studies with beams from the proposed accelerator, much of the phase space depicted in Fig. II.A.1 can be probed and a very rich variety of the phases of nuclear matter will be accessible to scientific inquiry.

We have already started to use the language of nuclear hydrodynamics to describe the interaction between two pieces of nuclear matter: the accelerated nucleus and the target nucleus. The validity of this hydrodynamical approach is discussed briefly in Section II.B. For the higher energy part of the physics regime that would be studied with the proposed accelerator, hydrodynamics is the most common language used. In addition to the normal conservation laws (energy, momentum, mass) the fundamental ingredient of nuclear hydrodynamics is the nuclear equation of state, $W(\rho, T)$, which relates the energy density W to the nuclear matter density, ρ , and the nuclear temperature, T . It is the determination of the equation of state for nuclear matter which would be a major goal of the experimental physics program on the

proposed facility. Knowledge of $W(\mu, T)$ would provide a stringent test of fundamental microscopic models of nuclear matter and it would be of inestimable value to astrophysical studies, such as those of supernovae and neutron stars, where nuclear matter at extreme temperatures and densities is achieved "naturally." It would provide new insights into the creation of the elements in our universe.

The beam energies available from the proposed facility span a number of significant thresholds. Some of these thresholds are:

1. Projectile particle energies far exceed the energy of nucleon Fermi motion (~ 30 MeV). For projectile energies below the Fermi energy Pauli blocking prevents many scatterings. The projectile nucleon sees only the average effect of all other nucleons, and specific details of individual nucleon-nucleon scattering are unimportant (i.e., mean-field theories work). As the projectile energies increase above the Fermi energy, blocking is increasingly less important, specific nucleon-nucleon scattering must be treated in detail, and the mean-field is no longer dominate.

2. Nuclear densities 2-5 times that of normal nuclear matter will be formed at elevated temperatures; i.e., hot compressed nuclear matter can be studied. The properties of such matter will provide critically important input to studies of neutron stars and supernovae.

3. The projectile velocities exceed the velocity of sound in nuclear matter, ~ 0.15 c, so that effects of shock waves propagating through nuclear matter might be observed.

4. The thresholds for the production of pions (π 's), kaons (K's), and excited state resonances of nucleons (Δ 's) are passed.

The thresholds for producing π 's, Δ 's, and k 's in nucleon-nucleon collisions are 140, 300, and 1600 MeV in the center of mass frame. With increased heating of the nuclear matter, new degrees of freedom are opened, entropy increases, and new forms of nuclear matter dominated by the free existence of these particles might be formed.

5. With beams from the proposed accelerator, it is very likely that nuclear matter can be formed in a state where the liquid and gas phases coexist. There are predicted experimental signals of this coexistence (for example, the distributions of heavy-ion reaction products as a function of temperature) that can serve to map out the nuclear equation of state at low densities.

6. At 1500 MeV/nucleon projectile energies, the center-of-mass kinetic energies of the projectiles are sizable fractions of the nucleon rest mass, i.e., relativistic effects beyond simple kinematic considerations may be observed. Accurate treatment of such results could require that the theoretical description of the interaction between two nuclei include a full treatment of the relativistic many-body problem.

7. Above 50 MeV/nucleon, the Coulomb interaction provides very large forward angle differential cross section for excitation of both isovector and isoscalar nuclear giant resonances.

8. Somewhat speculatively, at the density of nuclear matter (several times normal) that can be realized in collisions of massive nuclei accelerated to high energies partial deconfinement of quarks may be manifested.

Most of the discussion has to this point dealt with bulk properties of nuclear matter at extremes of temperature and density. However, the proposed accelerator facility will provide the capability for new and unique experimental research in many areas of physics. Heavy ions have been used to expand significantly our understanding of the collective response of nuclei to external fields through the study of giant resonances. The higher energy new beams will allow the study of giant multipole resonances to extend to higher spins and excitation energies than was possible previously. Heavy ions accelerated to ~ 1.5 GeV/nucleon produce large fields of virtual photons -- so large as to become the definitive probe in photonuclear studies. With a variety of high-quality, high-energy beams, the selectivity of charge-exchange reactions will be used to extend greatly the study of spin excitations of nuclei. The beams from the proposed accelerator will be used to produce many new nuclear isotopes of known elements or new elements far from β -stability, and new highly-collective rotational states of nuclei. Experiments with low-energy heavy ions have already pushed back the frontiers in some of these directions. This search will continue in the new regions made available with the beams produced in the proposed new accelerator. The availability of beams at high energies with good intensity and low emittance for an unprecedented variety of accelerated beam species will greatly enhance the search for new phases of nuclear matter. Furthermore, nuclear reactions using radioactive secondary beams produced by the new accelerator could lead to the study of nuclear systems never before available in the laboratory. Some of these new systems would be of particular interest in astrophysics. There are

numerous fascinating studies to be made with the fully stripped or few-electron high-Z systems produced in the proposed accelerator. For example, the Lamb-shift for hydrogen-like uranium would be much larger than those previously measured.

In this brief introduction, we have addressed only a few of the topics to be studied with the proposed accelerator. Many other topics which cover a broad range of physics are discussed below. We discuss first heavy-ion reaction dynamics and nuclear matter. We discuss reactions that might shed the most light on the nuclear equation of state and manifestations of the thresholds outlined above. The experiments discussed there could reveal detailed information on modes of energy deposition and/or dissipation in high-energy collisions. Next we discuss nuclear spectroscopy. Direct reactions and nuclear structure experiments will extend traditional "light-ion" nuclear physics concepts to higher energies and heavier projectiles, and, thereby, provide new detailed information on nuclear shapes at high spin, on giant electromagnetic multipole resonances, and on new modes of collective nuclear response. We also discuss there the production of exotic nuclei and secondary radioactive beams. Finally, we discuss the vast field of new and exotic atomic phenomena, and nuclear physics experiments that have a strong connection with other branches of physics.

II.A.1. References

- C185 F. E. Close, R. L. Jaffe, R. G. Roberts, and G. G. Ross,
Phys. Rev. A 31, 1004 (1985).
- Ma84 J. A. Maruhn and W. Greiner, Treatise on Heavy Ion Science
(Plenum Press, New York, 1984, ed. D. A. Bromley).
- Na84 S. Nagamiya and M. Gyulassy, High Energy Nuclear Collisions,
in Advances in Nuclear Physics 13 (Plenum Press, New York,
1984, eds. J. W. Negele and E. Vogt).
- Sh85 Proceedings of the LAMPF Workshop on Dirac Approaches to
Nuclear Physics, ed. by J. R. Shepard, C. V. Cheung, and
R. L. Boudin, LA-10438 (Conference Proceedings, May 1985).
- Si84 P. J. Siemens, Nucl. Phys. A428, 189c (1984).

II.B. NUCLEAR MODELS FOR PHYSICS WITH INTERMEDIATE-ENERGY HEAVY-ION BEAMS

The beams available from the proposed facility cover a wide energy range from a region dominated by macroscopic models to the region where microscopic cascade models and/or hydrodynamic models are relevant. The highest energies from the proposed accelerator are close to the limit where the nucleon-meson picture of nuclei is relevant. At high energies, the quark-gluon coordinates must be treated explicitly. It is worthwhile to review some of the nuclear models that will be used to describe the experimental measurements over the energy range of the proposed accelerator. This discussion illustrates how the physics is viewed, and points to some of the discrepancies of the theoretical models. Unless otherwise noted, the material in this section is adopted from review articles by Maruhn and Greiner [Ma84] and by Clare and Strottman [Cl85].

At low energies, ~ 10 - 15 MeV/nucleon, the physics of heavy-ion collisions is dominated by the average nuclear potential, and microscopic mean-field theories such as the time-dependent Hartree-Fock (TDHF) theory describe [Da84] much of the heavy-ion reaction data. Pauli blocking at these low energies is very strong and internucleon collisions are rare.

For projectile energies > 50 MeV/nucleon, Pauli blocking becomes weaker, so that more final scattering states are available in a given collision between nucleons in the colliding nuclei. Details of residual two-body collisions therefore increase in importance and collision effects beyond those embodied in the mean field must be treated more

accurately. Extensions of TDHF calculations [Wo79] have been made to include two-body collisions explicitly. To date, these calculations have not been successful. However, considerable progress has been made in the last few years with the Boltzmann-Uehling-Uhlenbeck equation being used to describe heavy-ion collisions at these energies [Ai85, Mo85]. The Boltzmann equation is a classical equation for the one-body distribution function. The Uehling-Uhlenbeck collision integral is included to approximate residual two-body scattering effects. The resulting classical equations are solved by stochastic methods. The model can be connected to the quantum-mechanical TDHF calculations and reproduces the latter results at low energies. First results with collision terms added to describe reactions at intermediate energy are promising. Relativistic effects have not been treated in this approach, to date.

A major justification for this proposed facility involves the use of beams at the highest energies available, up to 1500 MeV/nucleon. It is worthwhile to outline the high-energy models in more detail because the terminology developed will be used throughout the report, and it is the refinement of these models that will be the objective of much of the proposed research program.

We first consider the general question of the need for relativistic and/or quantum mechanical treatments for heavy-ion reactions at beam energies of 1000-1500 MeV/nucleon, energies available from the proposed accelerator.

Relativity - In the center-of-mass reference frame, the kinetic energy of each nucleon in the accelerated ions for the highest-energy projectiles from the proposed accelerator is 500-600 MeV -- roughly half

of the nucleon rest energy. For these energies, $\beta = v/c = 0.8$ and $\gamma = (1-\beta^2)^{-1/2} = 1.6$. To describe heavy-ion collisions at these energies, a fully covariant relativistic theory must be considered. Until now, relativity has been introduced in heavy-ion collisions through geometrical contraction, time dilation, and the use of relativistic kinematics. However, retardation effects have generally been ignored.

Quantum Mechanics - At an energy of ~ 1.5 GeV, the nucleon de Broglie wavelength is ~ 0.1 fm, which suggests that classical models should be valid. The two major types of classical models used for high-energy, heavy-ion physics are the microscopic equation-of-motion models and the macroscopic hydrodynamic models. Partially relativistic versions of both classes of models have been developed.

Classical Equations of Motion - It is now possible to "solve" numerically the classical Hamiltonian for a many-particle system with an assumed classical nucleon-nucleon potential. The major shortcomings of such an approach are: nucleon-nucleon scattering is described poorly by the classical potentials, Pauli effects are ignored, and ground state properties of nuclei are not well described. Such models can include effects due to particle production only crudely. Various approximations within the classical equations-of-motion framework have been implemented. Cascade calculations solve the classical Hamiltonian by Monte Carlo techniques and use nucleon-nucleon cross sections instead of a classical potential. If a "dilute" approximation is made so that each nucleon scattering is treated as a complete scattering in free space, and if these scatterings are treated incoherently,

a Boltzmann equation is reached to describe the single-particle distribution function.

There are means, in principle, to construct relativistic equations-of-motion models, but these treat mesonic effects very inaccurately. The equations-of-motion calculations have had success in describing inclusive particle-production spectra resulting from intermediate energy heavy-ion collisions, and they are very valuable as a model for exact many-body solutions.

Hydrodynamic Models - If, in the interaction of two nuclei, the energy in the interacting region is quickly equilibrated over a large number of participating nucleons, the volume in the interacting region can be treated by classical hydrodynamic equations. Equations that follow from the local conservation of energy, momentum, and mass are then solved. To complete the hydrodynamical approach, an equation of state must be specified. It is the determination of this equation of state that is a principal focus of intermediate-energy heavy-ion physics.

There are three criteria for the validity of hydrodynamics: (1) a large number of particles, (2) a short particle mean-free path, λ_{mfp} , and (3) an equilibration time that is short compared to the total reaction time. For very heavy species (e.g., uranium + uranium), the number of particles is greater than 400 and increases significantly if the bombarding energy is high enough for pion production. In such cases, criterion (1) is moderately well satisfied. At 250 MeV/nucleon, $\lambda_{\text{mfp}} \sim 0.3$ fm, while at 1-2 GeV/nucleon, $\lambda_{\text{mfp}} = 2-4$ fm. Since typical radii for heavy systems ($A = 100-400$) are 5 to 7 fm, the "short mean-free

path" criterion is poorly satisfied. The third criterion is fairly well satisfied. A nucleon-nucleon collision time is on the order of 10^{-24} seconds, and nuclear collision times are generally $> 10^{-23}$ seconds.

In heavy-ion collisions there are factors that may make the use of hydrodynamics more nearly valid. For instance, compression of nuclear matter would decrease the mean-free path, and equilibrium would be more likely. There are some Fermi gas model calculations that suggest that transverse momentum is equilibrated within 2-4 nucleon-nucleon collision times, a relatively short time compared to total collision times.

There is a problem with hydrodynamic models that should be mentioned here. During the decompression stage of the collisions, the particle density will decrease to a point where it is too low for the hydrodynamic picture to be valid. One arbitrarily picks this point, the "freeze-out" point, and uses a different model to extrapolate to final observables. There is considerable arbitrariness in how this procedure is implemented.

To date, relativistic effects have been included in hydrodynamic models in only an approximate way. In relativistic hydrodynamical models currently in use, the hydrodynamic equations are Lorentz transformed to a rest frame, and a relativistic equation of state in that frame is specified. It is entirely possible that a more nearly complete relativistic many-body theory will have to be worked out to understand fully the experiments with beams in the energy regime of 1 GeV/nucleon. Relativistic quantum field theory is the best starting point for an

improved theory. A model hadronic field theory exists [Wa74] and has successfully described many nuclear observables, (static nuclear properties, electron interactions with nuclei, and proton-nucleus interactions). Progress has been made [Cu85] in developing computer algorithms to apply this model to a variety of heavy-ion observables. Some results on collective flow are discussed below. The full development of models that treat relativistic effects more or less completely will be an essential part of the physics program described here.

This brief review of theory is intended mainly to give a picture of the relative uncertainty in the field. The theoretical justifications of the high-energy models are not strong. The application of hydrodynamics and the relatively low-order treatment of relativistic effects are certainly questionable. Much of the early data taken at the Bevalac on reactions with projectile energies at ~ 1 GeV/nucleon was singles-inclusive data (often in coincidence with multiplicity triggers). Most of the existing theoretical "high-energy" models can be tailored to fit these inclusive data. In the last few years more exclusive measurements have been made and these have been very useful to begin refining nuclear models. There is need for highly detailed data, preferably exclusive data from large acceptance experiments that can more clearly distinguish between the many models proposed. The definitive data can be obtained only at a facility such as the one proposed here, where experimenters have access to beams of high energy, high current, low emittance, and high duty factors. Such beams are not available from existing accelerator facilities.

The physics of heavy-ion reactions at projectile laboratory energies from 1000-1500 MeV/nucleon is at a stage where experiment must provide guidance to theory. More fully relativistic models of heavy-ion collisions are being developed. A major program on the proposed facility will be to establish the importance of relativistic effects at these intermediate energies.

II.B.1. References

- Ai85 J. Aichelin and G. F. Bertsch, Phys. Rev. C 31, 1730 (1985).
- Ca85 Y. Casagnou, private communication.
- Cl85 R. B. Clare and D. Strottman, Los Alamos preprint LA-UR-85-3692.
- Cu85 R. Y. Cusson, P.-G. Reinhard, J. J. Molitoris, H. Stöcker, M. R. Strayer, and W. Greiner, Phys. Rev. Lett. 55, 2786 (1985).
- Da85 K.T.R. Davies, K.R.S. Devi, S. E. Koonin, and M. R. Strayer: Treatise on Heavy-Ion Science, Vol. 3, p. 3, ed. D. Allan Bromley (Plenum Publishing Corporation, New York, N.Y., 1985).
- Ma84 J. A. Maruhn and W. Greiner, Treatise on Heavy Ion Science (Plenum Press, New York, 1984, ed. D. A. Bromley).
- Mo85 J. J. Molitoris and H. Stöcker, Phys. Rev. C 32, 346 (1985).
- Wa74 J. D. Walecka, Ann. Phys. 83, 491 (1974).
- Wo79 C. Y. Wong and H.H.K. Tang, Phys. Rev. C 20, 1419 (1979).

II.C. HEAVY-ION DYNAMICS AND NUCLEAR MATTER

A primary goal of the proposed accelerator facility is to learn about the bulk properties of nuclear matter under extreme conditions of density and temperature, and to map out in some detail the nuclear equation of state for nuclear matter densities up to 2-5 times normal nuclear matter density and for temperatures up to 100-150 MeV. In this section, we focus primarily on this topic, and on what can be learned about the bulk nuclear properties from heavy-ion reactions using intermediate to high energy projectiles ($50 < \text{MeV/nucleon} < 1500 \text{ MeV}$), over the full range of impact parameters. For brevity, we do not discuss a number of topics of great current interest in low-energy heavy-ion physics -- heavy-ion fusion, deep-inelastic and quasi-elastic reactions, subthreshold pion production, etc. The field of low-energy heavy-ion physics continues to reveal new insights into the behavior of nuclei and many of these research areas would be extended with the availability of the proposed facility.

Much of our present understanding of intermediate-energy heavy-ion physics is expressed in terms of geometrical participant-spectator models of nuclear reactions, and since much of our discussion will use the same language, a qualitative description of this concept is appropriate. Consider a collision between a projectile ion and a target ion occurring at an impact parameter such that there is an interaction region where the two ions overlap. In the laboratory system, throughout the reaction all matter moves in a straight line in the initial direction of the projectile ion. The parts of the

projectile and target ions that do not overlap are referred to as "spectator" regions, while the parts that do overlap are assumed to form a thermally equilibrated "participant" region. After a collision, in the laboratory system, the target spectator fragment remains essentially at rest with a low energy, and the projectile spectator fragment moves at a velocity close to the initial projectile velocity with an excitation energy somewhat higher than that of the target spectator. The nuclear matter in the participant region is at high density and high temperature and moves at a velocity which is a fraction of the initial projectile velocity. It is the participant region that is the source of information on nuclear matter in extreme conditions.

The size of this hot participant region varies with the impact parameter of the initial collision. For equal mass ions at zero impact parameter, the participant region involves all the projectile and target nucleons. It is this case in which the highest densities and temperatures are expected to be created, and so these central collisions are of primary significance. It is important for many experiments that a reliable measure of impact parameter be available to serve as primary "trigger" to select events for more detailed analysis. Central collisions should be the most violent, and large numbers of particles should be produced in such collisions. It has now [Sa80] been established that the highest charged particle multiplicities can be correlated with central collisions, and this charged-particle multiplicity trigger is widely used. Similarly, decreasing multiplicity can be correlated with increasing impact parameter. The spectator-participant picture and the use of charged-particle

multiplicity as an analysis trigger are powerful tools with which to search for new information on nuclear matter.

We deal in this section with the creation of areas of hot, dense nuclear matter, with the determination of the size and temperature of these areas, with the determination of heavy-ion collision times, and with the possible observation of transitions between different phases of nuclear matter. We do not present in-depth discussions of all these topics, but we suggest the potential excitement of the physics that could be studied in quantitative detail for the first time with the proposed accelerator.

Much of what has been learned (and discussed below) about hot, dense nuclear matter has come from experiments at the Bevalac, a "large-cross section" facility. The experiments designed to explore the questions set forth in this discussion will inevitably be small cross section experiments, often involving correlation measurements. At a minimum, they will require the use of 4π -detectors to record information that will characterize the general features of a given reaction, as well as single or double-arm spectrometers. Many of these experiments will be possible only with beams of high intensity and 100% duty factor.

- With the availability of low emittance beams it will be possible to maximize the acceptance of the spectrometers for a given volume of detector. Thorough study of the new fascinating possibilities suggested by recent Bevalac work can only go forward at a productive rate with a facility such as is proposed here.

II.C.1. Evidence for Nuclear Matter Compression in High-Energy Heavy-Ion Collisions

There is evidence suggesting that hot high-density nuclear matter is formed in heavy-ion collisions with projectiles accelerated to energies similar to those which would be available from the proposed accelerator. Cascade calculations predict [St82] that high density nuclear matter will be formed and that the pion production rate will be a maximum at the peak of compression of the interacting matter. Pion production in $^{40}\text{Ar} + \text{KCl}$ collisions at energies from 400-2000 MeV/nucleon has been studied [Na84]. The pion multiplicity increases with increasing bombarding energy to the point where pions dominate the particle production multiplicity. The energy spectra of pions produced in the reaction $\text{Ne} + \text{NaF}$ has been measured for neon beams at incident energies between 180 MeV/nucleon and 2 GeV/nucleon. Under the assumption that particles are emitted from a thermally equilibrated source, a source temperature is extracted for the pions as seen in Fig. II.C.1. The deduced temperature of the pion source ranges up to 100 MeV. These findings are consistent with the development of a dense hot region of nuclear matter where pions and deltas in "chemical" equilibrium are produced copiously.

There is recent evidence [Gu84] of collective flow of nuclear matter in high energy nucleus-nucleus reactions. A signature of a compression effect predicted by hydrodynamics would be a collective flow of matter all in a given direction during expansion, what is popularly called a "bounce-off". The experiment involves measuring the momenta of all charged particles in a high-energy collision

Fig. II.C.1. Spectra of π^- 's produced at 90°_{cm} in Ne + NaF collisions at four laboratory projectile energies. The four spectra, from top to bottom are for 2.1 GeV/nucleon, 0.8 GeV/nucleon, 0.4 GeV/nucleon, and 0.18 GeV/nucleon, respectively. E_0 's are the source temperatures extracted from the spectral slopes [Na84].

between heavy ions. A signature of the collective flow can be found by calculating and diagonalizing the so-called sphericity, or kinetic flow tensor

$$F_{ij} = \sum_{\nu} p_i(\nu)p_j(\nu)/2m(\nu), \quad (\text{II.C.1})$$

where ν labels a given particle detected in an event and $p_i(\nu)$ is the momentum in the i -th direction (either parallel or transverse to a given incident direction), and $m(\nu)$ is the mass of the particle labeled by ν . If all particles in a given collision can be detected and if this tensor can be constructed and diagonalized, a set of principal axes which characterizes the final momentum flow of nuclear matter is then defined. (The usual assumption is that the neutral particles behave approximately as do the charged particles.) The angle between the direction of maximum momentum flow and the beam axis defines a flow angle. Figure II.C.2 summarizes the experimental results, extracted from experiments on Nb+Nb at 400 MeV/nucleon, for the flow angle, along with typical predictions of cascade and hydrodynamical model calculations. The cascade calculations predict a small flow angle; i.e., no bounce-off. The hydrodynamical calculation predicts a non-zero flow angle with a distinct dependence on impact parameter, i.e., a maximum bounce-off for small impact parameters. The hydrodynamical predictions agree well with the experiment. This result strongly suggests that at 400 MeV/nucleon the hydrodynamic models are valid. It is true, however, that cascade models can be developed that also reflect the flow angle data.

Fig. II.C.2. Flow angle (see text) of emitted charged particles observed in Nb+Nb collisions at 400 MeV/nucleon and calculated values of flow angles as a function of impact parameter from representative cascade and hydrodynamical calculations. M_c labels charged particle multiplicity [Gu84].

A third possibility, the Walecka relativistic mean field model, has recently been used [Cu85] to calculate the flow angle in the collision of $^{16}\text{O} + ^{16}\text{O}$ at 600 MeV/nucleon at impact parameters of 1-2 fm. The model accounts for relativistic effects in that it is correctly time dilated and Lorentz contracted, includes retarded interactions, and propagates covariantly a system of many Dirac spin-1/2 particles. The results for the calculations of the collective flow angle are shown in Fig. II.C.3, where similar calculations in the Vlasov-Uehling-Uhlenbeck (VUU) model are also shown. This figure shows only a comparison of theories. The relativistic mean field calculation (with no collisions) shows a non-zero flow angle (reflected by the non-zero mean value of the transverse momentum, k_y) of a considerable magnitude, distinctly larger than the VUU calculations (with collisions). The flow angle in the relativistic calculation results from a sensitive, time-dependent cancellation effect between large vector and scalar potentials. The Walecka model calculation offers an alternative picture of these "bounce-off" reactions with a clear connection to a fundamental interference effect. This is one example of the potential importance of this energy region to study the onset of relativity in many-body nuclear physics.

There remain many open questions: is the observed bounce-off effect a collective, compressional effect; does it arise from details of the nucleon-nucleon cross sections as used in cascade calculations; or is it a reflection of relativistic dynamics? There are many ambiguities in and between the various models, and experiments will have to be designed to resolve these.

Fig. II.C.3. Calculated [Ca85] mean transverse (k_y) momentum as a function of longitudinal momentum (k_z) for $^{16}\text{O} + ^{16}\text{O}$ ions at 600 MeV/nucleon center-of-mass energy. Curves for $b = 1$ fm and $b = 2$ fm are results for near central collisions as calculated in a relativistic mean field approximation. VUU is the result calculated in Vlasov-Uehling-Uhlenbeck approximation.

The experiments will utilize a wide range of projectile and target masses, particularly for projectile energies > 1 GeV/nucleon, where relativistic effects become increasingly important.

II.C.2. Pion Production and the Nuclear Equation of State

The measurement of pion multiplicities in high energy nucleus-nucleus collisions has been used [St82, Ha85] to deduce the nuclear equation of state for nuclear matter densities far above the ground state densities. In a high energy nucleus-nucleus collision, after the nuclei interact, there is a period during which nuclear matter is compressed to a maximum density and/or raised to a maximum temperature, followed by a period when the matter expands to a rarified density, and then to the final state. Thus the density of nuclear matter changes throughout the reaction, while information is desired on the nuclear equation of state for various fixed densities. It is argued that the number of pions produced in a given collision is a direct measure of the maximum density achieved during the reaction. The argument is as follows. The nucleus-nucleus pion production cross section is a strong function of the relative energy of the colliding nucleons. The kinetic energy from the incident beam is degraded during the expansion phase. Cascade calculations suggest that the number of pions and deltas remains constant during the decompression stage and reflects the number produced at the time of maximum compression. Cascade calculations have successfully reproduced pion production in proton-nucleus collisions at 1-2 GeV proton energy. However, in experiments such as Ar+KCl at projectile energies of 1000-1800 MeV/nucleon, the pion production yields are consistently lower than those predicted in the cascade models. If it is assumed that the cascade models accurately predict the pion production for a given amount of thermal energy, the discrepancy between cascade

model calculation and experiment indicates that thermal energy is lost to potential or compressional energy. The projectile energy needed to reproduce the experimental pion yield can be calculated. The difference between the calculated energy and the experimental energy is then the compressional energy. By combining these "experimental" compressional energies with calculated densities, one can construct an equation of state $W(\rho, T=0)$ such as shown in Fig. II.C.4. (This involves an assumption that the temperature dependence of $W(\rho, T)$ is small and negligible at the temperatures realized in these experiments.) With the commonly used parabolic assumption for the energy-density equation of state, i.e.,

$$W(\rho, T=0) = \frac{K}{18\rho_0^2} (\rho - \rho_0)^2, \quad (\text{II.C.2})$$

the best fit value of the compressibility of nuclear matter, K , is found to be 250 MeV. This value can be compared to several others. A value of $K \approx 200$ MeV is consistent with the measured [Be81] energy of the isoscalar giant monopole resonance and calculations [Ba85] of properties of supernova seem to imply a value of $K \approx 100$ MeV. Comparison of data on flow angles (see Section II.C.1.) with calculations [Mo85] in the Boltzmann-Weiling-Uhlenbeck model (mean field + collisions) suggest $K \approx 280$ MeV. This type of analysis suggests that nuclear matter at normal nuclear densities is softer than at the higher densities formed in high-energy collisions and that the simple parabolic parametrization of the equation of state is not valid over a large density range.

The parabolic approximation for the equation of state has been widely used for properties of nuclear matter near the ground state density and temperature. There is no firm theoretical basis for this

ORNL-DWG 85-18980

Fig. II.C.4. Semiempirical energy-density equation of state. The shaded area represents the equation of state dependence extracted from π -production experiments. The circles along the curve labeled FP represent the equation of state extracted from data on supernovae. The curves are various theoretical estimates of the equation of state [Sa85, Fr81, Bo83].

approximation, at higher densities (or temperatures). There are a number of theoretical calculations of the equation of state shown in Fig. II.C.4, and the calculations vary by at least as much as do the "experimental" numbers. The calculated curves include those using relativistic models [Bo83], microscopic models [Fp81], and conventional hydrodynamic calculations [Sa85]. This interpretation of the pion data is still very controversial as is discussed in the next section. It is clear that if this type of experimental data and analysis can be refined and extended, it will provide a strong indication of the correctness of the assumptions of the various theoretical models. The experiments should be extended to the heaviest possible systems of colliding nuclei to increase the volume of high density nuclear matter. The data in Fig. II.C.4 for densities $\rho < 2$ are suggested by calculations of supernova properties. It would be of great interest to obtain data in this region from the "pion thermometry" experiments for the largest systems possible at energies from 100-300 MeV/nucleon. The independent measurement of π^+ , π^- , and π^0 production cross sections would significantly refine this "pion thermometry" method. (Such measurements are required when the target $T_Z \neq 0$, as is always true for heavy systems. In such cases, one cannot assume $N_{\pi^+} = N_{\pi^-} = N_{\pi^0}$.) The proposed accelerator facility would produce uranium beams at an intensity ($\sim 10^9$ particles/sec) that is several orders of magnitude larger than that of any presently available uranium beams at these high energies, so that the desired experiments with heavy beams would become practical. The refined experiments in this field will involve 4π detectors to characterize reactions in

coincidence with spectrometers. Again, the beam quality, intensity, and duty factor of the proposed accelerator facility are essential for such experiments.

II.C.3. Subthreshold Kaon Production and the Equation of State

The validity of the analysis discussed in the previous section of pion production rates to determine the nuclear equation of state has been questioned [Be84, Kr85]. The pions, because they are strongly interacting particles, are influenced by final-state interactions during the expansion period that follows the initial nuclear compression in heavy-ion reactions. Microscopic calculations [Be84, Kr85] that include the mean field and residual nucleon-nucleon collisions and/or blocking do not display a very strong dependence of pion production on the equation of state. For example, in [Kr85], for two equations of state which yield compressibilities of $K = 200$ MeV and $K = 375$ MeV, the π^- yields are 2.45 and 2.13, respectively. The situation is different for kaons because their interactions with nucleons are much weaker. Furthermore, because kaons have strangeness +1, they cannot be reabsorbed by the nucleus. For these reasons, kaon production rates may be more sensitive to the nuclear equation of state than are pion production rates. Using the Boltzmann-Uehling-Uhlenbeck model of heavy-ion collisions, it has been shown [Al85a] that for central collisions between heavy nuclei at incident energies around 700 MeV/nucleon, the number of kaons produced differs by a factor of two to three for different forms of the equation of state. Thus, the sensitivity for kaons is an order of magnitude larger than for pions, and the sensitivity appears at energies below the threshold for kaon production. The model includes both the mean field and Pauli-blocking, and uses published kaon production cross sections. The excitation of

nucleons to delta-resonances is also included. Two postulated equations of state are used:

$$\text{Stiff: } W(\rho, T=0) = -62(\rho/\rho_0) + 23.5 (\rho/\rho_0)^2 \text{ MeV}$$

$$\text{Soft: } W(\rho, T=0) = -178(\rho/\rho_0) + 140(\rho/\rho_0)^{7/6} \text{ MeV}$$

These give nuclear compressibility $K = 380 \text{ MeV}$ and $K = 200 \text{ MeV}$, respectively.

In Fig. II.C.5 the total kaon production probability, P_K , is shown as a function of the collision time for collisions of Nb + Nb at an impact parameter $b = 0.5 \text{ fm}$ and a projectile energy of 700 MeV/nucleon . The solid curve is obtained by using the soft equation of state, while that from the stiff equation of state is denoted by the dashed curve. Also shown in the same figure are the values (ρ/ρ_0) of the central density, ρ , in units of the normal nuclear matter density, ρ_0 , as a function of the collision time. The curve with open squares is from the soft equation of state while the curve with open circles is from the stiff equation of state. The maximum density reached in the collision is calculated to be higher for a soft equation of state than for a stiff equation of state. In both cases, kaons are produced in the compression stage by the time the density has reached its maximum value of $(2-3)\rho_0$. The calculations indicate that most kaons are produced from deltas that result from nucleons that have already undergone a few collisions.

The calculations predict that, during the expansion stage of the reaction, there are essentially no kaons produced. Thus P_K is a good measure of the density of nuclear matter when the density is a maximum. Table II.C.1 shows the total kaon production probability for

Fig. II.C.5. Calculated [Ai85a] values of normalized central density (ρ/ρ_0) and P_K , the probability for kaon production, as a function of time for the collision of Nb + Nb at 700 MeV/nucleon and an impact parameter $b = 0.5$ fm.

Table II.C.1. Kaon production probability P_K for collisions between nuclei with mass number A at an incident energy 700 MeV/nucleon and at an impact parameter $b = 0.5$ fm. Results from both a soft and a stiff equation of state are shown. The ratio between the two is given by R .

A	$P_K(\text{soft})$	$P_K(\text{stiff})$	R
20	8.8×10^{-5}	5.2×10^{-5}	1.7
40	3.2×10^{-4}	1.3×10^{-4}	2.5
93	2.0×10^{-3}	7.0×10^{-4}	2.8

central collisions between various symmetric systems at an incident energy of 700 MeV/nucleon. For both equations of state, the kaon production probability P_K increases with the mass number A of the colliding nuclei. The ratio, R , of $P_K(\text{soft})/P_K(\text{stiff})$ also increases as the system becomes heavier. For collisions of Nb + Nb at 700 MeV/nucleon, an impact-parameter-averaged cross section of 0.89 ± 0.04 mb and 0.46 ± 0.03 mb are predicted for the soft and the stiff equation of state, respectively. Calculations at a lower beam energy of 650 MeV/nucleon show a reduction of the kaon cross section by a factor of 2 but leave the ratio, R , essentially unchanged. This ratio becomes smaller for calculations at a higher beam energy of 800 MeV/nucleon. These results indicate that subthreshold kaon production is sensitive to the equation of state, and that the kaons are produced at the time of maximum density. The calculations suggest that the strongest sensitivity is for the most massive systems at projectile energies in the range 500-800 MeV/nucleon. Count rates for the detection of K^+ 's in a single-arm experiment have been estimated under the assumptions of a 1 mm thick Au target, a spectrometer of acceptance 10^{-3} and a production cross section of 0.1 mb. A beam of 6×10^7 ions/sec yields 1000 counts in one 8-hour shift. A beam of 5×10^9 ions/sec would allow the detection of a 1 nb cross section. Some studies of kaon production have been carried out [Sn82] at 2.1 GeV/nucleon. The results are reproducible with cascade calculations and without use of an equation of state. This is consistent with the calculations [A185a] discussed here, i.e., the sensitivity of kaon

production rate to the equation of state decreases above 800 MeV/nucleon. The proposed accelerator with its ability to accelerate the heaviest ions to 500 MeV/nucleon with an intensity of $\sim 10^9$ ions/sec is well suited for measurements of strange particle production rates.

II.C.4. Particle-Particle Correlations

One of the most fundamental goals of intermediate energy heavy-ion physics is the characterization of localized interaction regions in reactions between two heavy ions in terms of such properties as temperature and density. Only when this is done will it begin to be possible to provide experimental data to quantify the phase diagrams of nuclear matter that play such a large role in our speculative discussions. Unfortunately, the problem of relating such quantities as temperature and density to experimental observables remains an extremely difficult and controversial one.

One established tool that should become even more important as high-intensity intermediate-energy facilities become available is particle-particle interferometry (the Hanbury-Brown-Twiss (HBT) effect) [Hb56, Ko74, Ya74, Ko77]. This technique provides information on the space-time extent and coherence of the source from which the particles are emitted. A two-particle correlation function, $R(p_1, p_2)$, is constructed from the singles and coincidence cross sections for the particles. The most important information is extracted from data taken at small relative momenta $\Delta p = |\vec{p}_1 - \vec{p}_2|$. High-energy heavy-ion collisions produce very large yields of identical particles ($\pi\pi, pp, \gamma\gamma$), and such collisions are, therefore, ideally suited for the exploitation of this method.

A number of experiments on (pp) and ($\pi^+\pi^-$) correlations have been carried out (e.g., [Za81, Be83]). Generally, the results from (pp) correlations indicate a source size for emission of the protons, R , of

2-3 fm, while ($\pi\pi$) correlations yield a size of 3-4 fm. It was also observed that the apparent source temperature for the pions is lower than for protons. These two results have led to the conjecture [Na82] that the proton correlations are characteristic of an earlier stage in the reaction than is the case for pions (the "sequential freeze out" picture). This plausible interpretation is questioned by recent (pp) results [Gu84] which appear to agree with the pion results, rather than with the earlier proton work.

The analysis of both pp and $\pi\pi$ correlations is complicated by strong final-state interactions. Furthermore, the sensitivity to the early stages of the reaction is limited by the large probability that the protons or pions will interact with surrounding nuclear matter after emission from the hot region. Consequently, there is great interest in correlation experiments that utilize more weakly interacting probes (gammas and kaons, for example). Kaon correlation experiments will be extremely difficult because of the relatively low subthreshold yield. (The NN process which gives rise to a K at the lowest NN energy is the $NN \rightarrow N\Lambda^0 K^+$ with a 1.6 GeV threshold.) Such experiments would be extremely interesting and could greatly supplement our knowledge of subthreshold production mechanisms in heavy-ion reactions.

Gamma-gamma correlation experiments (the real HBT effect) have at least two great virtues. The photons suffer no final-state interactions and no interactions with nucleon remnants on the way out of the hot central interaction region. In addition, the photons couple to well-defined, well-understood, currents which makes the comparison with

theory much less ambiguous. Yields may again pose some difficulty since high-energy photons (~ 100 MeV) must be used if good spatial resolution is to be obtained.

As discussed below, bremsstrahlung photons carry information on the time dependence of the stopping process as one nucleus collides with another. It has been pointed out [Ko85] that the magnitude of the correlation function at zero relative momentum, obtained from these gamma rays, carries information about the relative contribution of coherent and incoherent bremsstrahlung. This example illustrates one of the general and most powerful aspects of the correlation technique - the determination of the extent, if any, of the coherence of the emitting source. In systematic studies of the nature of the participant region (or fireball), and of its subsequent freezeout, such information may be of equal interest to the space-time properties that are usually emphasized.

At the highest beam energies, very high particle multiplicities are expected from reactions between very heavy projectiles and heavy targets. Under such conditions, a new approach to interferometry, called speckle interferometry, may be appropriate. (The name "speckle interferometry" is derived from optical studies and refers to the appearance of "speckles" when coherent light is scattered from a rough surface.) It was pointed out [Wi84] that the standard two-particle correlation method is applicable to situations where the probability of two particles occupying the same small volume of relevant phase space is negligible. However, at high multiplicities, it is not desirable to

neglect information contained in correlations between more than two particles. The experimental approach requires full azimuthal coverage, but momentum resolution requirements may be less stringent than in the two-particle correlations. The method involves the study of the statistical significance of clustering as expressed by means of a correlation function obtained from measurements of the power density for a fixed particle energy (or wavelength). The results can be expected to yield information on the actual shape of the source (e.g., is it spherical, pancake-shaped or pear-shaped) and, possibly, on the interrelationship between its time and space properties. It is possible that this approach may open up a whole new field of investigation.

In summary, measurements of source size using particle-particle interferometry should provide important information about collision geometry and dynamics and should also provide necessary input for the estimation of the nuclear matter densities produced in heavy-ion collisions. Thus, with temperatures deduced from other experiments, it will be possible to begin to map out reaction dynamics as a function of density and temperature of nuclear matter.

II.C.5. Liquid-Gas Phase Transitions

With the availability of heavy-ion beams in the energy range from 10-1500 MeV/nucleon, nuclei will be formed with properties that fall in many parts of the nuclear matter phase space (Fig. II.A.1), and it might be expected that the nuclei formed would go through phase transition regions. For example, a nuclear matter liquid-gas phase transition might occur during the expansion of a heated nucleus formed in a heavy-ion collision [Si84]. As a liquid is heated, it passes through a phase in which bubbles of gas form in the liquid, or as the gas is cooled, there is a point where liquid drops of various sizes co-exist with the gaseous state. From the shape of the equation-of-state curve, it can be predicted that there will be phase mixtures in nuclear matter under some conditions. Figure II.C.6 shows an equation of state for nuclear matter where pressure is plotted as a function of nuclear matter density for several different nuclear temperatures. At low temperatures, the "molecules" of the nuclear "fluid" are the neutrons and protons. The nucleon-nucleon interaction is repulsive at very short ranges but becomes attractive at intermediate ranges. At very low density there is a positive thermal pressure for all values of temperature. As the density increases and average "molecular" spacings become smaller, the nucleons feel attraction from the intermediate-range nuclear force, and the pressure decreases. At higher densities, the Fermi-gas kinetic energy and the short-range repulsion between nucleons become dominant, and the thermal pressure increases. The nucleon-nucleon attraction thus produces a minimum in the equation of state at

Fig. II.C.6. Pressure-density equation of state as a function of temperature [Sc81].

low temperatures. Because of this minimum there are points on the equation-of-state curves where the pressure is equal at two different densities. At these points, the fluid can undergo a transition to a mixture of the liquid and gas phases that minimizes the thermodynamic potential while maintaining constant temperature, pressure, and chemical potential. For higher nuclear temperatures, the calculations plotted on Fig. II.C.6 show that the thermal pressure washes out the effects of the attractive part of the nucleon-nucleon force, and there is no minimum in the equation of state. The critical temperature, T_c , is that temperature where there is no longer a minimum in the phase diagram. In a liquid-gas mixture of nuclear matter, expressions have been worked out for the relative probability of finding a nuclear "drop" of mass A as

$$P_A \approx -\exp[-(G_V - G_G)A + \sigma \Sigma(A) + KT \ln A]/T], \quad (\text{II.C.3})$$

where G_V and G_G are the Gibbs free energy per particle in the liquid and gas phases, σ is the surface tension of the liquid drop, $\Sigma(A)$ is the surface area of the drop,

$$\Sigma(A) = 4\pi r_0^2 A^{2/3}, \quad (\text{II.C.4})$$

and T is the nuclear temperature. The derivation of (III.C.3) involves an assumption that the drop of size A is large enough to allow a liquid-drop model expansion of the droplet energy. The expression for P_A can finally be written as

$$P_A \approx A^{-K} \exp(-b(T)A^{2/3}), \quad (\text{II.C.5})$$

where

$$b(T) = 4\pi r_0^2 (T)\sigma(T)/T, \quad (\text{II.C.6})$$

and K is a temperature independent parameter that can be extracted from

measurements of fragment distributions (see below). There are reasonably reliable methods to calculate $r_0(T)$, so a measurement of $b(T)$ is a measurement of $\sigma(T)$. If nuclear systems are formed at temperatures near the critical temperature where there is a liquid-gas mixture, and if the mass distribution, P_A , of fragments emitted in the heavy-ion reaction can be extracted from experimental measurements, then the surface energy $\sigma(T)$ of nuclear "liquids" at elevated temperatures can be measured. In Fig. II.C.7, calculated values of P_A as a function the mass (A) of the emitted fragment are plotted for several ranges of T . One striking prediction from the calculations shown on the figure is that the ratio $\ln P(A=20)/\ln P(A=10)$ increases to a maximum value as $T \rightarrow T_C$. This prediction is in contrast to our intuitive picture (away from critical phenomena) of vaporization with increasing temperature, or equivalently, large fragments breaking into small fragments as the temperature increases. The predicted trend is a general feature of long-range properties associated with critical phenomena.

In addition to the intrinsic interest to nuclear physics and the many-body problem, these temperature-dependent surface energies (e.g., $\sigma(T)$) are of critical importance to studies of matter created at the bounce-off stage of supernova evolution, where it is believed that the heavy, $Z > 26$ (iron), nuclei are created.

There are well-defined ideal conditions for studies of liquid-gas phase transition of nuclear matter:

- 1) The critical temperature is ~ 20 - 25 MeV, which implies projectile energies of ~ 100 MeV/nucleon.

Fig. II.C.7. Fragment distributions in a liquid-gas mixture for representative temperatures above and below the critical temperature [S183].

- 2) The projectile and target should each be large systems which collide at small impact parameters.

These criteria maximize the probability of forming a large, equilibrated volume of nuclear matter. The large systems also make a liquid-drop model more likely to be appropriate.

This liquid-gas analysis has been applied already to data on several proton-nucleus and nucleus-nucleus reactions where P_A has been measured for nuclear fragments in the range $6 < A < 28$. At the critical temperature, T_c , the surface energy, $\sigma(T_c)$ vanishes, and it can be seen from equation II.C.5 that the leading term of P_A , A^{-K} , yields a simple power law. At temperatures away from T_c , the mass yields are determined by the exponential term in equation II.C.5.

A summary of some of the data is given in Fig. II.C.8 for the following systems: $p + Ag$ at $E_p = 480$ MeV (crosses [Gr84]), $^{12}C + Ag$ (squares [Ch83]) at $E(^{12}C) = 360$ MeV, $p + Xe$ (x's [Hi84]) at $E_p = 80$ to 350 GeV, $^{20}Ne + Ag$ (circles [Ca85]) at $E(^{20}Ne) = 1$ GeV, and $^{20}Ne + Au$ (diamonds [Wa83]) at $E(^{20}Ne) = 42$ GeV. Plotted in Fig. II.C.8 are the experimental multiplicities M , defined as $M = \sigma_Z / \sigma_t$, where σ_Z , the cross section for a fragment with charge Z , has been obtained from the given references and σ_t is the total geometrical cross section calculated with the parameters given in [Wi80]. The solid lines drawn through the data are the results of the least squares fit of the power law Z^{-K} with the values of K indicated for each curve. As can be seen, the exponent changes from 3.24 at the lowest energy (crosses) to 2 at the highest (diamonds). This strong variation in K indicates that the critical temperature has not been reached in these experiments. A possible first

ORNL-DWG 85-18979

Fig. II.C.8. Charge distribution of fragments produced in reactions indicated in the legend. The extracted power law dependence, K , is discussed in the text.

indication of a critical temperature effect can be seen by comparing the multiplicities between the $p + \text{Xe}$ (Δ 's) and $^{20}\text{Ne} + \text{Ag}$ (circles), which are nearly identical in spite of the fact that there is a tremendous difference in the available center-of-mass energy. (It is important to point out that the cross sections measured by the group in [Hi84] are essentially constant from 80 to 350 GeV.) There are still very significant ambiguities in these analyses, particularly with regard to the extraction of the source temperature T .

With the availability of higher-quality and higher-energy beams from the proposed accelerator, it will be possible to start a more detailed study of these problems. One approach will certainly be to refine the measurements of temperature by studying particle-particle correlations in the decay of excited fragments [Mo84, Po85]. The correlation experiments will require high duty factors, and the detectors used in such experiments generally have very small acceptances. Therefore, the ability of the proposed facility to generate high current, well-focused beams of high mass and easily varied energy is an essential prerequisite to the performance of such experiments.

II.C.6. Cold Deconfinement

We next come to a particularly speculative concept, the formation of large volumes of deconfined quark-gluon matter in intermediate-energy heavy-ion collisions. The quark-gluon model of QCD is recognized as the best description of the internal structure of the nucleon, and it is therefore natural to look for conditions under which nuclear matter might make the transition to this form of plasma (see Fig. II.A.1). Many careful estimates of the deconfinement temperature converge [Sa85a] on a temperature of about 200 MeV which is believed to require a center-of-mass collision energy of 3 to 6 GeV/nucleon for heavy-ion reactions with colliding beams, clearly outside the energy range of the current proposal.

A very speculative calculation of the deconfinement transition region vs temperature and density is shown in Fig. II.C.9. The value of 200 MeV for nuclear temperature at normal nuclear matter density is actually inferred from the $A = 2$ united system, e.g., from baryon-baryon scattering. For the purpose of the curve on Fig. II.C.9, the density of the $A = 2$ system is considerably below the density of cold nuclear matter. The value of the density at which cold deconfinement might occur is highly uncertain and is arrived at using rather speculative model assumptions. The lack of experimental data for very heavy united systems leaves a possibility that, in uranium+uranium collisions at laboratory projectile energies as low as 50 to 250 MeV/nucleon, densities more than double that of cold nuclear matter could be reached. For quark deconfinement purposes this could be already as much as 10 to 15

Fig. II.C.9. Postulated temperature-density phase diagram for hadronic matter [Sa85]. C and CH label critical values for color and chiral deconfinement. n_B labels the baryon density. The present estimate for the value at which $T_C = T_{CH}$ is ≈ 200 MeV.

times the effective density for $A = 2$ deconfinement at $T = 200$ MeV. Since the temperature of the colliding nuclear matter is low (perhaps 5 to 10 MeV) for low bombarding energies, the excitation energy of the deconfined united nuclear system is low enough that the system could de-excite by radiation emission, rather than baryon emission. This suggests the possibility of forming stable superheavy baryons -- i.e., a large "bag" containing many quarks.

The usual considerations for the stability of superheavy nuclei, such as being below the neutron drip line, may have only a very small relevance for the stability and formation dynamics of the superheavy baryons. The relevant considerations could instead be the formation of the heaviest possible united system at a bombarding energy perhaps just high enough to reach the required density and yet low enough to maximize the chances of radiative cooling to the ground state. The best possibility for the production of superheavy baryons might be in the collision of a very heavy beam with a very heavy target at laboratory energies in the range 50 to 250 MeV/nucleon.

Could superheavy baryons be the ingredients of neutron stars? Should this be the case, we would conclude that the gravitational field served only the initial purpose of condensing the star. It has been pointed out [Te85] that the very strong γ -ray bursts observed from space might be emitted from chunks of matter accreting into a neutron star. This possibility could be easier to understand if the star were an ultraheavy baryon instead of an ultraheavy nucleus.

There already exist experimental data, the EMC effect [Bi84], which might point in this direction. The results have been interpreted to suggest that the nucleon size is altered when the nucleon is embedded in nuclear matter. One estimate [Cl85a] is that the nucleon radius increases by 20% over the value for a free nucleon when the nucleon is in an $A = 200$ system.

A slightly different explanation [Pi81] of the EMC effect is that there is a finite probability of having more than 3-quark clusters inside nuclei. This is, of course, a significant departure from the lowest order models in which quarks are well insulated inside their bag and suggests the possibility that, in "sufficiently" dense nuclear matter, clusters of more than three quarks might be as probable as the 3-quark nucleon clusters. This is yet another way to characterize cold deconfinement, and preliminary studies [Ke85] suggest that such a possibility is consistent with the current accuracy of the data on quarks inside finite nuclei. Other groups [Gr85] have estimated that the cross-over where the deconfined state might be lower in energy than the normal state could be around $A = 500$. Although this is all very speculative, it is to be expected that further activities along those lines will take place in the next few years, and experimental data on intermediate-energy, very-heavy-ion scattering could play an essential role in fixing the parameters of the deconfinement models.

II.C.7. Heavy-Ion Reaction Dynamics

It would be extremely interesting to have direct measures of the time-dependent behavior of heavy ions during collisions. How fast do the ions slow down and accelerate during a collision? What is the time for a given reaction? Such information would provide significant information relevant to the question of energy equilibration during collisions. There are two types of measurement which would utilize the capabilities of the proposed facility; one technique, crystal blocking, is already proven. The second technique, the use of electromagnetic bremsstrahlung, has still to be established as a useful method.

The use of the crystal blocking technique in conjunction with the proposed facility offers the unique opportunity of measuring nuclear decay times, as short as 3×10^{-20} sec, for cases where the decaying nucleus emits light particles. This technique consists of producing the nuclear reactions by bombarding, in a random direction, a high-quality mono-crystal target. The reaction products emerge along the principal crystallographic direction (planes or axis) with probabilities which depend directly on the lifetimes of the emitted nuclei. Long lifetimes imply high yields along the principal directions and vice versa. With this technique, emitted light charged particles from (p, p') or similar light-ion reactions [Ka78], or the residual heavy fragments from heavy-ion fission [An76] or fusion [Go83] reactions, are measured. Primarily because of the increase in recoil velocity (10% of the velocity of light) from the use of heavy-ion

beams, the crystal blocking technique has already been used to measure times on the 10^{-19} sec scale [Go83].

Figure II.C.10 shows two examples of the results from crystal blocking with heavy-ion beams. Figure II.C.10(a) shows the extracted decay times for the production of evaporation residues ($Z = 12$ to 6) from the fusion of 120-MeV $^{16}\text{O} + ^{12}\text{C}$ (diamond target) [Go83]. The solid data points are the extracted times, and the histograms are the results of a Monte Carlo Hauser-Feshbach calculation [Go80]. For this reaction, the study of the decay times provides an example of complete fusion and equilibrium decay. (Incomplete fusion and/or pre-equilibrium decay would lead to substantially shorter times than those measured). Shown on Fig. II.C.10(b) are the extracted times (solid points) for the projectile-like fragments from the reaction $^{40}\text{Ar} + \text{Ge}$ (crystal) for 1.76-GeV ^{40}Ar from Ref. [Go85]. The histograms are the results of Monte Carlo calculations coupled to an abrasion-ablation model of the reaction [Ba84] which predicts the distribution of primary fragments. An amount of 20 to 30 MeV of internal excitation energy for the primary fragments is required in order to reproduce approximately the measured decay times. The sole fact that these times reach the 10^{-18} sec scale is indicative that secondary evaporative effects are still very important even at 50 MeV/nucleon. These two examples show the usefulness of the crystal blocking technique in addressing a number of interesting nuclear phenomena in heavy-ion reactions and represent the beginning of a technique that should be explored further. As heavier ions and higher energies become available, even higher recoil velocities can be achieved, which should offer the possibility to study nuclear reaction

ORNL-DWG 86-7568

Fig. II.C.10. (a) Decay times (τ) extracted for the evaporation residues from the $^{16}O + ^{12}C$ (diamond) fusion reaction. (b) Decay times (τ) extracted for the projectile-like fragments from the $^{40}Ar + Ge$ (crystal) reaction for 1.76 GeV ^{49}Ar . The histograms are Monte Carlo predictions obtained with the assumption of equilibrium decay for light particles (n, p, α).

lifetimes as short as 3×10^{-20} sec, the limits being imposed by the thermal vibration of the lattice in available crystals. Essential to all the blocking experiments is good beam quality (spot sizes of ~ 1 mm and beam divergence < 0.01 deg) and beam intensities on the order of 10^{10} particles/sec. There is no facility in operation that provides this combination of intensity and beam quality for high-energy heavy-ion beams. With beams from the proposed accelerator and appropriate collimation, it would be possible to reach this limiting lifetime for a large variety of reactions. For example, a projectile fragmentation study of 1-GeV/nucleon ^{40}Ar on Ge can provide a lower time limit of 3.8×10^{-20} sec, which is a factor of ten smaller than the present limit of such measurements. On this timescale features of the primary reaction could be revealed. Furthermore, since blocking spectra of many charged fragments (e.g., electrons, pions, protons, and alpha particles) can be studied, it would be of great interest to see if the emission times of these particles reach the 10^{-20} sec scale and, if so, this could be an indication that thermalization processes are important at such high projectile energies.

It has been proposed [Ka77] that bremsstrahlung radiation can be used to study heavy-ion reaction dynamics -- the slowing down and speeding up of ions during a collision. The heavy systems carry large charges, and they undergo acceleration during the collision process, so there is no question that bremsstrahlung radiation will be emitted. The acceleration rate is determined by the dynamics of the collision process. The questions are whether the bremsstrahlung radiation can be

experimentally isolated and how sensitive is the radiation to reaction dynamics. Bremsstrahlung would have the usual advantage that there are no problems with final-state interactions.

There have recently been reported [Ko85a] theoretical studies of nuclear bremsstrahlung radiation in terms of an intranuclear cascade model. The calculations for projectile energies of 100 MeV/nucleon indicate that the spectrum of bremsstrahlung photons between 10 and 20 MeV is sensitive to reaction dynamics. The sensitivity is strongest for heavy systems around Pb and for central collision events. The calculations ignore Pauli blocking effects, Fermi momentum distributions, and mean-field effects. Improved calculations using the Boltzmann-Uehling-Uehlenbeck model are in progress. Experiments in this area will require the use of a 4π gamma-ray detector.

II.C.8. Studies of the Properties of Nucleon Excited States in Intermediate-Energy, Heavy-Ion Collisions

As nuclei are heated and compressed in a high-energy, heavy-ion collision, the individual nucleons may become excited to higher-lying resonance states. Experiment [Na84] suggests that, in heavy-ion collisions at 800 MeV/nucleon, there is a pion produced for every 10 nucleons in the colliding system, and the number of pions increases rapidly with bombarding energy up to 1500 MeV/nucleon. Certainly, a significant fraction of these pions are produced through the delta resonance state. The study of the formation, interaction, and decay of such a "soup" of deltas and nucleons is an interesting subject of investigation. It might be expected that, because of the change in effective confinement volume, the quark orbitals will be altered with a corresponding change in the level spacing of the excited states of the nucleon. As discussed below, there are signs from studies of single Δ 's in nuclear matter that the properties of the Δ are strongly impacted by the nuclear media. As the spectroscopic studies discussed in Section II.D.6 show, the energy and width of the Δ -resonance in nuclear matter are the same as the free-space values. But the width should be significantly altered by Pauli blocking effects and by effects of allowed collisions with other nucleons. Apparently, these strong effects cancel. The effects should be different in the nuclear surface and in the interior of the nucleus. They should be altered by the high densities and temperatures formed in heavy-ion collisions. More refined measurements and analyses might provide a means of doing nucleon spectroscopy in the nuclear medium with

extreme variations of the nuclear density and corresponding variations of the effective confinement volume.

In heavy-ion reactions, a large volume of Δ -rich matter can be formed. In such systems there is a much higher probability that there will be a Δ - Δ interaction than is the case in light-ion-induced reactions, where only one or two Δ 's are formed over a large volume.

II.C.9. The Giant Dipole Resonance Under Extreme Conditions

In this section we discuss a different type of experiment from those described above. In this case we consider the use of a well-known collective nuclear state, the isovector giant dipole resonance, as an indicator of the nuclear shape at high excitation energy and as an indication of the general integrity of the nucleus at high temperature. As has been discussed in several preceding sections of this proposal, the range of heavy-ion bombarding energies and the variety of probes available from the proposed accelerator should make possible the creation of nuclear matter under a wide range of conditions. The study of particularly simple states of the nucleus, for example, the giant multipole resonances, forms an essential part of the efforts to understand the nucleus as a many-body system. It is possible that we may be able to trace the evolution of some of these simple giant resonance states over at least a part of the range of nuclear temperatures (densities) and angular momenta that will be made available. On the other hand, if it is understood how some properties of these states behave as a function of the changing properties of the colliding nuclear matter, then the states can be used as probes to carry information about the environment in which they exist. The Giant Dipole Resonance (GDR) is a good candidate for such a role.

It has been known for many years that the strength function that governs the emission of high energy E1 gamma rays from highly excited nuclei should reflect the shape of the GDR built on the excited states through which the gamma cascades proceed. The experiments of Newton

and collaborators [Ne81] demonstrated that the GDR shape can be observed experimentally in the gamma spectra produced in compound-nucleus reactions. Those measurements have stimulated a large body of work over the last five years. [See the reviews [Sn84], [Ga85], and references therein.]

Data now exist on excited-state GDR shapes and strengths up to excitation energies corresponding to temperatures, T , < 2 MeV and over a range of spins up to about 60. It is of great interest to chart the evolution of the GDR over a much wider range of conditions. Such data would provide an invaluable benchmark against which to test theory.

Data are available which demonstrate that the GDR can be used as a practical tool to investigate nuclear shapes, at least at moderate nuclear temperatures [Ga85, Go85, Bo85]. Many calculations suggest that exotic nuclear shapes exist, at least briefly, at higher temperatures (in the range 10 to 20 MeV). Is there any hope of using the gamma decay of the GDR to deduce the existence of exotic nuclear shapes? To how high an excitation energy can such studies of the GDR through its gamma decay be pushed? In this section the behavior of the GDR under extreme conditions of temperature and spin will be discussed, and the prospects for experiments based on some of these speculations will be briefly explored.

There is considerable evidence that the GDR energy [Ci84, Ba74, Sa84] and strength [Be85, Ci84, Sa84] do not vary significantly with increasing temperature. This is not true for the spreading width of the resonance. The spreading of the GDR has been calculated for nuclei at various finite temperatures and rotational frequencies [Ga85, Eg82, Ci83, Eg80, Fa83,

Ri84, Do82, Ne82]. Contributions to the observed width of the giant dipole resonance come from five major sources: Landau damping, rotations, quantum surface fluctuations, particle-particle collisions, and static deformation. Of these, only shape changes have large effects at finite temperature. This is why the GDR can be a valuable "shape meter." The effect of static deformation on the ground-state GDR has been known for many years from photoabsorption experiments. Axially symmetric deformations, for example, lead to a splitting of the GDR strength into two pieces, with a separation that increases with increasing deformation and a distribution of strength between the pieces that depends on the sign of the deformation. As the nuclear temperature increases, shell effects, which play a decisive role in determining shapes near $T = 0$, decline in importance and eventually vanish. The macroscopic effects of angular momentum, surface tension, and Coulomb repulsion determine the shape. The effective surface tension also decreases with increasing temperature, leading to nuclei that become softer with respect to deformation with increasing temperature. Some calculations [Wo85] predict that nuclear shapes that are very different from the spheroidal shapes seen near $T = 0$ could exist, at least briefly, near the temperature at which the nucleus surface tension vanishes (10 to 20 MeV), and the addition of angular momentum should enhance these effects [Zh85]. Such shape changes would have dramatic effects on the GDR.

Experiments designed to chart the behavior of the GDR under extreme conditions will have to be much more sophisticated than the low-energy experiments done so far. They will need to rely on more complex triggers to select nearly central collisions since they will

have to deal with more complex reactions than the complete fusion process, which is used at low energy. As the bombarding energy is increased, many other sources of gamma radiation in the 10 to 20 MeV range, where the GDR lies, become increasingly important. The availability of a wide variety of accelerated ions will be an advantage. If, for example, nuclear bremsstrahlung proves to be an important source of background, light beams like ^{12}C and alpha particles would offer advantages. A composite nuclear system must exist at least for times on the order of the period of the giant dipole vibration before any effects of the GDR will be visible. This limits experiments to temperatures below the "boiling point" of nuclear matter, T_c , currently thought to lie between 8 and 20 MeV. The detection of a compact GDR may prove to be a useful signal to help map the nuclear boiling point as a function of other nuclear parameters [Br85].

II.C.10. Relation to Total Reaction Cross Section

The intermediate energy region of 50-1500 MeV/nucleon in heavy-ion reactions is expected to be a transition region between low energies where reactions are described by mean-field phenomena, and relativistic energies, where individual nucleon-nucleon collisions are dominant. In this transitional energy domain, the nucleon-nucleon total reaction cross section (σ_R) decreases with increasing beam energy, a feature that is also seen for the nucleon-nucleus [Re72] and some alpha-particle nucleus reactions [De82].

It has been pointed out [De79] that for heavy-ion reactions a signature of the effects of individual nucleon-nucleon collisions could be obtained by studying possible deviations of σ_R from the geometrical values. A microscopic calculation [De79, De80] which makes use of the Glauber theory was put forward to predict σ_R in this intermediate energy region, treating the nucleus-nucleus case essentially as a superposition of incoherent nucleon-nucleon collisions. These calculations have been successful in explaining the measurements for the nucleon-nucleus [Di80] and alpha-particle- ^{12}C [De82] reaction cross sections.

It was not until very recently [Ko85a], when new accelerators such as GANIL and SATURNE-II became available, that measurements of σ_R for light heavy-ion reactions were made. Results of measurements of σ_R , with the beam attenuation technique, are shown on Fig. II.C.11 for ^{12}C and ^{20}Ne beams. Measurements of σ_R by means of elastic scattering are also possible but are not available above 100 MeV/nucleon because

Fig. II.C.11. Variation of the total reaction cross section as a function of the incident energy/nucleon for $^{12}\text{C} + ^{12}\text{C}$ (a) and $^{12}\text{C} + \text{Zn}$, $^{12}\text{C} + ^{27}\text{Al}$, $^{12}\text{C} + \text{Fe}$, and $^{20}\text{Ne} + ^{12}\text{C}$ (b). Full circles are data of Ref. [Ko85] and open circles from [Ja78].

the required energy resolution and beam intensities at these energies are not available at existing accelerators. The solid lines are the results of the microscopic calculations, and from the quality of the fit it can be concluded that incoherent nucleon-nucleon collisions seem to be the dominant feature in the total reaction cross section.

However, it must be realized that existing measurements have involved only very light projectiles. To rule out the presence of coherent or collective effects, it will be necessary not only to extend the presently available measurements to a wider energy range and to heavier systems but also to provide elastic scattering data. A typical beam energy resolution of $\sim 1 \times 10^{-4}$ for $A \approx 100$ will be required to be able to measure the elastic scattering from 100-1500 MeV/nucleon for most targets. In addition good beam emittance is mandatory since the angular distributions must be measured with an accuracy of ~ 0.02 degrees. The proposed accelerator will be capable of providing the necessary beams to measure the total reaction cross section by both elastic scattering and attenuation methods for a wide range of energies and masses of the projectiles.

II.C.11. References

- Ad84 S. Adachi and Nguyen Van Gai, Phys. Lett. 149B, 447 (1984).
- Ai85 J. Aichelin and G. F. Bertsch, Phys. Rev. C 31, 1730 (1985).
- Ai85a J. Aichelin and C. M. Ko, Joint Institute for Heavy Ion Research preprint, 1985.
- Am76 J. U. Anderson, E. Laegsgaard, K. O. Nielsen, W. M. Gibson, J. S. Forester, J. V. Mitchell, and D. Ward, Phys. Rev. Lett. 36, 1539 (1976).
- Ba74 Brack and Quentin, Physica Scripta 10A, 163 (1974).
- Ba83 J. Barrette and A. M. Sandorfi, Comments on Nucl. & Part. Phys. 12, 57 (1983).
- Ba84 J. Barrette, p. 561 in Proc. XXII Int. Meet. on Nucl. Phys., Bormio, Italy (1984).
- Ba85 E. Baron, M. Cooperstein, and S. Kahana, Nucl. Phys. A440, 744 (1985).
- Ba86 Batel, Brack, and Durand (to be published).
- Be81 F. E. Bertrand, Nucl. Phys. A354, 129c (1981).
- Be83 D. Beavis, S. Y. Fung, W. Gorn, A. Huie, D. Keane, J. J. Lu, R. T. Poe, B. C. Shen, and G. VanDalen, Phys. Rev. C 27, 910 (1983).
- Be83a G. F. Bertsch, P. F. Bortignon, and R. A. Broglia, Rev. Mod. Phys. 55, 287 (1983).
- Be84 G. F. Bertsch, H. Kruse, and S. Das Gupta, Phys. Rev. C 29, 673 (1984).
- Be85a M. Beckerman, R. L. Auble, F. E. Bertrand, J. L. Blankenship, B. L. Burks, C. W. Glover, E. E. Gross, R. O. Sayer, D. Shapira, Y. Sugiyama, and R. L. Varner, to be published.
- Be85 G. F. Bertsch, Bull. Am. Phys. Soc. 30, 1278 (1985).
- Bi84 R. P. Bickerstaff, M. C. Birse, and G. A. Miller, Phys. Rev. Lett. 53, 2532 (1984).
- Bo81 O. Bohigas, Nguyen Van Giai, and D. Vautherin, Phys. Lett. 102B, 105 (1981).

- Bo83 J. Boguta and H. Stocker, Phys. Lett. 120B, 289 (1983).
- Bo85 B. Bochev, T. Kutsarova, H. P. Morsch, R. M. Lieder, W. Gast, G. Lebbinghaus, A. Kramer-Flechen, W. Urban, and J. P. Dideley, to be published.
- Br72 D. M. Brink, Phys. Lett. 40B, 37 (1972).
- Br84 R. Brockman, J. W. Harris, A. Sandoval, R. Stock, H. Strobel, G. Adyniec, H. G. Pugh, L. S. Schroeder, R. F. Renfordt, D. Shall, P. Bangert, W. Rauch, and K. L. Wolf, Phys. Rev. Lett. 53, 2072 (1984).
- Br85 R. A. Broglia and G. F. Bertsch, private communication.
- Ca85 Y. Casagnou, private communication.
- Ch83 C. B. Chitwood et al., Phys. Lett. 131B, 289 (1983).
- Ci83 O. Civitarese, S. Furni, M. Ploszajczak, and A. Faessler, Nucl. Phys. A408, 61 (1983).
- Ci84 O. Civitarese, R. A. Broglia, and C. H. Dasso, Ann. Phys. 156, 142 (1984).
- C185 R. B. Clare and D. Strottman, Los Alamos preprint, LA-UR-85-3692.
- C185a F. E. Close, R. L. Jaffe, R. G. Roberts, and G. G. Ross, Phys. Rev. D 31, 1004 (1985).
- Cu85 R. Y. Cusson, P.-G. Reinhard, J. J. Molitoris, H. Stöcker, M. R. Strayer, and W. Greiner, Phys. Rev. Lett. 55, 2786 (1985).
- De79 R. M. DeVries, p. 513 in Proc. Symp. Heavy Ion Physics from 10 to 200 MeV/amu, July 16-20, 1979, BNL-51115, Vol. 2, ed. J. Barrette and P. D. Bond.
- De80 R. M. DeVries and J. C. Peng, Phys. Rev. C 22, 1055 (1980).
- De82 R. M. DeVries, N. J. DiGiacomo, J. S. Kapwstinsky, J. C. Peng, W. E. Sondheim, J. W. Sunier, J. G. Cramer, R. E. Loveman, C. R. Gruhn, and H. H. Wieman, Phys. Rev. C 26, 301 (1982).
- Di81 N. J. DiGiacomo, R. M. DeVries, and J. C. Peng, Phys. Rev. Lett. 45, 527 (1980).
- Do82 T. Dossing and K. Neergaard, Contribution to the 4th Nordic Meeting on Nuclear Physics, Fuglso, Denmark (1982).

- Dr82 J. E. Draper, J. O. Newton, L. G. Sobotka, K. H. Lindenberger, G. J. Woyniak, I. G. Moretto, F. S. Stephens, R. M. Diamond, and R. J. McDonald, Phys. Rev. Lett. 49, 434 (1982).
- Eg80 J. L. Egido, H. J. Mang, and P. Ring, Nucl. Phys. A339, 390 (1980).
- Eg82 J. L. Egido and P. Ring, Phys. Rev. C 25, 3239 (1982) and Nucl. Phys. A388, 191 (1982).
- Fa83 M. Faber, J. L. Egido, and P. Ring, Phys. Lett. 127B, 5 (1983).
- Fi67 M. E. Fisher, Rep. Prog. Phys. 30, 615 (1967).
- Fr81 B. Friedman and V. R. Pandharipande, Nucl. Phys. A361, 502 (1981).
- Ga82 J. J. Gaardhoje, XX International Meeting on Nuclear Physics, Bormio, Italy, Ricera Scientifica ed. Educazione Permanente, Suppl. 25, 107 (1982).
- Ga83 E. F. Garman, K. A. Snover, S. H. Chao, S.K.B. Hesmondhalgh, W. N. Catford, and P. M. Walker, Phys. Rev. C 28, 2554 (1983).
- Ga84 J. J. Gaardhoje, C. Ellegaard, B. Herskind, and S. G. Steadman, Phys. Rev. Lett. 53, 148 (1984).
- Ga85 J. J. Gaardhoje, p. 519 in Proceedings of the Niels Bohr Centennial Conference on Nuclear Structure, May 1985, ed. R. Broglia, G. Hagemann, and B. Herskind, North-Holland, Amsterdam, 1985.
- Ga86 M. Gallardo, M. Diebel, T. Dossing, and R. A. Broglia, Nuclear Physics (in press); M. Gallardo, Doctoral Thesis, Departamento de Fisica Atomica y Nuclear, Universidad de Sevilla, Spain, May 1985 (unpublished).
- Go80 J. Gomez del Campo and R. G. Stokstad, LILITA a Monte-Carlo Code, ORNL/TM-7295 (1980), unpublished.
- Go83 J. Gomez del Campo, D. Shapira, J. A. Biggerstaff, C. D. Moak, P. D. Miller, N. Neskovic, R. W. Fearick, and J.P.F. Sellschop, Phys. Rev. Lett. 51, 451 (1983).
- Go84 A. L. Goodman, J. I. Kapusta, and A. Z. Mekjian, Phys. Rev. C 30, 854 (1984).
- Go85 C. A. Gossett, K. A. Snover, J. A. Behr, G. Feldman, and J. L. Osborne, Phys. Rev. Lett. 54, 1486 (1985).

- Go85a J. Gomez del Campo, J. Barrette, R. A. Dayras, J. P. Wieleczko, E. Pollacco, F. Saint-Laurent, M. Toulemonde, N. Neskovic, and R. Ostojec, *Nouvelles de Ganil* 12, 14 (1985).
- Gr84 R.E.L. Green, R. G. Korteleng, and K. P. Jackson, *Phys. Rev. C* 29, 1806 (1984).
- Gr85 W. Greiner, private communication.
- Gu84 H. A. Gustafsson, H. H. Gutbrod, B. Kolb, H. Loehner, B. Ludewigt, A. M. Poskanzer, T. Renner, H. Riedesel, H. G. Ritter, A. Warwick, F. Weik, and H. Wieman, *Phys. Rev. Lett.* 52, 1590 (1984).
- Gu84a H. A. Gustafsson, H. H. Gutbrod, B. Kolb, H. Lohner, B. Ludewigt, A. M. Poskanzer, T. Renner, H. Riedesel, H. G. Ritter, A. Warwick, F. Weik, and H. Wieman, *Phys. Rev. Lett.* 53, 544 (1984).
- Ha85 J. Harris, R. Bock, R. Brockmann, A. Sandoval, R. Stock, H. Stroebele, G. Odyniec, H. G. Pugh, L. S. Schroeder, R. E. Renfordt, D. Shall, D. Bangert, W. Rauch, and K. L. Wolfe, *Phys. Lett. B* 153, 377 (1985).
- Hb56 R. Hanbury-Brown and R. Q. Twiss, *Nature* 178, 1046 (1956).
- He83 W. Hennerici, V. Metag, H. J. Heinrich, R. Repnov, W. Wahl, D. Habs, K. Helmer, U. V. Helmut, H. W. Heyng, B. Kolb, D. Pelte, D. Schwalm, R. S. Simon, and R. Albrecht, *Nucl. Phys. A* 396, 329C (1983).
- Hi84 A. S. Hisch et al., *Phys. Rev. C* 29, 508 (1984).
- Ja78 J. Jares et al., *Phys. Rev. C* 18, 273 (1978).
- Ka77 J. I. Kapusta, *Phys. Rev. C* 15, 1580 (1977).
- Ka78 E. P. Kantes, K. P. Kollwe, K. Fowaski, I. Levca, G. M. Temmer, and W. M. Gibson, *Nucl. Phys. A* 229, 230 (1978).
- Ke85 A. K. Kerman, private communication.
- Ko74 G. I. Kopylov, *Phys. Lett.* 50B, 472 (1974).
- Ko77 S. Koonin, *Phys. Lett.* 70B, 43 (1977).
- Ko85 C. M. Ko, G. Bertsch, and J. Aichelin, *Phys. Rev. C* 31, 2324 (1985).
- Ko85b S. E. Koonin, in Proceedings of the Workshop on Intermediate Energy Heavy-Ion Collisions, Oak Ridge, 1985 (Conf-8509176).

- Ko85a S. Kox, A. Gamp, C. Perrin, J. Arvieux, R. Bertholet, J. F. Bruandet, M. Buenerd, Y. El Masri, N. Longequeue, and F. Merchez, *Phys. Lett.* **159B**, 15 (1985).
- Kr85 H. Kruse, B. V. Jacob, and H. S. Stöcker, *Phys. Rev. Lett.* **54**, 289 (1985).
- Ma84 J. A. Maruhn and W. Greiner, Treatise on Heavy Ion Science (Plenum Press, New York, 1984, ed. D. A. Bromley).
- Ma85 H. Machner, *Phys. Rev. C* **31**, 127 (1985).
- Mo84 D. J. Morrissey, W. Benenson, E. Kashy, B. Sherrill, A. D. Panagiotou, R. A. Blue, R. M. Ronningen, J. vander Plicht, H. Utsunomiya, *Phys. Lett.* **148B**, 423 (1984).
- Mo85 J. J. Molitoris and H. Stöcker, *Phys. Rev. C* **32**, 346 (1985).
- Na82 S. Nagamiya, *Phys. Rev. Lett.* **49**, 1383 (1982).
- Na84 S. Nagamiya and M. Gyulassy, "High Energy Nuclear Collisions," in Advances in Nuclear Physics **13** (Plenum Press, New York, 1984, eds. J. W. Negele and E. Vogt).
- Ne81 J. O. Newton, B. Herskind, R. M. Diamond, E. L. Dines, J. E. Draper, K. H. Lindenberg, C. Schuck, S. Shih, and F. Stephens, *Phys. Rev. Lett.* **46**, 1383 (1981).
- Ne82 K. Neergaard, *Phys. Lett.* **110B**, 7 (1982).
- Pa84 A. D. Panagiotou, M. W. Curtin, H. Toki, D. K. Scott, and P. J. Siemens, *Phys. Rev. Lett.* **52**, 496 (1984).
- Pi81 H. J. Pirner and J. P. Vary, *Phys. Rev. Lett.* **46**, 1376 (1981).
- Po85 J. Pochodzalla, W. A. Friedman, C. K. Gelbke, W. G. Lynch, M. Maier, D. Ardouin, H. Delagrange, H. Doubre, C. Gregoire, A. Kyanowski, W. Mittig, A. Peghaire, J. Peter, F. Saint-Laurent, Y. P. Vijoyi, B. Zwioglinski, G. Bizard, F. Lefebvres, B. Tamain, and J. Quebert, *Phys. Rev. Lett.* **55**, 177 (1985).
- Re72 P. U. Renberg, D. F. Measday, M. Pepin, P. Schwaller, B. Favier, and C. Richard-Serre, *Nucl. Phys.* **A183**, 81 (1972).
- Ri84 P. Ring, L. M. Robledo, J. L. Egido, and M. Faber, *Nucl. Phys.* **A419**, 261 (1984).
- Sa80 A. Sandoval, R. Stock, H. E. Stelzer, R. E. Renfordt, J. W. Harris, J. P. Brannigan, J. V. Geaga, L. J. Rosenberg, L. S. Schroeder, and K. L. Wolfe, *Phys. Rev. Lett.* **45**, 874 (1980).

- Sa83 A. M. Sandorfi, J. Barrette, M. T. Collins, D. H. Hoffman, A. a. Kreimer, D. Braunford, S. G. Steadman, and J. Wiggins, Phys. Lett. 130B, 19 (1983).
- Sa84 H. Sagawa and G. F. Bertsch, Phys. Lett. 146B, 138 (1984).
- Sa85 M. Sano, M. Gyulassy, M. Wakai, and Y. Kitazoe, Phys. Lett. 156B, 27 (1985).
- Sa85a H. Satz, RHIC 1985 Workshop, Brookhaven National Laboratory, BNL-51921.
- Sc82 S. Schnetzer, M.-C. Lemaire, R. Lombard, E. Moeller, S. Nagamiya, G. Shapiro, H. Steiner, and I. Tanihata, Phys. Rev. Lett. 49, 989 (1982).
- Sc84 B. Schwesinger and J. Wambach, Phys. Lett. 134B, 29 (1984).
- Si84 P. J. Siemens, Nucl. Phys. A428, 189c (1984).
- Sn84 K. Snover, p. 660 in Capture Gamma-Ray Spectroscopy and Related Topics, AIP Conference Proceedings No. 125, ed. S. Raman, AIP, New York (1985).
- St82 R. Stock, R. Bock, R. Brockman, J. W. Harris, A. Sandoval, H. Stroebele, K. L. Wolf, H. S. Pugh, L. S. Schroeder, M. Maier, R. E. Renfordt, A. Dacal, and M. E. Ortiz, Phys. Rev. Lett. 49, 1236 (1982).
- Te85 E. Teller, Distinguished Scientist Colloquium, Duke University, Durham, N.C., (1985).
- Vo85 W. von Oertzen, Phys. Lett. 151B, 95 (1985).
- Wa74 J. D. Walecka, Ann. Phys. 83, 491 (1974).
- Wa83 A. I. Warwick, H. H. Wieman, H. H. Gutbrod, M. R. Maier, J. Peter, H. G. Ritter, H. Stelzer, F. Weik, M. Freedman, D. J. Henderson, S. B. Kaufman, E. P. Steinberg, and B. D. Wilkins, Phys. Rev. C 27, 1083 (1983).
- Wi80 W. Wilcke et al., Atomic and Nuclear Data Tables 25, 389 (1980).
- Wi84 W. J. Willis, Nucl. Phys. A418, 425c (1984).
- Wo79 C. Y. Wong and H.H.K. Tang, Phys. Rev. C 20, 1419 (1979).
- Wo85 C. Y. Wong, Phys. Rev. Lett. 55, 1973 (1985).
- Ya74 F. B. Yano and S. E. Koonin, Phys. Lett. 78B, 556 (1974).

- Za81 F. Zrbakhsh, A. L. Sagle, F. Brochard, T. A. Mulera, V. Perez-Mendez, R. Talaga, I. Tanihata, J. B. Carroll, K. S. Ganezer, G. Igo, J. Oostens, D. Woodard, and R. Sutter, Phys. Rev. Lett. **46**, 1268 (1981).
- Zh86 J. Y. Zhang and C. Y. Wong, to be published.

II.D. NUCLEAR SPECTROSCOPY

The proposed accelerator will offer many unique opportunities for investigation of nuclear structure. The very large Coulomb excitation cross sections that can be achieved with high-energy heavy ions will greatly enhance the detailed study of how giant resonances decay. The combination of beams of a variety of ions ($A = 2-40$) with energies up to 1500 MeV/nucleon, high beam intensity ($\sim 10^{11}$ particles/sec), high energy resolution ($\Delta E/E \sim 10^{-4}$), and good beam emittance which can be produced with the proposed accelerator are not available elsewhere. Experience has shown that use of a variety of probes and energies is essential for quantifying giant resonance parameters because of the considerable overlap in energy of resonances having different angular momentum, isospin, and parity. At the energies of the proposed accelerator, charge-exchange reactions are believed to proceed via a direct one-step process, rather than to be contaminated, or even dominated, by multistep processes. This will provide opportunities to study a variety of spin-isospin modes of excitation and two-nucleon correlations. With the high energy beams from the accelerator it will be possible to produce delta excitations of the nucleon and to study how deltas interact in the nuclear medium, as well as how such excitations decay. The use of reverse kinematics (i.e., where the role of target and projectile are interchanged) to study selected transfer reactions should prove fruitful. The large beam intensities will make possible the production of many new isotopes and will extend our knowledge of the nuclear mass surface and nuclear level systematics. The use of secondary beams to

initiate reactions offers many new research opportunities. The use of inverse kinematics will permit the measurement of g-factors of some short-lived excited states for the first time.

The research programs described in this section will require a variety of experimental apparatus. The studies of direct reactions with high-energy beams having good energy resolution will necessitate the use of a large magnetic spectrograph. The spectrograph must be capable of matching the beam momentum resolution of $\sim 10^{-4}$ and should have a broad momentum acceptance in order to accommodate the giant resonance research programs. Its detector system must provide unique particle identification. Studies of the delta nucleon resonance region will require less resolution but will require detector systems capable of measuring decay products. Studies of giant resonance decay will necessitate large arrays of photon detectors similar to the Spin Spectrometer. The study of exotic nuclei will need an isotope identification system composed of a spectrometer for selecting and focusing fragmentation products and a variety of solid state detectors for measuring both particle and γ -ray emission.

II.D.1. Coulomb Excitation of Giant Resonances and the Virtual Photon Field

It has recently been suggested [Wi79, Ho84, Me84] that, for the higher-energy heavy ions available from the proposed accelerator, the cross sections for excitation of giant resonances via Coulomb excitation will exceed those generated by nuclear forces by several orders of magnitude. Furthermore, the Coulomb excitation cross sections for exciting isovector and isoscalar resonances will be comparable. Such large cross sections are a necessity for performing coincidence studies to understand the detailed manner in which giant resonances decay.

To understand the evolution of the Coulomb excitation process with increasing beam energy, it is instructive to think of the rapidly changing Coulomb field created at the target by a projectile passing at high velocity in terms of the equivalent virtual photon field [Wi35, Ja75, Go84, Be85]. The Coulomb excitation process is then equivalent to the photonuclear absorption of the virtual photons. Figure II.D.1a shows virtual photon spectra, $n_{E1}(E_\gamma)$, for electric dipole radiation as seen by a ^{208}Pb target for a range of ^{16}O incident energies between 50 and 1500 MeV/nucleon. The rapid fall-off of photon intensity with increasing energy for the 50 MeV/nucleon case shows why Coulomb excitation with low-energy projectiles is limited to the study of low-lying states. In contrast, the spectrum at 1500 MeV/nucleon is almost flat in the 10-50 MeV photon energy range. The cross section for Coulomb excitation for various multipoles, $E\lambda$, is given in terms of $n_{E\lambda}(E_\gamma)$ by [Ja75, Go84, Be85a]

Fig. II.D.1. (a) $E1$ virtual photon intensity spectrum seen by a ^{208}Pb target due to 50, 500, and 1500 MeV/nucleon 160 beams. (b) E_λ virtual photon spectra for $\lambda = 1, 2, 3$, seen by a ^{208}Pb target bombarded by 1500 MeV/nucleon 160 .

$$\sigma_{E\lambda} = \int_0^\infty \frac{n_{E\lambda}(E_Y) \sigma_{E\lambda}(E_Y)}{E_Y} dE_Y, \quad (\text{II.D.1})$$

where $\sigma_{E\lambda}(E_Y)$ is the photonuclear absorption cross section as a function of energy. Calculations of $n_{E\lambda}(E_Y)$ are shown in Fig. II.D.1b for $\lambda = 1, 2$, and 3 for the same beam-target combination as used for the calculations shown in Fig. II.D.1a (magnetic multipoles are, of course, also present). Even though the virtual photon intensity is greater for the higher multipoles, the E1 excitation dominates the calculated cross sections, as shown in Fig. II.D.2a. It is assumed in these calculations that a beam of ^{16}O excites a state located at 22 MeV in ^{208}Pb and which fully exhaust the energy weighted sum rules (EWSR) for the various multipoles. The large enhancement ($\propto Z^2$) obtained in the cross sections when higher Z projectiles are used is shown in Fig. II.D.2b for excitation of the 14-MeV, $T = 1$, giant dipole resonance in ^{208}Pb by oxygen, zirconium, and lead beams. In these calculations the methods of Ref. [Be85] have been used, and only impact parameters greater than the sum of the nuclear radii have been included.

These large Coulomb excitation cross sections will offer an opportunity for studying the details of how giant resonances decay and thus provide unique information (not available by other means) with which to test nuclear structure theories.

ORNL-DWG 85-18977

Fig. II.D.2. (a) Total cross section for excitation of a fictitious state in ^{208}Pb at 22 MeV which exhausts the full EWSR for the multipolarity given. The beam is ^{16}O . (b) Cross sections for excitation of the $1 = 1$ E1 state at 14 MeV (GDR) in ^{208}Pb by various beams.

II.D.2. Giant Resonance Decay

Giant multipole resonances in heavy nuclei are simple nuclear states embedded in a dense spectrum of more complex states with which they mix. The consequent damping of the giant resonances offers an excellent test of our understanding of many-body physics in atomic nuclei. The questions now being asked concerning the microscopic structure and damping of the resonances [Be83, Bo81] require more detailed experiments than those which have served to build up a systematic catalog of their gross properties over the last decade [Be76, Be80, Be81]. What is needed are data pertaining to the particle and gamma decay of the resonances, which can be used to test microscopic calculations of giant resonance structure. This will require measurements of coincidences between the inelastically scattered projectile and decay products. Such experiments will become feasible with the very large excitation cross sections achievable with the high energy heavy-ion beams from the proposed accelerator. Beams with good energy resolution, high intensity, and low emittance will be required, as well as scattered particle detectors with good particle identification and resolution. It is envisaged that the decay products will be detected with nearly 4π coverage. Although there is an advantage of utilizing relatively light, loosely bound projectiles like ^{17}O , heavier ions would excite the resonances with considerably larger cross sections (see Fig. II.D.2b). It will be important to identify particularly favorable projectiles with $Z \gtrsim 40$ and to design experiments to help separate effects of target and projectile excitation.

Decay experiments will focus mainly on obtaining more detailed information pertaining to the microstructure of known giant resonances. However, a particularly enhanced decay mode may be used to isolate a resonance which is otherwise difficult to separate from nearby or underlying states. A simple example of the latter case is the proposal [Sp85, Be83] to identify the $T = 1$, E2 resonance near 22 MeV in ^{208}Pb by observing its strongly enhanced E1 photon decay to the 3^- , 2.61-MeV state.

II.D.3. Isoscalar Giant Resonances -- Singles Measurements

The calculated energy dependence of the differential cross sections for excitation by inelastic scattering of the isoscalar giant quadrupole resonance (GQR) in ^{208}Pb by ^{17}O ions is shown in Fig. II.D.3. At the lower energies, the cross section is mainly from the nuclear interaction, while at the higher energies Coulomb excitation dominates. The peak cross section for excitation of the isoscalar GQR increases by over two orders of magnitude between 25 MeV/nucleon and 500 MeV/nucleon. From experience with light ions as well as ^{17}O , we expect the peak to continuum cross sections to improve with higher energy heavy ions.

A very important aspect of the proposed accelerator is the capability to accelerate an unprecedented variety of ions to energies as high as 1500 MeV/nucleon. It will be possible to study giant resonances through inelastic scattering of alpha particles, a probe that has provided much of the existing data, as well as with high-energy beams of deuterium and lithium ions for which there are few data at any incident energy. Use of a wide variety of probes provides the potential for more selective excitation of giant resonances, especially as a function of their spin and isospin transfer. Figure II.D.4. shows calculated angular distributions for $L = 2, 3$, and 4 states at 11 MeV in ^{208}Pb excited via inelastic scattering of 1000 MeV (250 MeV/nucleon) alpha particles. Also shown on the same figure is the calculated angular distribution for the GQR excited by 172-MeV alpha particle inelastic scattering. All cross sections are normalized to 100% depletion of the respective EWSR. Unlike the case with incident heavy ions, the nuclear

Fig. II.D.3. Calculated angular distributions for the isoscalar giant quadrupole resonance excited by inelastic scattering of various energy ^{17}O ions.

Fig. II.D.4. Calculated angular distributions for excitation of $L = 2, 3$, and 4 states at 11 MeV in ^{208}Pb by 1000-MeV alpha particle inelastic scattering and for $L = 2$ only, by 172-MeV alpha particles.

interaction, rather than the Coulomb interaction, dominates the reaction for light ions. At high incident energies, the angular distributions retain the strongly oscillatory character observed at lower energies and show more phase difference between neighboring L-transfer values than is observed for lower-energy alpha-particle scattering. At 1000 MeV, the maximum cross sections are 7-10 times larger than those at lower energies. The larger cross sections attainable using higher-energy incident alpha particles may make the observation of weak resonance states possible as well as provide large yields for decay experiments.

Figure II.D.5 shows the calculated maximum cross section for inelastic excitation of the isoscalar GQR in ^{208}Pb (100% EWSR) as a function of incident energy for ^{17}O , alpha-particles, and, for comparison, protons. The cross sections for excitation by ^{17}O rise very rapidly with increasing incident energy and are over an order of magnitude larger than those calculated for incident alphas at the high energies. Furthermore, the heavy ion cross section is nearly three orders of magnitude larger than that expected for inelastic proton scattering.

Fig. II.D.5. Maximum cross sections calculated for inelastic excitation of the isoscalar giant quadrupole resonance in ^{208}Pb by protons, alpha particles, and ^{17}O as a function of the incident particle energy.

II.D.4. Isovector Resonances – Singles Measurements

Although many different multipolarity isoscalar giant resonances have been observed, information [Be81] on the existence of isovector giant resonances other than the long established giant electric dipole resonance, and more recently the M1 resonance, is rather sparse. This comes about because of the weakness of the isospin part (v_T^C) of the nucleon-nucleus interaction compared to the strength of the v_0^C term, which provides the excitation of the $T = 0$ states (see discussion in section II.D.5). For example, in ~ 100 MeV (p,p') reactions the cross section is about 10 times smaller for a $T = 1$ state located at the same energy and having the same sum rule depletion as for a $T = 0$ state [Be76]. Of course, in alpha-particle and deuteron inelastic scattering, isovector states are not excited at all through the nuclear potential.

As pointed out above, isovector states can be strongly excited through Coulomb excitation using heavy-ion beams, and this provides exciting new possibilities for study of isovector giant resonances. Figure II.D.6 shows calculated angular distributions for excitation of an isovector GQR in ^{208}Pb located at an excitation energy of 22 MeV and exhausting 100% of the EWSR strength. For inelastic scattering of 25 MeV/nucleon ^{17}O , the maximum cross section expected for the $T = 1$ GQR is about 1 mb/sr, compared to a measured cross section of about 60 mb/sr for the $T = 0$ state. As the incident energy is increased, the cross section for the isovector GQR increases very rapidly, reaching a value of about 10,000 mb/sr at 500 MeV/nucleon. Figure II.D.7 shows for ^{208}Pb the calculated ratio of the cross section for excitation of

Fig. II.D.6. Calculated angular distributions for excitation of the isovector giant quadrupole resonance in ^{208}Pb by inelastic scattering of ^{17}O ions of several different energies.

Fig. II.D.7. Ratio of calculated cross sections for excitation of the isovector ($T = 1$) GQR (22 MeV) and isoscalar ($T = 0$) GQR (10.6 MeV) by inelastic scattering of various energy ^{17}O ions.

the $T = 0$ GQR (10.6 MeV) relative to the $T = 1$ GQR (22 MeV) as a function of energy of the incident ^{17}O beam. The cross sections for excitation of the $T = 1$ and $T = 0$ GQR arise mainly from Coulomb excitation and are nearly equal at 500 MeV/nucleon.

These calculations show that inelastic scattering of high-energy heavy ions provides, for the first time, a probe that yields cross sections for the isovector giant resonances which are as large as those for the isoscalar giant resonances. Thus, an entirely new class of fundamental modes of nuclear excitation will become available for systematic study.

II.D.5. Charge-Exchange Reactions

During the past ten years, there has been prolific growth in both experimental and theoretical study of charge-exchange reactions. Experimentally, the major impetus has come from the availability of beams of intermediate energy protons and pions, although other projectiles, such as neutrons and ions with $A > 2$, have also been employed. Concurrently, theoretical investigations of the reaction mechanisms have been vigorously pursued. Elucidation of the energy and momentum dependence of the various components of the nucleon-nucleon (N-N) interaction have provided a useful guide for such studies [Pe81, Lo82, Fr85]. As can be seen in Fig. II.D.8a, an important feature of the energy dependence of the N-N interaction is that v_0^C , which is independent of spin and isospin and is the strongest component in the interaction, has a broad minimum between 200 and 500 MeV/nucleon. This provides a reaction "window" with several consequences. For one, this window implies a certain degree of transparency in the optical potential U , which means that direct reactions become less peripheral and become more sensitive to the nuclear interior than is the case at lower energies. This will result in the sampling of a greater portion of the transition density for nonelastic excitations and, hence, larger cross sections. Within this window, the possibility of observing spin and isospin dependent transitions should be enhanced since the ratio of v_0^C to v_τ^C , v_σ^C , and $v_{\sigma\tau}^C$ becomes smaller.

In Fig. II.D.8b are shown the dependences of the central, spin-orbit, and tensor components of the N-N interaction versus linear momentum transfer (q) at an energy of 135 MeV. At small q , the spin-orbit

Fig. II.D.8. (a) Energy dependence of the volume integrals of the central components of the nucleon-nucleon interaction. (b) Volume integrals of the central (C), spin-orbit (LS), and tensor (T) components of the nucleon-nucleon interaction versus momentum transfer at $E = 135$ MeV [Pe81].

term is weak, but it dominates for $q > 2 \text{ fm}^{-1}$. Love and Franey [Lo82] have mapped out the energy and q dependence of the different components of the N-N interaction. It is clear from their work that, by the proper choices of probe and reaction, the nuclear response of a target nucleus for transitions designated by the transfers of angular momentum (L), spin (S), and isospin (T) might be selectively explored. In addition, these response functions may also be investigated as a function of q .

Some of these features have been exploited in the use of intermediate-energy protons for several years. The proposed accelerator will be capable of accelerating a large variety of beams which will have energy resolution adequate for these measurements and which will have energies spanning the "window" region. Hence, it will be possible to investigate the evolution of the nucleus-nucleus interaction over a large energy range, and also study many different types of nuclear excitations.

II.D.5.1. Single Charge Exchange

The most exciting progress in single charge-exchange studies within the past several years has been concerned with the giant Gamow-Teller (GT) resonance. The giant GT resonance was predicted [Ik63] in 1963 and first observed with 45-MeV protons [Do75] in 1975. However, the truly giant nature of this resonance was clearly demonstrated in (p,n) measurements using 100-200-MeV protons, where the GT resonance was found [Go80, Ba80, Ho80] to dominate completely small angle spectra ($\theta \approx 0^\circ$). The systematics of the GT resonance in both energy and strength, as observed by the (p,n) reactions, has been

established throughout the periodic table. Only about 60% of the GT sum rule strength has been observed experimentally, and this has stimulated considerable theoretical discussion as to whether the quenching arises as a result of configuration mixing or mixing with delta-nucleon hole excitations.

A giant spin dipole resonance has also been identified using the (p,n) reaction at intermediate energies [Ba80, Ho80, Ga81]. In this case, the situation is more complicated than that for the GT resonance because the vector coupling between $L = 1$ and $S = 1$ can lead to final states with spins of $J = 0, 1$, and 2 .

At small momentum transfer the isospin part of the effective N-N interaction is dominated by the central components v_{τ}^C and $v_{\sigma\tau}^C$ (see Fig. II.D.8b) [Pe81, Lo82, Fr85]. Furthermore, as can be seen in Fig. II.D.9, $v_{\sigma\tau}^C$ should dominate the interactions for energies in the range 100-600 MeV. To date, the theoretical predictions have been reasonably well confirmed [Ta82] up to $E \sim 200$ MeV.

Low-energy work with $A > 3$ projectiles has been hindered by strong contributions to the cross section from compound nucleus reactions and multistep processes, as well as by large distortion effects. Comparison of experimental data from the $^{28}\text{Si}(^{18}\text{O}, ^{18}\text{F})^{28}\text{Al}$ reaction at 19.5 MeV/nucleon with microscopic calculations suggests that the direct single-step excitation process accounts for only about 30% of the observed cross section [Ho85].

If the nucleus-nucleus interaction reflects the energy and momentum transfer dependence of the N-N interaction, then spectra from heavy-ion charge exchange reactions should be similar to those from (p,n)

ORNL-DWG 85-18969

Fig. II.D.9. Energy dependence of the ratio of spin-isospin ($t_{\sigma\tau}$) to isospin (t_{τ}) components of the nucleon-nucleon interaction as a function of energy [Fr85].

reactions for beam energies ≥ 100 MeV/nucleon. The observance of such a similarity would indicate that charge-exchange with $A > 3$ projectiles proceeds by a direct single-step reaction mechanism similar to that of the (p,n) reaction. This has recently been demonstrated for ^3He projectiles [E183] at 200 MeV/nucleon and ^{12}C and ^{20}Ne [Ga85] at 900 MeV/nucleon. A comparison between (p,n) and ($^3\text{He},t$) spectra taken at 200 MeV/nucleon is shown in Fig. II.D.10. The strongest peak corresponds to a GT transition between the ground states of ^{12}C and ^{12}N .

The (d,2p) reaction, in which the two protons are emitted in an isovector spin-singlet S-state, would be expected to lead to GT transitions similar to those of the (n,p) reaction. This is because the deuteron is an isoscalar, spin-triplet particle and, hence, the (d,2p) reaction gives rise to spin-isospin transitions. For a $T = 0$ target such as ^{12}C , the spectra for the (p,n) and (n,p) charge-exchange reactions should be similar since the final states are members of an isospin triplet. Preliminary data [Ga85] for the $^{12}\text{C}(d,2p)$ reaction at $E_d = 650$ MeV are shown in Fig. II.D.11 along with spectra for the $^{12}\text{C}(p,n)$ reaction at $E_p = 200$ MeV. (Note that for the (p,n) spectra, excitation energy is plotted in the opposite direction than for the (d,2p) reaction, and the scales differ.) The close similarity between the spectra for the two reactions confirms that the (d,2p) reaction should yield the same nuclear structure information as the (n,p) reaction when intermediate energy projectiles are used to initiate the reactions.

The use of ions with $A > 2$ for charge exchange could offer advantages over the use of light probes such as protons or neutrons. Some of these advantages are: the possibility to achieve better energy resolution,

ORNL-DWG 85-48968

Fig. II.D.10. Comparison of $^{12}\text{C}(p,n)$ and $^{12}\text{C}(^3\text{He},t)$ reactions at 200 MeV/nucleon at angles corresponding to similar momentum transfer [Ga85a].

Fig. II.D.11. Comparison of $^{12}\text{C}(p,n)$ and $^{12}\text{C}(d,2p)$ reactions at angles corresponding to similar momentum transfer [Ga85]. The largest peak in each spectrum corresponds to excitation of the analogue 1^+ state.

greater selectivity for the transferred quantities L , S , and T , and larger cross sections. For example, at energies (> 100 Mev/nucleon) where the charge-exchange reaction is expected to be essentially single step, the (${}^6\text{Li}, {}^6\text{He}$) and (${}^{18}\text{O}, {}^{18}\text{F}$) ground-state to ground-state reactions should lead to only $S = 1$ excitations of the target. On the other hand, the (n, p) reaction can involve both $S = 0$ and $S = 1$ transitions. By judicious choice of projectile, energy, and momentum transfer, it should be possible with heavy ions to enhance selectively a particular type of transition characterized by L , S , and T transfers. The large variety of high-energy beams available with very high beam quality from the proposed accelerator will provide an ideal environment for study of charge-exchange reactions.

II.D.5.2. Double Charge Exchange

The study of double charge-exchange reactions (DCX) can yield information pertaining to two-nucleon correlations. In the past few years, there have been exciting results from investigations of the DCX reaction with pion experiments in which both double-isobaric-analog (DIAS) and nonanalog transitions have been observed [Se83, Bl83]. There is evidence [Mo84] from DCX with pions at $T_\pi = 164$ MeV on $T = 0$ targets that there is a small admixture of delta-nucleon hole (ΔN^{-1}) states into low-lying nucleon-nucleon hole states (NN^{-1}). Such an admixture is also suggested from inelastic pion scattering to $T = 0$ and $T = 1$, 1^+ states in ${}^{12}\text{C}$.

To date there has been very little success in exciting DCX transitions with heavy ions. Some of the problems associated with the use of low-energy heavy ions, such as distortion effects and mismatch of momentum transfer, could be ameliorated with high-energy heavy ions. Heavy ions could then provide an excellent means for studying double charge-exchange transitions.

III.D.6. Baryonic Resonances

The effects of the $\Delta(1232)$ resonance of the nucleon on nuclear structure observables has gained increased attention in the past several years. At excitation energies above those of the nuclear giant resonances, excitation of the delta resonance has been found to dominate the spectra. Investigation of how the delta behaves in the nuclear medium to which it is strongly coupled is being carried out by means of many different kinds of experiments, as well as in different theoretical models. An objective of such research is to study the question of how nuclear wave functions and matrix elements are to be expressed in terms of nucleon and quark degrees of freedom. The apparent necessity of considering nucleon-nucleon (NN) and delta-nucleon (ΔN) admixtures to explain some recent reaction data seems to be serving as an impetus to bridge the areas of low- and high-energy nuclear physics.

In a recent triple-coincidence measurement of the $^{13}\text{C}(p,d2p)$ reaction, where the outgoing protons were detected in back-to-back geometry, a narrow structure was observed at an energy similar to that expected for the formation of a delta near minimum momentum transfer [Mo83]. The observed energy of this structure corresponds to a shift downward of about 60 MeV from the 300 MeV expected for a ΔN^{-1} excitation. A possible mechanism for production of the back-to-back protons could be a delta + nucleon ($\Delta + N$) interaction (e.g., $p + \Delta^+ \rightarrow p + p$ or $n + \Delta^{++} \rightarrow p + p$). In measurements of the $(^3\text{He},t)$ reaction at 2 GeV, excitation of the delta has been observed with ~ 100 mb/sr cross sections at 0° for targets from hydrogen to lead. The centroid of the observed

resonance, however, is found to be shifted downward by about 40 MeV in excitation energy relative to the position expected for quasifree delta production [Ga85]. The cross section seems to saturate near $A \sim 50$, and this has been interpreted as an indication that the $(^3\text{He}, t)$ reaction is surface localized.

On the other hand, a strong resonance in total photoabsorption cross sections is found [Ha85] at an excitation energy of 300 MeV, the energy of the delta resonance. The position of this resonance appears to be nearly independent of nuclear mass, and the cross section per nucleon is essentially constant. This implies that the photoabsorption interaction takes place essentially over the whole nuclear volume.

Excitation of the delta has also been observed in heavy-ion charge-exchange reactions using 900 MeV/nucleon beams [Ba85]. In this case an interesting feature is the sensitivity, to the choices of projectiles and targets, of the ratios of the relative cross sections for excitation of the nuclear giant resonances to that for the delta resonance.

The variety of projectiles that will become available with the proposed accelerator will open a new range of studies of the delta excitation. These could include investigations of the effects of forming a delta with different momentum transfer or in different final states. It is envisaged that such experiments would include measurements of both singles and coincidence events. Detectors capable of recording delta modes of decay will be required.

II.D.7. Transfer Reactions

Reactions involving the transfer of one or more nucleons between target and projectile nuclei have been used for many years to study nuclear structure. For the most part, these reactions have involved relatively low-energy, light projectiles and the techniques for data analysis and theoretical interpretations are well-developed. Heavy ion induced reactions, however, offer a diversity of projectiles which allow the study of reactions not accessible with light ions. Measurements of transfer reactions with low-energy heavy ions have already provided a wealth of data on nuclear reaction mechanisms and nuclear structure, and the availability of good quality high-energy heavy projectiles will allow extension of these studies to previously unexplored mass and energy regimes.

II.D.7.1. "Spectral Function" Determination

One of the primary reasons for studying pickup reactions is to determine the energy and momentum distribution, or "spectral function," for nucleons bound by the nuclear potential. Proton spectral functions have traditionally been studied by using $(e,e'p)$ and $(p,2p)$ reactions. Until recently, these measurements suffered from poor energy resolution and included only nuclei with $A < 60$ (see [Fr84] for review of earlier data). However, there have now been made high resolution $(e,e'p)$ measurements which include ^{90}Zr and ^{208}Pb targets and also provide data on low-lying excited states of the residual nuclei [La85]. By careful choice of projectile-ejectile combinations, heavy-ion-induced pickup reactions may

be tuned to study selected excitation energies [As84] and provide a powerful technique for measuring both proton and neutron spectral functions. The knockout data can then be used to test the spectroscopic strengths extracted in the pickup reaction. Such tests have proven useful in the case of ^{90}Zr , where apparent discrepancies between $(e,e'p)$ and $(d,^3\text{He})$ strengths may indicate that problems exist in the analysis of transfer data even at low (52 MeV) projectile energies [De85]. Ideally, measurements should be made for a variety of projectile masses and energies to determine the reaction processes contributing to nucleon transfer (multi-step processes are expected to become more important at higher energies [As84]) and to develop techniques for extracting the spectral function. Beams available from the proposed accelerator would be ideal for these studies. At present, there is little overlap of the knockout and transfer reaction data for deep-hole states. The pickup results have been summarized by Gales [Ga83, Ga85a] and mostly involve neutron pickup from heavier targets. Thus, emphasis might be placed initially on the study of proton pickup from targets for which knockout data already exist.

II.D.7.2. Inverse (p,2p) Reactions

A technique which has been proposed for studying nuclear structure with high-quality, heavy-ion beams is the inverse of the $(p,2p)$ reaction; a heavy-ion beam is used to bombard a proton target [Ha84]. The major advantage of this inverse reaction, as noted by Faessler [Fa85], is that the background due to multistep processes would be kinematically focused

at small angles. The inverse-knockout reaction might also prove to be one of the cleanest ways to search for correlated nucleon structures, such as α -clusters, by studying more exotic processes such as the inverse $(p, p\alpha)$ reaction. Other possible extensions might include the use of polarized targets (polarized gas jet?) to study the spin-orbit splitting for tightly bound nucleons. The viability of making asymmetry measurements has been demonstrated for the case of $(p, 2p)$ reactions with polarized beams [Ki80, An81].

Multinucleon transfer reactions have been used extensively to study exotic excited states of nuclei [Ar84]. For these reactions, the use of heavy ions becomes particularly attractive since certain types of states, such as proton-pairing vibrations, are not readily studied with light projectiles. For example, strong excitation of the 0^+ ground state has been observed in the $(^{14}\text{C}, ^{16}\text{O})$ reaction at low (4-7 MeV/nucleon) bombarding energies [Wa84, Bo83, Pe82].

II.D.8. γ , β , and Particle Spectroscopy of Nuclei Far from Stability

Of the more than 7000 nuclei predicted to be particle stable only about one-fourth have been observed (see Fig. II.D.12). Naturally occurring stable and radioactive nuclei number 300 or so, while another 1600 radioisotopes have been identified and studied during the past 50 years. Our knowledge of nuclear physics is thus, perforce, based on the properties of these 1900 nuclides. One can only speculate what the implications for both nuclear physics and astrophysics will be as the boundaries of known nuclei are extended closer to the limits of particle stability, the so-called neutron and proton drip lines.

The richness of new phenomena still to be explored can be illustrated by noting highlights observed in the study of exotic nuclei during the past few years (see, e.g., the recent review of Hamilton et al. [Ha85a]). Exemplifying these new phenomena are: coexistence of deformed and spherical shapes in nuclei, closed subshells at Z equal to 40 and 54, and new regions of very strong deformation around $N = Z = 38$ and around $Z = 38$, $N > 50$. Ground-state proton decay has been identified for several rare earth isotopes, and β -delayed $2n$, $3n$, $2p$, and ^3He emissions have been seen in the light-mass region. Along the line of stability ^{14}C decay has been observed from $^{222,223,224}\text{Ra}$, while the number of known elements has been extended to 109 with the discovery of the alpha decay of one atom of $^{266}109$.

The investigation of exotic nuclei probes an important dimension in nuclear structure represented by large changes in the number of protons vs neutrons. Nuclear density for example is remarkably constant

Fig. II.D.12. Nuclidic chart shown as a plot of neutron number vs proton number. Beta-stable nuclides are indicated by black squares. The shaded area encompasses isotopes that have been synthesized. The white areas, delineated by the proton and neutron drip lines, include nuclei that have been predicted to be stable with respect to particle decay.

throughout the known periodic table. Should the density decrease in nuclei with many extra neutrons, the use of theoretical mass formulas for estimating nuclear stability could be in serious error. An imbalance in either neutrons or protons might affect the relative importance of the effective nn, pp, and np interactions. Detailed understanding of extremely neutron-rich nuclei such as ^{40}Mg and ^{70}Ca would be a challenge for existing models that have been developed and tested near the valley of stability.

Since the limits of neutron stability have been reached only in the very light mass region, a vast number of nuclei existing under extreme conditions still remain to be investigated. Explorations of the properties of these nuclei will involve mass and Q-value determinations, half-life measurements, studies of energy level systematics, examinations of the continuum of highly excited states fed in β decays, and searches for new modes of radioactivity.

II.D.8.1. Very Neutron-Rich Nuclei

As seen in Fig. II.D.12, it is the neutron-rich nuclei that present the most challenging limit because they can exist so far beyond the presently known nuclides. Approximately three-fourths of the isotopes still to be found are on the neutron-rich side of stability. Two methods to produce these nuclei are currently in use: deep inelastic scattering or transfer reactions and fragmentation. By necessity, both approaches utilize heavy-ion reactions.

The first of these methods, pioneered by Volkov and collaborators [Ar71], is based on the fact that the neutron-to-proton ratio is

equilibrated rapidly during the early stage of the deep inelastic reaction. A composite system is formed which then separates into two fragments with kinetic energies equal to the Coulomb repulsion and with N/Z ratios of the intermediate system. Thus, a heavy target will enrich the projectile-like fragment in neutrons. Limitations of this method are the large angular and energy dispersions of the ejectiles and the necessity of using thin targets.

Relativistic heavy-ion projectile fragmentation as a source of neutron-rich nuclides has been investigated at the Bevalac [Sy79, We79] and, more recently, at the GANIL Laboratory [La85a, Gu85]. In this technique, a high-velocity heavy nucleus impinges on a light target producing a nuclear reaction in which a large part of the projectile does not interact. The noninteracting part of the projectile proceeds very much as a spectator with about the same initial velocity along the projectile trajectory. The resulting "fragmentation" products are focused in a narrow cone around the projectile direction. Since detection apparatus usually have small angular acceptances, the forward angle focusing of the products means a gain of several orders of magnitude in detection efficiency. In addition, because of the high energies involved, thick targets (g/cm^2 instead of mg/cm^2) can be used without hindering the escape of the exotic products. These factors compensate for the low intensities that are presently available for heavy ions in the 200-1000 MeV/nucleon energy regime.

The most recent and comprehensive endeavors in the production of nuclei far from stability by means of fragmentation have been made at

GANIL by using Ar, Ca, and Kr beams with incident energies in the range of 30 to 80 MeV/nucleon. The basic component of the isotope identification system used in these studies is a spectrometer which is a triple-focusing analyzer using two identical dipoles. The first 45° dipole magnet selects the $B\rho$ of the fragments while the second compensates for the dispersion and focuses products onto a series of solid-state detectors used to measure energy loss and total energy. With this system, a total of about 20 new neutron-rich nuclides have been identified. A display of the observed fragments is shown in Fig. II.D.13. Significantly, 15 of these isotopes, ranging from ^{47}Ar to ^{70}Co , were produced in ^{86}Kr irradiations [Gu85] despite the fact that the Kr ion energy, 33 MeV/nucleon, was clearly not optimum for the fragmentation process. Higher energies would ensure a better focusing of the fragments around zero degrees and, thus, provide a much improved collection and concomitant detection efficiency. To illustrate the improved capabilities provided by the proposed accelerator, we have made fragmentation calculations for the production of ^{50}Ca by ^{86}Kr projectiles from the proposed accelerator assuming, at 33 MeV/nucleon, a momentum spread of $\Delta p/p = 7.6\%$ and an emittance $\epsilon = 74 \pi \text{ mm-mrad}$ and at 800 MeV/nucleon, $\Delta p/p = 2.4\%$ and $\epsilon = 16 \pi \text{ mm mrad}$. The higher energy corresponds to an enhancement of about 70 in the phase space density, which will make possible a large improvement in the detection efficiency. The net result is that the study of many nuclei having very small fragmentation cross sections becomes feasible.

Up to now, most fragmentation investigations have involved only the determination of the existence or nonexistence of specific nuclei.

ORNL-DWG 86-7212

Fig. II.D.13. Isotopes of various elements produced in the fragmentation of 33-MeV/nucleon ^{86}Kr ions incident on a target of titanium [Gu85].

In a majority of studies, half-lives, decay modes, and nuclear masses have not been determined; thus a wealth of spectroscopic and mass information remain to be established for the identified isotopes. It must also be remembered that existing facilities such as GANIL are not appropriate for the investigation of new medium and heavy nuclei because of accelerator limitations in projectile mass, energy, and intensity. The proposed accelerator will provide ion beams with $A > 200$ and with energies in excess of 500 MeV/nucleon which will open the possibility for production of hundreds of new exotic nuclei. The beam intensity from the proposed accelerator will be adequate to produce sufficient quantities of the new nuclei to permit the study of their decay characteristics. The recoil mass spectrometer, for which a proposal is being developed at HHIRF, will be very useful for these studies.

II.D.8.2. Use of Secondary Beam to Produce Exotic Nuclei

Beams of secondary particles produced by means of heavy-ion fragmentation reactions can be used to induce nuclear reactions which cannot be studied by other means. An example of the use of this technique is a recent experiment to measure the radii of exotic nuclei [Ta85]. High energy beams of ^{20}Ne and ^{11}B bombarded a Be target and produced energetic nuclear fragments. Lithium and beryllium nuclei, the secondary products from the initial reaction, with 790 MeV/nucleon were identified with the use of magnetic analysis, time-of-flight information, and charge discrimination and were used to bombard targets of Be, C, and Al. From the measured total interaction cross sections, root-mean-square

nuclear radii were deduced for ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^8\text{Li}$, ${}^9\text{Li}$, ${}^{11}\text{Li}$, ${}^7\text{Be}$, ${}^9\text{Be}$, and ${}^{10}\text{Be}$. Appreciable differences between the radii of isobars were observed for the first time. In addition, it was found that ${}^{11}\text{Li}$ seems to have an extremely large radius, indicating either strong deformation or a long tail in the ${}^{11}\text{Li}$ matter distribution. It is readily envisioned that the technique of secondary particle reactions will be applicable over a wide range of mass and atomic numbers, possibly extending to both the neutron and proton drip lines.

Secondary beams from fragmentation can also be used to produce exotic nuclei through compound-nuclear reactions. However, the high energies of such beams render them unsuitable for directly initiating compound-nuclear reactions. This limitation can be overcome by re-injecting the secondary beams into a synchrotron ring for cooling and deceleration. The fully stripped secondary beams can be stored at pressures of $\sim 10^{-11}$ Torr for several minutes because their electron-loss cross sections are zero and the capture cross sections are less than 1 mb. These beams can therefore be decelerated to energies as low as 5 MeV/nucleon, and used to bombard external targets, etc.

Secondary neutron-deficient beams should prove especially beneficial for the production of proton-rich nuclei near the proton drip line, where the evaporation of charged-particles overwhelms the emission of neutrons from the compound system. Secondary projectiles, such as ${}^{38}\text{Ca}$ and ${}^{56}\text{Ni}$, would produce compound nuclei located much closer to the heavier isotopes of interest than can be achieved by reactions initiated by beams of conventional, stable ions. As a result of using

incident proton-rich beams, the number of neutrons to be evaporated is reduced, leading to an increased yield relative to reactions involving charged-particle evaporation. With a primary beam of $\sim 10^{11}$ particles/s, secondary beams of $\sim 10^6$ or 10^7 particles/s can be produced [Bi85]. For a reaction cross section of 1 mb, a production (or disintegration) rate in the range of 0.01 to 0.1 per second is anticipated for the production of nuclei near the proton drip line. These rates are acceptable for measurements of decays such as α -particle or proton emission. As an example, the superallowed β -decay of ^{35}Ca was recently identified [Ay85] by observing a total of 20 two-proton decay events. Despite the low statistics, it was possible to determine both the half-life, 50 ± 30 ms, and the mass excess, 4453 ± 60 keV, of ^{35}Ca . With only a few hours of beam time, the production rates mentioned above as achievable with the proposed accelerator would lead to much better statistical quality data than that obtained in the ^{35}Ca experiment [Ay85].

Neutron-rich secondary beams can also be utilized to produce isotopes on the proton-deficient side of stability via compound-nuclear reactions. In this case, because of the large region of predicted neutron-stable nuclei, such reactions will not be able to probe nuclear structure near the neutron drip line. Nevertheless, the use of secondary beams may prove to be advantageous in many cases where reaching a certain neutron number might be critical.

II.D.8.3. g-Factor Measurements Utilizing Energetic Beams

Since the proposed accelerator will produce nuclei having both extremely large recoil velocities and highly stripped electron configurations, the new facility should provide an unusual opportunity for the measurement of nuclear gyromagnetic ratios (g-factors). The value of the nuclear g-factor is an important quantity in that it is very sensitive to the microscopic structure of nuclear states. From g-factor measurements, it has been possible to differentiate between neutron and proton configurations of single-particle states. Further, from the collective g-factor, it is possible to determine the relative contributions of protons and neutrons to the moment of inertia.

The g-factor is measured by observing the Larmor precession of a nuclear state in a magnetic field. To achieve a precession angle θ , the lifetime of the state has to be longer than

$$\tau = 20.9 \theta / g B \quad \text{ps},$$

where θ is in mrad, g is the g-factor, and B is the magnetic field strength in tesla (T). It is obvious that, to study short-lived nuclear states, a strong magnetic field has to be used. When a superconducting magnet and the hyperfine field at the nucleus are used, it is feasible to produce a field of the order of 10 - 100 T; hence, states with lifetimes ranging from 200 to 20 ps can be studied. Recently, a technique [Ha80] that made use of the transient magnetic field experienced by nuclei while slowing down in polarized ferromagnetic media was developed to provide even higher fields. The strength of the transient field increases with the recoil velocity, v , and the atomic number, Z , of

the nucleus until the velocity reaches Zv_0 (v_0 is the Bohr velocity, $c/137$). Except for a few cases of light nuclei, such as carbon and oxygen, this maximum field has not yet been reached [Sp81], due to the low recoil velocities available in most reactions. An empirical formula for the transient field, B , has been derived from experimental data [Ha80]. It gives

$$B = 11 Z v/v_0 \quad \text{Tesla} \quad (v/v_0 > 1.4). \quad (\text{II.D.1})$$

It can be seen that a field strength in the range of a thousand Tesla can be achieved for heavy ions. With an "inverse reaction" where a light target is bombarded with a heavy projectile, it is possible to achieve a very large recoil velocity and hence very large transient fields. For example, with a 2-GeV ^{164}Dy beam and ^4He target, the compound nucleus formed has a recoil velocity of $0.16c$, which will give a field of ~ 17 kT. Under these conditions, states with lifetimes as short as 0.1 ps can be studied. Such a measurement, with a primary beam intensity of 10^{10} particles/sec, can yield greater than 10,000 counts/sec in typical experimental arrangements.

The expression (Eq. II.D.1) for the effective transient field is based on low-velocity systematics (up to $v/v_0 \sim 5.5$). It is conceivable that the transient fields for heavy recoils at very high velocities could be much larger than the formula indicates. The large transient fields experienced by fast ions traversing magnetized foils appear ([Sp81] and references therein) to arise from the effective magnetic fields produced at the nucleus by bound unpaired electrons (primarily in s-orbitals). The ultimate limit to the transient field,

therefore, must be some fraction of B_{1s} (the effective field due to a 1s electron in a hydrogen-like ion):

$$B_{ns} = \frac{16.7 Z^3}{n^3} F_{1s} \text{ Tesla,} \quad (\text{II.D.2})$$

where F_{1s} is a relativistic correction factor which is nearly one for small Z (<30), and reaches ~ 3 at large Z values. Clearly, the ultimate limit of B_{1s} for the field strength is very large (~ 7.9 MT for $Z = 66$) and is expected to be approached at velocities $v/v_0 \sim Z$. At lower velocities, the fraction of B_{1s} observed would be given roughly by the fraction of ions in the 1s orbital during passage, multiplied by the net s-electron polarization of these ions traversing the foil. It is conceivable that fields as large as a few percent of B_{1s} might be reached in transient field experiments at high velocities, making it possible to study excited states with lifetimes as short as $10^{-14} - 10^{-15}$ seconds.

Experimental methods utilizing the nuclear quantum-beats effect [Ra73, Li78] have been devised to use the B_{1s} field directly in free hydrogen-like ions. These techniques have been limited by existing accelerators to light ions. The proposed accelerator will provide energies which will allow production of hydrogen-like ions of any element. Quantum beats in hydrogenic high- Z ions could produce measurable perturbed angular correlation effects in states with lifetimes near 10^{-17} seconds, offering, in principle, the possibility of g-factor measurements on even unbound resonance states. In this type of experiment the properties of the secondary products are measured directly. Thus, the $10^5 - 10^6$ secondary particles/second, which can be

produced in a typical fragmentation reaction with the proposed accelerator, will be sufficient for the study of many nuclei. Such studies are possible only with a high-intensity primary beam as provided by the proposed accelerator.

III.D.9. References

- An81 L. Antonuk, P. Kitching, C. A. Miller, D. A. Hutcheon, W. J. McDonald, G. C. Neilson, W. C. Olsen, and A. W. Stetz, Nucl. Phys. A370, 389 (1981).
- Ar71 A.G. Artukh, U.U. Avdeichikov, G.F. Gridnev, V.L. Mikheev, V.V. Volkov, and J. Wilczynski, Nucl. Phys. A176, 284 (1971).
- Ar84 A. Arima and S. Kubono, p. 463 in Treatise on Heavy-Ion Science, Vol 1, ed. D. A. Bromley (Plenum Press 1984)
- Ar85 P. Armbruster et al., Phys. Rev. Lett. 54, 406 (1985).
- As84 R. J. Ascuitto and E. A. Seglie, p. 463 in Treatise on Heavy-Ion Science, Vol. 1, ed. D. A. Bromley (Plenum Press 1984).
- Ay85 J. Aystö, D. M. Moltz, X. J. Xu, J. E. Rieff, and Joseph Cerny, Phys. Rev. Lett. 55, 1384 (1985).
- Ba80 D. E. Bainum, J. Rapaport, C. D. Goodman, D. J. Horen, C. C. Foster, M. B. Greenfield, and C. A. Goulding, Phys. Rev. Lett. 44, 1751 (1980).
- Ba85 D. Bachelier, J. L. Boyard, T. Hennino, J. C. Jourdain, M. Roy-Stephan, D. Contardo, J. Y. Groissord, A. Guichard, J. R. Pizzi, R. Radvanyi, J. Tinsley, C. Ellegaard, C. Gaarde, and J. S. Larsen, submitted to Phys. Lett.
- Be76 F. E. Bertrand, Ann. Rev. Nucl. Sci. 26, 457 (1976).
- Be80 F. E. Bertrand, ed., Giant Multipole Resonances, (Harwood Academic, New York, 1980).
- Be81 F. E. Bertrand, Nucl. Phys. A354, 129 (1981).
- Be83 G. F. Bertsch, P. F. Bortignon, and R. A. Broglia, Rev. Mod. Phys. 55, 287 (1983).
- Be85 C. A. Bertulani and G. Baur, Nucl. Phys. A442, 739 (1985).
- Bi85 R. Bimbot, S. Della Negra, P. Aguer, G. Bastin, R. Anne, H. Delagrange, and F. Hubert, Z. Phys. A322, 443 (1985).
- Bl83 L. C. Bland, R. Gilman, M. Carchidi, K. Dhuga, C. L. Morris, H. T. Fortune, S. J. Greene, P. A. Seidl, and C. F. Moore, Phys. Lett. 128B, 157 (1983).

- Bo69 A. Bohr and B. R. Mottelson, *Nuclear Structure*, Vol. I (Benjamin, New York, 1969).
- Bo75 A. Bohr and B. R. Mottelson, Vol. II (Benjamin, New York, 1975).
- Bo81 P. F. Bortignon and R. A. Broglia, *Nucl. Phys.* A371, 405 (1981).
- Bo83 P. D. Bond, R. F. Casten, D. D. Warner, and D. Horn, *Phys. Lett.* 130B, 167 (1983).
- De85 J.W.A. Den Herder, P. C. Dunn, E. Jans, P.H.M. Keizer, L. Lapikas, E.N.M. Quint, P.K.A. De Witt Huberts, H. P. Blok, and G. Van Der Steenhoven, *Phys. Lett.* 161B, 65 (1985).
- Do75 R. R. Doering, A. Galonsky, D. M. Patterson, and G. F. Bertsch, *Phys. Rev. Lett.* 31, 1961 (1975).
- E183 C. Ellegaard, C. Gaarde, J. S. Larsen, C. Goodman, I. Bergqvist, L. Carlen, P. Ekstrom, B. Jakobsson, J. Lyttkens, M. Bedjidian, M. Chamcham, J. Y. Grossiord, A. Guichard, M. Gusakow, R. Haroutunian, J. R. Pizzi, D. Bachelier, J. L. Boyard, T. Hennino, J. C. Jourdain, M. Roy-Stephan, M. Boivin, and P. Radvanyi, *Phys. Rev. Lett.* 50, 1745 (1983).
- Fa85 A. Faessler, *Workshop on Intermediate Energy Heavy Ion Physics*, Oak Ridge, 1985.
- Fr84 S. Frullani and J. Mougey, in *Advances in Nuclear Science*, Vol. 14, ed. J. W. Negele and E. Vogt (Plenum Press 1984).
- Fr85 M. A. Franey and W. G. Love, *Phys. Rev. C* 31, 488 (1985).
- Ga81 C. Gaarde, J. Rapaport, T. N. Taddeucci, C. D. Goodman, C. C. Foster, D. E. Bainum, C. A. Goulding, M. B. Greenfield, D. J. Horen, and E. Sugarbaker, *Nucl. Phys.* A369, 258 (1981).
- Ga83 S. Gales, p. C4-14 in Proceedings, International Symposium on Highly Excited States and Nuclear Structure, Orsay 1983.
- Ga85a S. Gales, *Niels Bohr Conference on Nuclear Structure*, Copenhagen, 1985.
- Go80a C. D. Goodman, p. 149 in The (p,n) Reaction and the Nucleon-Nucleon Force, ed. C. D. Goodman, S. A. Austin, S. D. Bloom, J. Rapaport, G. R. Satchler (Plenum Press, New York, 1980).

- Go80b C. D. Goodman, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, C. C. Foster, W. G. Love, and F. Petrovich, *Phys. Lett.* **44**, 1755 (1980).
- Go84 A. Goldberg, *Nucl. Phys.* **A240**, 636 (1984).
- Gu83 C. Guet, *Nucl. Phys.* **A400**, 191c (1983).
- Ha84 D. Habs, p. D-3 in Workshop on the Physics with Heavy-Ion Cooler Rings, Heidelberg 1984.
- Ha85 Evans Hayward, p. 131 in Capture Gamma-Ray Spectroscopy and Related Topics-1984, ed. S. Raman (American Institute of Physics, New York, 1985).
- Ha85a J. H. Hamilton, P. G. Hansen, and E. F. Zganjar, *Rep. Prog. Phys.* **48**, 631 (1985).
- Ho80 D. J. Horen, C. D. Goodman, C. C. Foster, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, E. Sugarbaker, T. G. Masterson, F. Petrovich, and W. G. Love, *Phys. Lett.* **95B**, 27 (1980).
- Ho84 B. Hoffman and G. Baun, *Phys. Rev. C* **30**, 247 (1984).
- Ho85 D. J. Horen, B. L. Burks, M.A.G. Fernandes, R. L. Auble, F. E. Bertrand, J. L. Blankenship, J.L.C. Ford, Jr., E. E. Gross, D. C. Hensley, F. Petrovich, R. O. Sayer, G. R. Satchler, D. Shapira, and T. P. Sjoreen, Phys. Div. Prog. Rept. for Period Ending Dec. 30, 1985, ORNL-6233.
- Ik63 K. Ikeda, S. Fujii, and J. I. Fujita, *Phys. Lett.* **3**, 271 (1963).
- Ja75 J. D. Jackson, Classical Electrodynamics, 2nd ed., Wiley, N.Y., 1975).
- Ki80 P. Kitching, C. A. Miller, W. C. Olsen, D. A. Hutcheon, W. J. McDonald, and A. W. Stetz, *Nucl. Phys.* **A340**, 423 (1980).
- La85 L. Lapikas, *Nucl. Phys.* **A434**, 85c (1985).
- La85a M. Langevin, E. Quiniou, M. Bernas, J. Galin, J. C. Jacmart, F. Naulin, F. Pougheon, R. Anne, C. Detraz, D. Guerreau, D. Guillemaud-Mueller, and A. C. Mueller, *Phys. Lett.* **150B**, 71 (1985).
- Li78 Y. C. Lin, Ph.D. Thesis, State University of New York at Stony Brook (1978).

- Lo82 W. G. Love and M. A. Franey, Phys. Rev. C 24, 1073 (1982); (E) Phys. Rev. C 27, 438 (1983).
- Me84 M. T. Mercier, J. C. Hill, F. K. Wohn, and A. R. Smith, Phys. Rev. Lett. 52, 898 (1984).
- Mo83 C. L. Morris, J. F. Amann, S. J. Seestrom-Morris, J. A. McGill, C. Glasshausser, K. Jones, S. Nanda, M. Barlett, G. W. Hoffman, C. Milner, C. F. Moore, J. R. Comfort, L. C. Bland, and R. Gilman, Phys. Lett. 123B, 37 (1983).
- Mo84 C. L. Morris, p. 161 in Spin Excitations in Nuclei, edited by F. Petrovich, G. E. Brown, G. T. Garvey, C. D. Goodman, R. A. Lindgren, and W. G. Love (Plenum Press, New York, 1984).
- Pe81 F. Petrovich and W. G. Love, Nucl. Phys. A354, 499c (1981).
- Pe82 D. Pereira, H.-J. Korner, G. Korschinek, W. Mayer, and H. J. Scheerer, Z. Phys. A308, 361 (1982).
- Ra73 W. L. Randolph, N. Myres de Campos, J. R. Beene, J. Binde, M. A. Grace, D.F.H. Start, and R. E. Warner, Phys. Lett. 44B, 26 (1973).
- Se83 P. A. Seidl, R. R. Kiziah, M. K. Brown, C. F. Moore, C. L. Morris, H. Baer, S. J. Greene, G. R. Burleson, W. B. Cottingham, L. C. Bland, R. Gilman, and H. T. Fortune, Phys. Rev. Lett. 50, 1106 (1983).
- Sp81 K. H. Speidel et. al., Z Phys. A302, 107 (1981).
- Sp85 J. Speth, D. Cha, V. Klempt, and J. Wambach, Phys. Rev. C 31, 2310 (1985).
- Sy79 T.J.M. Symons, Y. P. Viyogi, G. D. Westfall, P. Doll, D. E. Greiner, H. Faraggi, P. J. Lindstrom, D. K. Scott, H. J. Crawford, and C. McParland, Phys. Rev. Lett. 42, 40 (1979).
- Ta82 T. N. Taddeucci, J. Rapaport, D. E. Bainum, C. D. Goodman, C. C. Foster, C. Gaarde, J. S. Larsen, D. J. Horen, T. Masterson, and E. Sugarbaker, Phys. Rev. C 25, 1094 (1982).
- Ta85 I. Tanihata, H. Hamagaki, O. Hashimoto, Y. Shida, N. Yoshikawa, K. Sugimoto, O. Yamakawa, T. Kobayashi, and N. Takahashi, Phys. Rev. Lett. 55, 2676 (1985).
- Wa84 R. Wadsworth, M. D. Cohler, S. M. Lane, M. J. Smithson, D. L. Watson, R. E. Brown, D. M. Drake, J. C. Peng, N. Stein, and J. W. Sunier, J. Phys. (London) G10, L79 (1984).

- We79 G. D. Westfall, T.J.M. Symons, D. E. Greiner, H. H. Heckman,
P. J. Lindstrom, J. Mahoney, A. C. Shotter, D. K. Scott,
H. J. Crawford, C. McParland, T. C. Aves, C. K. Gelbke, and
J. M. Kidd, Phys. Rev. Lett. 43, 1859 (1979).
- Wi35 E. J. Williams, Matt. Fys. Medd Dans. Vid. Selsk 13, No. 4
(1935).
- Wi79 A. Winther and K. Alder, Nucl. Phys. A319, 518 (1979).

II.E. INTERDISCIPLINARY STUDIES AND ATOMIC PHYSICS

The availability of ions of any element in the Periodic Table ($1 < Z < 92$) with a specific energy greater than 0.5 GeV/nucleon allows for the production, with substantial yield, of the fully stripped ($q = Z$) ionic species. Unique and important research opportunities are provided in atomic physics, and in the interface areas of atomic physics with nuclear physics and with solid state physics, when the selective preparation of the fully stripped, one-, two-, and few-electron atomic systems are possible for the highest- Z elements. Ions with ionic charge, q , result from collisions when the ion velocity exceeds the orbital velocity of the last bound electron in the $(q-1)$ species. This simple ion-velocity dependence, the "Bohr criterion" for the electron-capture and electron-loss processes, has been found to be generally valid although subject to various refinements and improvements. The approximate ion velocity, or specific ion-energy, required to produce substantial yields of the hydrogenlike (1e), heliumlike (2e) and lithiumlike (3e) atomic systems as a function of the atomic number of the ion, Z , is displayed in Figure II.E.1.

Precision tests of quantum electrodynamics (QED) in strong Coulomb fields, important benchmarks for QED, are possible in studies of the one-, two-, and few-electron systems of the highest Z ionic systems. These include energy level splittings and lifetime determinations, determination of the single electron hyperfine structure and determination of the anomalous magnetic moment, gJ , for bound electrons in a strong

Fig. II.E.1. The approximate velocity dependence, $\beta = v/c$, required for the production of significant population of the 1-, 2-, and 3-electron ion as a function of atomic number, Z . For the proposed accelerator, the production of all ionic charges up to $q = Z$ is possible.

Coulomb field. In collisions, the study of superheavy "quasi-atoms" in the critical field QED limit is possible, as are extensions of the entire broad field of atomic collision physics. The spectroscopy of unique ionic species has applications in the study of both astrophysical and fusion plasmas. Of astrophysical interest is the possibility, provided by radioactive beams, for the determination of reaction rates for low energy neutron capture reactions on normally unstable targets by measuring the (d,p) reaction with inverted kinematics.

The large magnitude of the magnetic field at the nucleus created by the presence of a single 1s electron in high-Z systems can permit the determination of nuclear g-factors for states with lifetimes as short as 0.01 femtosec, and the hyperfine splitting may permit a unique resolution of the problem of "hyperfine structure anomalies."

Channeling and blocking of relativistic heavy ions traversing single crystals also provides new and unique research opportunities, including the selective production of spin polarized ions, the study of ion capture and loss processes in a dense "electron gas," and determinations of nuclear reaction times on the scale of 10^{-20} sec.

Some of the more unique of these research opportunities are outlined in this section.

II.E.1. Strong Coulomb Field Quantum Electrodynamics ($Z > 80$)

Field theory quantum electrodynamics (QED), the first of the successful quantum-gauge theories, provides an accurate description of electromagnetic interactions. The theory is well understood, is moderately tractable, although cumbersome (and tedious) perturbative techniques must be used, and precision tests of the theory have been provided in atomic and muonic systems. The so-called anomalous magnetic moments ($gJ-2$) of the electron and muon, energy level shifts (Lamb shifts) in one-, two-, and few-electron systems and in muonic systems, positronium and muonium levels, and determinations of the hyperfine structure in hydrogen have all provided important confirmations of the validity of QED. No real conflicts between theory and experiment exist and refinements in both experiment and theory have been made for those cases where there was apparent disagreement. Good reviews of this topic are found in references [Dr82, Bo85, Br78, and Le81].

The validity of QED is a necessary prerequisite for more general unified field theoretical development, and more stringent tests of QED remain to be done. One of the most important regions to probe is the strong Coulomb field, bound state regime, such as that provided by the study of high- Z one-, two-, and few-electron systems. In this case, perturbative expansions are of limited usefulness because the potential is comparable to the rest mass of the electron ($Z\alpha \approx 1$). One important research component connected to any accelerator capable of accelerating the highest- Z ions to energies required for the production of the

fully stripped species will be the investigation of the validity of QED in this strong field limit.

The proposed accelerator will provide unparalleled opportunities for such investigations. Several unique experimental tests are envisaged which probe various aspects of, and terms in, QED in strong Coulomb fields. With single-electron, hydrogenlike ions as an example, the important QED corrections to the Dirac binding energy for the 1s electron are shown in Fig. II.E.2. The calculations are from the recent work of Johnson and Soff [Jo84], which are in agreement with the limited calculations ($Z < 40$) of Mohr [Mo83].

The various terms in Fig. II.E.2 are the total energy shift (LAMB), the self energy (SELF), the vacuum polarization (UEHL), the finite nuclear size (FS), the finite size correction to the self energy (S-FS), finite size correction to vacuum polarization (U-FS), higher order terms in the vacuum polarization (W.K.), and higher order corrections (H.O.). The dominant corrections to the Dirac binding energy are the radiative terms, self energy and vacuum polarization, and the finite size corrections which become about 30% of the total shift at $Z = 92$. The total shift for the 1s level in uranium is about 460 eV, to be compared to the energy of the Lyman-alpha (2p-1s) line of about 98 keV. To be at least as significant to QED as the most precise previous measurement for $Z > 10$, that of Beyer et al. [Be85] for argon ($Z = 18$), a measurement in uranium for the Lyman-alpha line would have to be made to an accuracy of 75 ppm. With cooled and decelerated uranium beams, such measurements could be performed with the proposed accelerator and would probe different terms in the QED shifts different from those studied in argon

1s LAMB-SHIFT IN HYDROGEN-LIKE IONS

Fig. II.E.2. Contributions to the Lamb-shift of K-shell electrons in hydrogenlike atoms versus the nuclear charge number Z . The energy shift ΔE is presented in units of $\alpha/\pi (Z\alpha)^4/n^3 mc^2$ [Jo84].

(see Fig. II.E.2). Lyman-alpha line measurements to high precision require both cooled and decelerated beams to minimize the Doppler shift and Doppler width corrections that must be applied. Typical energy and emittance design goals for the highest precision measurements are $\sim 10^{-5}$ for $(\Delta E/E)$ and < 0.01 mm-mrad as discussed by Deslattes [De 85].

Determination of the anomalous magnetic moment of an electron bound in a strong Coulomb field (e.g., gJ in hydrogenic $^{23}\text{Pu}(91^+)$ in the $1s$ state) may also provide unique QED sensitivity. An experiment of this type would involve the selective production of electron spin polarized ions in, for example, direct K-shell radiative electron capture from polarized electrons. This could be accomplished by channeling in ferromagnetic single crystals. An atomic-beam magnetic resonance experiment could be performed in a Ramsey double-loop apparatus to provide the electron spin-flip transition frequency. Such experiments have been proposed and could best be performed at the proposed accelerator (see [Go83, Go85, and Be86]) because of the high quality beam characteristics. The beam characteristics for efficient utilization in channeling include angular divergences $\sim 0.01^\circ$ and beam areas $\sim 1 \text{ mm}^2$.

High- Z , few-electron systems, in particular the two-electron system, also provide QED sensitivity. Recent calculations by Mohr [Mo85] have provided the computational basis which must include the additional complexities of the electron-electron interaction for the two-electron case. An experiment sensitive to the $2^3P_0 - 2^3S_1$ energy separation in heliumlike uranium has been discussed by Gould [Go85]. More experiments of this type will be performed at accelerators of the type

proposed here. Newer accelerators with cooled beams and higher beam intensities than are presently available at existing accelerators will permit more accurate experiments to be performed.

II.E.2. Hyperfine Interactions in High-Z, 1-Electron Ions

A determination of the hyperfine structure (HFS) interval for selected high-Z ions with only one 1s electron may provide unique tests of QED in the high field limit where traditional methods are not applicable (see section II.E.1). In Dirac theory the one-electron atom and its hyperfine structure, for those cases where the nuclear spin, I , is not zero, is exactly calculable to within QED uncertainties. This is in contrast to the multi-electron ion, where exact calculations are not possible. The splitting interval between the two hyperfine states ($F = I \pm 1/2$) for the 1s-case extends across the visible region for high-Z atoms, which suggests that a crossed beam laser resonance experiment is possible. A direct observation of the optical M1 radiation between hyperfine states may also be possible in storage rings. The 1s HFS interval, A , where A is the difference in energy between the two 1s hyperfine states, is shown in Fig. II.E.3 for ions with $60 < Z < 100$ for two different values of the nuclear g-factor ($g_I = \mu_N/I$). The splitting is calculated with the Dirac equation and includes first order nuclear size corrections and corrections due to an assumed uniform distribution of magnetism within the nucleus. Units for the HFS interval in the figure are in angstroms.

Specific proposals to study high-Z one-electron hyperfine structure have been made [Go83], and aspects of 1s hyperfine interactions have been discussed at recent conferences [Be85a, Sp84, and Ot84]. As an example, we discuss the determination of the 1s HFS interval in a pair of thallium isotopes, ^{203}Tl and ^{205}Tl , both of which have nuclear spin,

Fig. II.E.3. Hyperfine structure splitting interval, A , in angstroms, for the one-electron ($1s$) case as a function of Z . The two curves show the splitting interval for two different nuclear g factors g_I . First order correction for finite nuclear size and the distribution of nuclear magnetism are included in the calculations.

$I = 1/2$. The 1s HFS interval is in the range 3800-3900 A (without QED corrections), and the determination of this interval for either isotope could provide the QED insight. Additionally, the determination for both isotopes could definitively address the topic of hyperfine structure anomalies because the nuclear magnetic moment ratio is known to an accuracy of 0.2 ppm from external field methods. Hyperfine anomalies refer to the differences in the nuclear moment ratios that often occur between internal field determinations (optical methods) and those determined via external field techniques (NMR for example). The optical methods suffer from the inability to calculate the structure of the multi-electron atom to sufficient accuracy to address the HFS anomaly, which in reality is related to the differences in the distribution of nuclear magnetism for the isotopic pair. The determination of the HFS for the isotopic pair ^{203}Tl and ^{205}Tl , would provide new insights into these effects.

The large magnitude of the magnetic field created at the nucleus by the presence of a single 1s electron has additional applications and consequences. This hyperfine field is measured in megatesla units and is shown in Fig. II.E.4 as a function of atomic number, Z . These intense fields become interesting for nuclear g-factor measurements when a significant rotation (of I about F) occurs during a nuclear lifetime (also see Section II.D.9.3). Nuclear g-factors may be measurable for states with lifetimes more than 100 times shorter than can currently be determined via the "transient field" method. These short nuclear

lifetimes correspond to the fastest electromagnetic transitions known in bound nuclear systems! Applications to moment determinations for high spin nuclei in the "back-bend" region are suggested.

Fig. II.E.4. The magnetic field at the nucleus $\langle I(0) \rangle$ generated by the presence of one, $1s$ electron as a function of atomic number, Z , is given in the units of megatesla.

III.E.3. Atomic Collision Physics at Ion Energies up to 1 GeV/nucleon

In this section, we discuss the broad scope of possible atomic collision studies with the use of an intermediate-energy, heavy-ion accelerator. Atomic collisions are defined to include all dynamical processes in which a single atom or ion interacts with matter through the electromagnetic interaction, whether such matter is a single atom, molecule, ion, or solid.

Uniqueness of Facility. Ionic projectiles are defined by Z , q , and v/c (A is less interesting to atomic physicists). For other than bare projectiles, the internal atomic state is of the greatest importance; the ions injected into a ring may be in metastable states or, once in the ring, they may be excited optically or collisionally. As shown in Fig. II.E.1, all ion charge states up to $q = Z$ and ions with $Z = 100$ are accessible.

Choice of "Ring" Technology. Ion storage rings offer the most exciting prospects for high-energy atomic physics. These prospects stem from such unique features as the enormous effective currents, high repetition rates, the ability to store improbable ions, and the ability to decelerate with cooling. At present, four dedicated ion storage/cooling rings are in various stages of construction in Europe for atomic collisions research. Only one of the four European projects provides an energy range equivalent to that of the proposed accelerator.

Novel Experimental Techniques. In addition to the traditional heavy-ion experiments with gas or foil targets, many new experimental techniques become possible.

- (a) Recoil Ion Sources. Slow ions in very high charge states may be extracted from a gas cell dwelling parasitically in the beam. The source is interesting in itself particularly if molecular gases which would allow the study of Coulomb explosions and ion-induced chemistry are used. Recoil ion sources are discussed below and, because of their expected importance, are discussed in detail in Section II.E.7.
- (b) Merged Beams. The most obvious and natural storage ring experiments use merged beam configurations. A merged electron-ion configuration serves as a cooling section for accelerated beams.
- (c) Crossed Beams. One of the most stimulating, though speculative, possibilities is the construction of self-crossing (even self-merging) ion beams, in the co-rotating mode. This would allow the study of collisions near zero energy in the center-of-mass frame.

We have now established the range of $(Z, q, v/c)$ and the meaning of "fast" or "slow" ion-atom collisions; we have also clarified the scope of feasible experiments. This information enables us to construct the problem matrices of Tables II.E.1 and II.E.2, which show the experimental techniques and theoretical motivations of experiments classified by target and velocity range. Many of these possibilities are discussed in more detail in subsequent subsections. Certain features of the tables stand out very clearly, e.g., the richness of ion-ion and ion-solid physics.

Table II.E.1. Problem Matrix of Experimental and Theoretical
Techniques Applicable to Processes Classified by Velocity/Target

VELOCITY	TARGET			
	gas cell/ neutral beam (G)	electron beam (E)	ion beam (I)	solid/surface (S)
slow (1)	t1 x1 t2 x2 t6	t1 x2 t2	t2	t5 x1 t6 x2 x3
inter- mediate (2)	t1 x2 t2	t1 x2 t2	t2	t1 x2 t2 x3
fast (3)	t1 x2 t3 t4	t1 x2 t3 t4	t3 t4	t1 x2 t3 x3 t5

***** KEY *****

Theory: t1 state-to-state cross sections
t2 multielectron processes
t3 relativistic processes
t4 high energy expansions
t5 condensed matter physics
t6 chemical reactions

Experimental techniques: x0 counting ions (default)
x1 recoil and secondary ions
x2 photon/e-/e+ spectroscopy
x3 surface/channeling physics

Table II.E.2. Cross References of Velocity/Target
Classification vs. Techniques

Theory	Experimental Technique			
	x0	x1	x2	x3
t1		G1	G1 G2 G3 E1 E2 E3 S1	S2
t2	I1 I2 I3	G1	G1 G2 S2	S2
t3	I3		G3 E3 S3	S3
t4	I3			
t5		S1	S1 S2 S3	S1 S2 S3
t6		S1 G1		

***** KEY *****

Theory: t1 state-to-state cross sections
t2 multielectron processes
t3 relativistic processes
t4 high energy expansions
t5 condensed matter physics
t6 chemical reactions

Experimental techniques: x0 counting ions (default)
x1 recoil and secondary ions
x2 photon/e-/e+ spectroscopy
x3 surface/channeling physics

II.E.3.1. Specific Areas of Atomic Collision Research

- (a) Ion-Atom and Ion-Ion Collisions. Collisions between two heavy atomic species dominate the physics of intense beams, inertial confinement fusion, and plasma-surface interactions. Their study is an essential preliminary to understanding ion-solid collisions, which so far cannot be addressed ab initio, but only through models. For theorists, the ion-atom and ion-ion collisions represent a greater challenge than electron-ion processes since the perturbation induced by the projectile is of the same magnitude as the field holding the target together. We begin by writing the generic two body process:

where the asterisk indicates that the state may be excited and hence may decay by emitting photons or further electrons.

Experiments may detect final charge states, electrons, or photons. The initial reactants may be provided by recoil ions or crossed (merged) ion-neutral beams or crossed (merged) ion-ion beams. The reactants may be pumped into excited states by lasers or collisions, or they may be allowed to relax to their ground states by storing for a controlled time. Excited species can even be polarized or aligned.

Theoretical approaches include multistate expansions, the time-dependent Hartree-Fock and Dirac-Fock (TDHF, TDDF) methods, and various ways of describing interelectronic correlation yet in their infancy.

- (i) Recoil Ions and Ion-Induced Chemistry. A gas cell placed in the beam acts as a source of very slow (a few eV/nucleon) ions in charge states determined by the beam energy. Small accelerator rings are expected to produce bare argon, but a ring operating at a few hundred MeV/nucleon could produce bare titanium at the rate of 10^{10} ions a second. A more detailed discussion of the example of a titanium recoil ion source is given in Section II.E.7. The yield of Ar ions observed in 15.5 MeV/nucleon uranium ion bombardment of argon gas shown in Fig. II.E.5, is taken from Ref. [Ri85].

Elaborate engineering would be required to isolate these experiments from the ultrahigh vacuum in the rings; some of these engineering aspects have obvious solutions and are discussed in Section II.E.7 below.

- (ii) Ion-Atom Collisions at Intermediate and High Energies.

Ion-atom collisions are ideally studied by crossing or merging the stored ion beam with a fast neutral beam. Low-energy electrons ejected from the target can then be studied by forward electron spectroscopy. The general trends of single-electron loss cross sections at low energies are well established and are well understood theoretically. Many multiple loss cross sections have been measured and are not understood theoretically. Progress might be made if we had some

Fig. II.E.5. Time-of-flight spectrum of Ar recoil ions created from 15.5 MeV/nucleon uranium ion bombardment of argon gas [Ri85].

clue as to the ejected electron distributions. Going beyond total cross sections, few measurements for specific final states have been published, and those that have are not consistent with each other or with any theory. These experiments will be made much easier by the high repetition rate in storage rings. Experiments with the very highly charged species provided by the proposed accelerator are attractive because most cross sections increase linearly with charge. Such measurements with the range of energies and projectiles supplied by the proposed accelerator are almost unexplored.

(iii) Ion-Ion Collisions. In spite of their potential significance in several applications, little interest has developed in experimental studies of ion-ion collisions. These applications include inertial confinement by heavy-ions and the stability of intense ion beams, with most work having been done in Europe [Ne82]. Storage rings may change this picture dramatically through the use of such novel techniques as self-crossing and co-rotating beams.

(b) Electron-Ion Collisions. Collisions between electrons and ions are the dominant mechanism governing the equilibrium and nonequilibrium behavior of high temperature plasmas. These plasmas occur in the interstellar medium, in stellar atmospheres, in quasars and near high-energy objects whose exact

nature is uncertain. In the laboratory, they are produced in magnetic confinement devices, X-ray lasers, and thermonuclear weapons. The intense level of activity in these areas is displayed in the series of topical conferences on "Atomic Physics in High Temperature Plasmas," of which the most recent was held at Asilomar in February, 1985.

When an electron collides with an ion A^{q+} , the outcome can usually be classified under one of three headings:

(1) Excitation:

(2) Recombination:

(3) Ionization:

The asterisk indicates an excited species which may decay by emitting a photon. It is safe to say that most of our knowledge of the composition of the universe rests on an understanding of these processes. What can be measured at very low count rates per single pass is the production of new charge states and the emission of photons (not in coincidence).

To appreciate the theoretical interest in these processes, it must be understood how they differ from electron-neutral atom processes. The latter are dominated up to quite high energies by dynamical mixing of target states induced by the presence

of the electron. In ions more highly charged than 6^+ , the target states are relatively unperturbed, so that excitation and ionization can be described by distorted wave approximations. Electron impact thus becomes a spectroscopic probe of the structure of the target. The unique region which could be explored with a large collider, such as the proposed accelerator, is that with ions having $Z > 60$ and fewer than 25 electrons. The structure of these ions is a relativistic many-body problem which is relatively unexplored but more tractable than that of heavy neutral species or lightly ionized species.

- (i) Excitation. This is the area of ion-atom processes least explored experimentally due to the difficulty of counting UV photons at very low rates in crossed beams. Laser pumping may be feasible in studying excitation to levels which do not decay radiatively or which emit photons at inconvenient wavelengths. Many new experimental opportunities will be opened up by the use of storage rings.
- (ii) Recombination. The term recombination usually refers to the electron-ion processes that occur in non-equilibrium plasmas, but we use the term here to refer to all electron-ion capture processes, whether "plasma-like" or not. Two recombination mechanisms may be distinguished, direct radiative (RR) and dielectronic (DR). Either may occur spontaneously or be

assisted by laser pumping. RR is believed to be completely understood for bare nuclei but generally unexplored for capture into low-lying states of non-bare nuclei. RR might provide a method of populating excited states for Lamb shift measurements.

Recent advances in experimental technique have only begun to probe DR. All the DR beam results to date for ions with $q > 1$ come from ORNL [Di83], but the measured values of the cross sections are so sensitive to ambient fields that theorists are uncertain whether a cross section should even be defined [Gr85a, Gr85b]. Progress in DR research will depend on probing the formation of individual final states with either photons or ejected electrons since most of the states are autoionizing. The study of autoionizing states by the technique of cusp electron spectroscopy connects DR with many other processes in ion-atom and ion-foil collisions and in basic atomic structure physics. Theory predicts surprising effects in very highly charged species, e.g., enormous cross sections into certain low-lying states. Figure II.E.6 shows a calculation for Fe^{23+} [Gr85c].

- (iii) Ionization. The richness of phenomena in electron impact ionization is illustrated by Figs. II.E.7 and II.E.8, which show the cross sections for single and double ionization of several low stages of xenon [Gr84,

Fig. II.E.6. The DR cross section for Fe^{23+} including all resonances with $n < 100$ convoluted with a 3.0 eV Gaussian. The dotted curve is with no field mixing, and the dashed curve includes complete field mixing.

ORNL DWG 83 15037

Fig. II.E.7. Single ionization of Xe^{2+} through Xe^{6+} . Relative uncertainties in the measurements at the 1 s.d. level are shown at representative points. Absolute uncertainties ($\pm 7.5\%$ of the peak cross section) at good confidence level are plotted near 100 eV (175 eV on the Xe^{6+} curve). Dashed curves are distorted-wave calculations of direct ionization (from Gr84).

Fig. II.E.8. Electron-impact double-ionization cross sections for (a) Xe^+ , (b) Xe^{2+} , (c) Xe^{3+} , and (d) Xe^{4+} . The experimental results are shown with the symbols o and Δ . The short-dashed curves labeled BEA are from direct ionization calculations in which the binary-encounter approximation is used; the long-dashed curves labeled CA are calculations for 4d ionization in which configuration-average wave functions plus direct ionization are used, and the solid curves labeled TDC are 4d ionization calculations in which term-dependent wave functions with ground-state correlations plus direct ionization are used (from [P184]).

Pi84]. Most of the observed structure is now quantitatively understood. As with recombination, autoionizing states play a major role. The magnitude of multiple ionization in complex systems (i.e., those having >30 electrons) is no longer a surprise. For $m > 2$, m -fold ionization does not fall off particularly rapidly. While indirect mechanisms can often be described by means of the theory of multistep processes, direct multiple ionization is possibly the most intractable few body problem known to mathematical physics.

Novel phenomena should be expected with very heavy, highly stripped targets. No covariant theory has been written for the interaction of a free electron with such an ion. Lepton pair production is perfectly possible, but no estimate is available.

- (iv) Simulation of Electron Scattering with Light, Neutral, or Crystalline Targets. An interesting suggestion [Go85] has been made that scattering of highly charged ions by very light simple targets (e.g., He, H₂) be used to mimic scattering by free electrons. Since the effective radius for exciting or ionizing ions at energies near threshold is roughly $10a_0/Z$, this is probably a valid assumption for $Z > 25$. With the targets mentioned, the internal momentum spread and energy transfer to internal degrees of freedom would

also be negligible. In addition, the electrons in an axial or planar crystalline channel could be used as a dense source of electrons to simulate a "sea of free electrons" to investigate unique aspects of electron impact ionization and of electron capture or recombination. Channeling may not be appropriate for stored beams, but the availability of cooled extracted external beams would greatly facilitate experiments of this type.

II.E.4. Condensed Crystalline Beams: the "Wigner Solid"

Since electron-beam cooling will be used in the storage ring of the proposed accelerator, the possibility arises of lowering the ion beam temperature so far that a phase transition can take place [Di84].

In electron cooling, the ions are merged with a magnetically confined electron beam extracted from a thermal cathode. Coulomb collisions bring the ions into thermal equilibrium with the electrons in a frame moving at the mean velocity of the electrons. The transverse energy spread arises from the finite cathode temperature and is typically 0.1 - 0.3 eV. However, the longitudinal momentum distribution is kinematically compressed so that for velocities between $0.1c$ and $0.9c$ the longitudinal temperature would range from 0.01 deg K to as low as 10^{-4} deg K! In planes perpendicular to the beam, the ions would describe orbits with radii of 10-100 microns, but below some critical temperature in the beam direction, they would arrange themselves in an ordered lattice. This behavior in a gas of charged fermions was predicted by Wigner in 1932, whence the ordered phase is called a Wigner solid, or perhaps more correctly, a "Coulomb solid."

The resulting ordered beam would represent a new type of condensed matter, viz., a charged quantum solid. From the perspective of condensed matter theory, this system would make an attractive test bench since it could be studied experimentally as a function of the interaction between the ions (the ionic charge) because of its one-dimensional nature. New experimental techniques would have to be devised as probes. One suggestion is to use Bragg backscattering: a laser directed axially

down the beam is tuned to resonance for some atomic process (for bare ions this could be radiative recombination with a cooling electron). At the right wavelength for Bragg reflection at 180 deg, stimulated backscattered photons are seen. These photons would be interesting in themselves, being doubly blueshifted and coherent. Applications of this particular possibility include "beam thermometry," a diagnostic for accelerator control and operation.

The proposed accelerator could greatly extend investigations of the Wigner solid, beyond those possible with small storage rings, by providing larger charge to mass ratios and higher velocities. Thus, the blueshifted photons would be reduced in wavelength by a factor of as much as 20.

II.E.5. Production of Elementary Particles in Strong Fields

Collisions between highly charged heavy ions produce the strongest electromagnetic fields available in the laboratory. A natural unit for electric field in fundamental problems is e^2/λ^2 , approximately 10^{16} V/cm. In these units, the field at the nucleus of a hydrogen atom is 10^{-6} , while that in the most powerful present day lasers is only 10^{-9} . In contrast, the maximum field in a peripheral uranium-uranium collision is >1000 . At such field intensities, we expect to probe nonperturbative aspects of quantum electrodynamics, which requires a full numerical time dependent theoretical treatment. Elementary particles may be produced in several ways. The most widely known is the Weizsacker-Williams mechanism [We34, Wi35], in which the virtual photons from the time-dependent Coulomb field are converted into fermion pairs.

The production of positrons in low energy collisions of ion pairs whose combined nuclear charge exceeds 170 has been studied by three groups at GSI for more than a decade [Gr83]. At the energies of the GSI UNILAC (5-7 MeV/nucleon), the colliding nuclei barely touch, thus maximizing the reaction time during which the strong field acts. The broad positron singles distribution agrees in qualitative detail with independent calculations that use strong field quantum electrodynamics [Gr83, Bo85a]. Superimposed on this broad distribution is a sharp spike which is not well understood, and it is sufficient to say that the GSI positron data provide no evidence for anomalously long-lived

(i.e., >10-20s) nuclear complexes. Theoretical and experimental interest has therefore moved to higher energies.

In the velocity range $0.3c - 0.9c$, the relative velocity of the ions matches that of the target K-shell electron, leading to large probabilities for K-K transfer and pair production by direct occupation of a K-shell vacancy. Figure II.E.9 shows the momentum distribution of the K-electron in Cm , and Fig. II.E.10 shows the probabilities of capture and pair production for head on U-Cm collisions calculated in a one dimensional model [Bo85b]. The latter increase from <0.1% to a few percent as velocity goes from $0.2c$ to $0.4c$, then remain fairly constant up to $0.9c$ and fall off very slowly thereafter. A great deal of physics in this regime could be studied with the proposed accelerator, which is almost custom designed for this purpose!

Many other types of physics could be explored at the same time, especially if a crossed or merged ion-ion beam mode were implemented. Thus, collisions with low center-of-mass energy could be studied using bare nuclei. If the center-of-mass energy is taken above 1 GeV/nucleon, muon pairs begin to appear. The theoretical interest in this field arises from the possibility of testing theories of Fermion fields coupled to Boson fields, which loom so large in the nuclear part of this proposal.

Spontaneous breaking of various symmetries in gauge theories implies the existence of new massive bosons. Depending on the symmetry breaking scale, it is possible that some of these bosons are light enough to be produced in heavy-ion collisions at energies between 1 MeV

ORNL-DWG 85-13526

Fig. II.E.9. Momentum distributions for the positive (full line) and negative (dotted line) energy components of the 1s orbital of Cm.

ORNL-DWG 85-13524

Fig. II.E.10. Combined final-state probabilities for the target and projectile frames as functions of the projectile velocity: (in) total inelastic; (e⁻) positive energy continuum (electrons); (e⁺) negative energy continuum (positrons). The flux lost by numerical approximations is shown by the dashed line.

and 1 GeV and that one such boson is responsible for the spike in GSI positron spectra around 300 keV [Si83, Cl84]. If this particle exists, its coupling strength to electrons and positrons is constrained by the fact that its contribution to the electron's anomalous magnetic moment has not yet been observed.

The standard theory of strong interactions, Quantum Chromodynamics, does not necessarily conserve CP invariance; however, there is no experimental evidence for CP violation in strong interactions. To resolve this puzzle, a neutral pseudoscalar particle called the axion has been introduced. Although the existence of this postulated boson is in harmony with current experimental, theoretical, and cosmological bounds, as illustrated in Fig. II.E.11, this boson is not the standard axion [Ba85]. The production mechanism of this particle in heavy-ion collisions is not understood, and extensive systematic work remains to be done. Fixed target experiments are greatly hindered by the low count rates which could be alleviated by the use of the proposed accelerator storage ring.

Finally, even more speculative explanations, such as a breakdown of standard Dirac-Maxwell (i.e., QED) theory at large field strengths, have not yet been excluded. Precision tests of QED are discussed in Section E.1 above.

Fig. II.E.11. Current experimental, observational, and cosmological bounds on the mass, (M_x), and on the ratio of the electron mass to the interaction strength, (F_x), for possible neutral, pseudoscalar bosons. The shaded areas are excluded by the indicated considerations. The dot denotes the position of the parameters of the postulated boson that could be responsible for the positron "spike" in the GSI experiments.

II.E.6. Resonant Atomic and Nuclear Coherent Excitations of Channelled Ions

Coherent interactions between moving charged particles and spatially periodic potentials, at rest in the laboratory system, have been observed in a variety of experiments, with the Smith-Purcell effect being the best known [Sm53]. With the discovery of channeling in the 1960's, it became apparent that coherent excitations of ions moving in the crystallographic periodic potentials could occur. In 1965 Okorokov proposed the possibility of resonant coherent excitation (RCE) of optical spectra [Ok65] and of coherent nuclear excitation (CNE) [Ok66], but these predictions for RCE were not verified until 1979 [Mo79]. Several resonances for the $n = 1$ to $n = 2$ states of one electron ions from boron to fluorine were observed at harmonic values, K , from 2 to 4 times the fundamental frequency. Moak et al. [Mo86] measured the first $K = 1$ resonance for C^{+5} in the $[100]$ axis of gold. The resonance velocities of the ions exhibit shifts and splittings, which are the results of the crystal fields acting upon the electrons of the ions, and comparisons with theory [Cr79] show good agreement. The theoretical width and cross sections have not yet been predicted. In all the experiments [Mo79, Mo86], the resonances have been studied by measuring the ratio of one-electron ions to the total; hence, secondary charge changing processes may make the measurement of the cross section very difficult. This can be better determined if the charge state measurements are complemented by detecting the de-excitation radiation, which is easier to measure for the higher- Z ions. With the proposed accelerator, these studies can be

extended to include all $K = 1$ resonances through ^{56}Fe , where the resonance will occur at 1.375 GeV/nucleon for $[100]$ Au. If X rays can be observed for the heavier ions, their polarization may give additional information about the crystal field, and it also may be possible to study resonant coherent de-excitation.

No experimental demonstration of the CNE has been possible to date because of the requirement of higher ion velocities for the cases of interest. With the proposed accelerator, a first attempt can be made by using the first excited state of ^{45}Sc (12.4 keV), for which the $K = 2$ CNE resonance should occur at $E = 1.15$ GeV/nucleon for $[100]$ Ge.

II.E.7. The Storage Ring as a Recoil Ion Source for Low-Energy, Highly-Ionized Ions

Fast, heavy ions colliding with lighter elements produce copious target multiple ionization. The large cross sections, together with surprisingly small recoil energies, allow high energy 'hammer beams' to be an efficient source for production of low-energy, highly charged ions [Co79, Gr80]. Many such Recoil Ion Sources (RIS) are in use around the world. At sufficiently high primary beam energies, where the electron-capture cross sections are small even for fully stripped projectiles, the perturbation on the projectile beam in passing through an RIS target region can be kept minor. It becomes feasible, then, to envision a RIS system operating parasitically in an ion-storage ring, where the stored beam is the hammer (Ma85, Ri85), repeatedly traversing the RIS cell at the beam cycle frequency of 10^6 Hz. To facilitate even thin target regions within the storage ring without seriously degrading the vacuum, considerable pumping speed is required. A self-pumping, condensable material, like Ti, confined as a vapor to a few centimeters of beam path length, would be ideal as a target material. Cross sections for recoil ion production by ions up to 15.5 MeV/nucleon U^{75+} impinging on targets as heavy as Xe have been measured at GSI [Ke85]. Rough extrapolation to fully stripped U^{92+} at hundreds of MeV/nucleon yields cross sections near 10^{-19} to 10^{-20} cm² for bare- and few-electron recoil ion production near $Z_{tar} = 22$.

The major deleterious effects on the stored beam are due to charge changing and to energy loss and straggling. The projectile beam fraction

lost to electron capture can be estimated from theoretical [Ei85] and measured cross sections [Go84]. At 500 MeV/nucleon, U^{92+} ions passing through 3×10^{13} atoms/cm² of Ti should suffer no greater than 1.5% charge capture per second. Only 50% of the original beam would be changed to U^{91+} in 50 seconds. If the storage ring could retain more than one charge state, the loss would be insignificant. Energy loss and straggling of the ions passing through the RIS region can be compensated to a great extent by the electron cooling system.

The possible RIS generated beam intensities for very highly stripped heavy ions from the proposed accelerator exceed those of any currently available source of similar ions. For example, with a Ti^{20+} production cross section of 1×10^{-19} cm² and 10^9 stored 500 MeV/nucleon U^{92+} ions, a Ti target of 3×10^{13} atoms/cm² would yield 10^{10} ions/second (26nAe) of Ti^{20+} . Recoil energies of the highly charged target ions can be estimated on the basis of quasi-elastic Coulomb scattering of the two nuclei, with the interesting and useful result that $E_{rec} = Z_p^2 Z_t^4 \times 10^{-4} (eV) / E_p (MeV)$ [Ma85]. For 500 MeV/nucleon U^{92+} producing Ti^{20+} , this estimate yields a recoil energy of 2 eV! Experiments in which maximum recoil energies have been inferred confirm the very low values ($\sim eV$), even for bare recoil nuclei [Be82, Pr83]. Intense beams of highly stripped heavy ions with such low initial energies open or expand a variety of research areas in atomic physics.

One of the first applications of RIS ions was in simple electron capture cross-section measurements [Co81, Ma81]. Similar experiments have since progressed to the complexity of energy-gain, (n,l) final

state-selective electron capture cross-section measurements (e.g., [Gi85]). With much more intense beams, measurements can be made differential in energy and in angle and extended to even lower energies. Differential cross sections are necessary for a more nearly complete understanding of the dynamics of the various capture processes including multiple-electron transfer.

The intense, slow ion beams available from a storage ring pumped RIS also would permit high-resolution X-ray measurements on few-electron, high-Z systems without significant Doppler shifts. Precision X-ray measurements at the 5 to 10 ppm level of accuracy [De84, Be85] have already been made on one- and two-electron Ar recoils generated by 5.9 MeV/nucleon U^{66+} ions. High intensities of even heavier few-electron ions will allow extension of these measurements to higher Z systems where QED effects become more important. With additional acceleration of RIS ions to relatively low energies (10 keV/nucleon), $\Delta E/E$ compresses to 4×10^{-6} for nearly Doppler spread-free measurements. This will enable spectroscopy of high q ions to be performed at greater precision than is presently possible [De84a].

RIS techniques have also been used recently to produce and identify various metastable multicharged molecular ions for the first time [Gr85]. The fast ion-induced chemistry is done by using molecular gases in the RIS cell. Little systematic work has been reported, but it appears that highly charged molecular ions which cannot be formed by other means, e.g., photo- or electron-ionization, are produced in the violent primary ion-molecule collision and subsequent relaxation which

may lead to molecular geometric rearrangement. The measured lifetime limits of molecules like $[\text{CH}_4]^{3+}$ are greater than 3 μsec .

Multicharged heavy ions can carry enormous potential energy. In slow encounters with solid surfaces, a variety of neutralization processes that occur involve radiative and Auger emission [Ha54, Ar73]. As the slow ions impinge on the solid, neutralization proceeds by long-range (10 Å outside the surface) resonance capture of one or several electrons into highly excited states. In the 10^{-13} to 10^{-12} seconds before the ion strikes the surface, rapid de-excitation occurs via Auger or radiative emission processes. In past experiments, mainly Auger electrons or reflected ions and neutrals have been studied. This is due to the fact that for relatively low- q ions, low energy (15-30 eV) Auger electrons dominate the emissions [De185]. Recent availability of nearly fully-stripped heavy ions has encouraged study of X-ray emission [Do83, Ge82] from slow ions striking metals.

Sufficiently slow ions can also be trapped in an ion trap for various experiments, especially those requiring relatively long measurement times. Preparation of certain excited states, in particular by selective electron capture followed by ion trapping, allows study in a relatively benign environment over lengthy periods. Measurements by laser excitation or electron impact excitation, possibly followed by high resolution spectroscopy (uv, X-ray, or Auger) of the de-excitation processes can then be envisaged.

II.E.8. Astrophysical Plasma Simulation

II.E.8.1. Atomic Physics Aspects of Astrophysical Plasmas

Collisions of high-energy heavy ions with matter allow the production of unique ionic species of considerable interest and relevance to modern astrophysics. One illustrative astrophysical application is in the determination of elemental abundances in interstellar media and in the sun and stars, which can then be related to nucleosynthesis, accretion, convection, and other processes [Ma85a]. Observation of the spectral lines, wavelengths, and intensities can provide this information if accurate transition oscillator strengths and wavelengths are known. As an example, about 70 elements have been detected by observation of the solar spectrum. The solar abundances of the rare earth elements are poorly known because the oscillator strengths for the observed transitions are poorly known for those rare earth ionic species that have been observed. Foil-excited beam spectroscopy can provide such information for those ionic states and configurations in the higher-Z elements that are presently beyond the reach of most modern heavy-ion accelerators. The isoelectronic sequences of Na, Mg, Al, Cu, Zn, etc., are of particular interest and these could be probed for the highest-Z elements in the periodic table with higher-energy, heavy-ion accelerators. Also of note is the possibility of quantitative studies of particular, normally forbidden, electric dipole transitions in long isoelectronic sequences for few electron systems, similar to the sequence known for triplet-P states in He-like ions.

II.E.8.2. Nuclear Physics Aspects: Determination of Neutron Capture Cross Sections Using the Inverse (d,p) Reaction and Radioactive Beams

The natural abundances of heavy elements ($Z > 26$) are far greater than can be produced in nuclear statistical equilibrium processes in the stellar environment. Astrophysicists have interpreted, to a good approximation, the nucleosynthesis of heavy elements in terms of a non-equilibrium mechanism consisting of a combination of neutron capture and beta decay, called the 's' and 'r' processes, respectively [C168]. In order to explain the observed abundances of heavy elements, it is necessary to know the neutron capture cross sections for each of the stable nuclei and beta decay rates for each of the unstable nuclei at each point along the path of the nucleosynthesis processes. It is also useful to measure neutron capture cross sections for unstable nuclei to determine the rate at which neutron capture competes with beta decay.

Neutron capture cross sections for light nuclei and for heavy nuclei with magic numbers of neutrons are smaller and more strongly energy dependent than for heavy nuclei. This is because the captured neutron is less tightly bound and is received at lower excitation energy, where the number of single particle states is much smaller than for heavy nuclei with configurations far from closed neutron shells. For these nuclei a number of narrow low-energy resonances appear in the neutron capture cross sections. These must be accurately measured in order to calculate the synthesis rates in the 's' process since many of these resonances occur at energies comparable to the energies of free

neutrons in the stellar environment. Although the nuclear physics community has been active for several decades in the field of neutron capture cross section measurements, there are many nuclei, both stable and unstable, for which data are still unavailable. Many of these nuclei will be extremely difficult, if not impossible, to study with common measurement techniques.

With the advent of modern fast-cycling, heavy-ion synchrotrons (such as the proposed accelerator) that deliver high intensity beams, the production of secondary beams with sufficient intensity to study the properties of rare or radioactive nuclei has become feasible. Along with the many other interesting measurements one might pursue with these beams, a measurement of astrophysical significance is to determine the neutron capture cross section for the secondary-beam nuclei. Rather than use these nuclei as targets for low-energy neutron bombardment studies — $A(n,\gamma)A+1$ — the reverse reaction could be used. That is, measure the inverse (d,p) reaction — $A(d,p\gamma)A+1$ — and determine the probability of neutron capture for the nucleus A equally well. A clean signature of the reaction of interest, neutron capture, could be obtained by coincidence detection of the emitted protons and gamma rays.

At least two possibilities exist for developing the low-energy intense secondary beams required for the proposed inverse (d,p) experiments. One of the design goals of the proposed accelerator is that it deliver a beam of approximately 10^{11} nuclei/sec of fully stripped uranium ions at 500 MeV/nucleon. The most commonly discussed technique for production of secondary beams entails bombardment of a target by this near relativistic, highly charged, intense uranium beam, causing

fragmentation of the heavy ion beam on the light target. To produce secondary beams near beta-stability, thick conversion targets ($1 - 10 \text{ g/cm}^3$) used with 500 MeV/nucleon uranium primary beams usually yield 0.1 - 1% conversion efficiencies [Ni85]. These secondary beams are emitted into a narrow phase space suitable to match appropriately designed storage and accumulator rings. To use these beams in direct experiments or to inject them into a storage ring, it will be necessary to provide cooling to reduce the large transverse and longitudinal momenta spreads. It will also be necessary to provide some form of beam analysis to isolate the desired secondary beam from the wide range of charge and mass fragments produced. For the neutron-capture cross section measurements and for many atomic and nuclear physics experiments, it will also be necessary to decelerate and bunch the secondary beam. There are many design difficulties and considerations that will not be discussed here, but it is fair to say that the problems involved in using these beams can be solved and that the general technique is feasible.

Another potential method for production of intense secondary beams of very low energies (keV/nucleon) is similar to the "hammer technique" in atomic physics [Ri85] (see also Section II.E.7). Highly charged uranium beams have been used to produce secondary beams of Ar and Xe by multiple ionization. Because of the high projectile charge and velocity, the direct multiple ionization cross sections for producing highly charged recoil-ion systems are very large. At the uranium projectile energies studied, 3 to 16 MeV/nucleon, the kinetic energy of the

Ar(17+) recoil ions is on the order of 10 eV. This technique could be applied even more successfully to produce low energy secondary beams of stable nuclei by using higher energy (500 MeV/nucleon) fully stripped uranium beams available from the proposed accelerator.

It is also possible to apply the "hammer technique" to the production of radioactive secondary beams. For example, the "virtual photon" field of a peripheral ^{238}U ion beam passing near a target nucleus, A, will Coulomb excite the target nucleus and also the ^{238}U projectile nucleus to the giant dipole resonance. The dipole resonance decays predominantly by neutron emission, leaving an A-1 isotope of the target nucleus. There will be minimal linear momentum transfer to the resulting nucleus, but it will be left in a high charge state. These nuclei could then be extracted from the interaction region and form a secondary beam. Since the interaction is Coulomb and one needs to generate the highest transient field possible to make the photon number of the virtual photon field large at the giant resonance region of the target nucleus, the cross section will be enhanced for higher energy uranium projectiles and for higher Z targets. The cross section for producing ^{150}V from an ^{160}Yb target bombarded with 500 MeV/nucleon fully stripped ^{238}U can be estimated to be about 40 mb, including contributions from excitation of the giant quadrupole resonance. This can be compared to a value of about 560 mb for production of a ^{50}V beam from a ^{51}V target.

The cross section for producing these secondary beams is surprisingly large. Since the beam is produced at low energies and with

high purity in the desired nuclei, the hardware required to analyze the beam, isolate the desired nuclei, and accelerate or decelerate the secondary beam to energies appropriate for the inverse (d,p) measurements or other astrophysical or atomic physics applications will be much simpler than in the conventional scheme described in the previous paragraph. It is clear that this technique could open a new field of precision spectroscopy with highly ionized, low-energy radioactive beams of a large range in mass not available at any current facility.

However, one of the keys to the successful application of this technique is to have an intense beam of fully stripped, high-energy uranium nuclei as the primary beam. For this reason the proposed heavy-ion accelerator provides a unique facility for measurements such as the determination of neutron capture cross sections via the inverse (d,p) reaction.

II.E.9. Selected Applications of High Energy Heavy-Ions

II.E.9.1. Nuclear Tracks

Ions moving through insulating solids produce regions of damage along their trajectories which remain intact indefinitely. These latent 'nuclear tracks' may be made visible by chemical etching which separates and/or removes the damaged material from the bulk. The shape of the resultant channel is dependent on the bombarding ion, the detecting material, and the exact method of etching. For a given detecting material and etching procedure, ions differing in nuclear charge, mass, and energy may produce different track shapes, so that projectile identification is possible. Although the exact mechanisms for track formation are not fully understood, this simple method of detecting and recording energetic particles has been used in a wide variety of fields ranging from nuclear science to geology and astrophysics [F175]. Many measurements have been made with few MeV/nucleon ions, but only a few measurements have been performed with long range, relativistic ions from accelerators [Ah82].

One important application of nuclear track techniques is the study of tracks produced by cosmic radiation. The energy spectra for heavy cosmic rays extends from a maximum intensity at ~200 MeV/nucleon to 10^6 MeV/nucleon. Above 10^7 MeV/nucleon, the composition has not been established [Si83]. The particles and their interactions with matter can be studied by measurements made on tracks formed in exposed solids. Meteorites containing certain crystalline silicate minerals, like

olivines, are good passive detectors of radiation in space and can yield a record of such radiations over very long periods, 10^9 years [F175, p.309]. Quantitative study requires calibration under controlled conditions of the various natural and artificial detecting materials with various species of high energy ions. There are currently very few heavy-ion calibration data, especially at relativistic energies [F175, p.338].

Nuclear-track techniques have also been used at low-to-intermediate energies for micro-machining and surface modification [Fi83]. At relativistic energies the former may still have important applications in the production of microscopic structures (narrow channels or spires) having very large aspect ratios.

II.E.9.2. Testing of Integrated Circuits

Intimately linked with the operation of solid-state electronic devices in an environment of high-energy particles is the effect that such radiations have on electronic circuitry. For the same physical reasons that semiconductor diodes are useful for detectors of ionizing radiation, integrated circuits composed of thousands of such elements are highly susceptible to operational failure under the penetrating high-energy component of cosmic radiation encountered in space. Just as in doped solid-state detectors, accumulated radiation damage eventually causes permanent failure of some critical element in an integrated circuit, rendering it useless. Typical lifetimes against this kind of failure in near-earth space environs may be of the order of years to tens of years. There are, however, electronic failures having much

higher probability which are instigated by penetration of a single ion. These are referred to as 'Latch-up' and 'Single Event Upset' or SEU events. Latchup is a permanent failure while SEU is recoverable. They both occur because of collection at a circuit node of ion-generated free charges which drives an electronic element to switch to an abnormal state. The ion's critical physical parameters are its range, which must be centimeters in order to reach the active portion of circuitry, and electronic stopping power, or Linear Energy Transfer (LET), which must be above some critical value, depending on the physical characteristics of the integrated circuit. Modeling from basic physical principles of charge deposition and subsequent prediction of failure rates in actual operating integrated circuits (RAMS, EPROMS, micro-processors, etc.) is currently receiving wide attention and effort [Ie85]. To date and in the foreseeable future, however, direct experimental testing of operating circuitry is the only way to predict full system failure rates confidently. Such testing is going on at many heavy-ion accelerators around the world. While measurements have been in progress since the 70's, a summary of all SEU and LATCHUP data can be compressed to tables only a few pages in length [Ie84]. In only one case have the measurements been made at an ion energy near that found in space on especially prepared circuit packages. Many more measurements with heavy ions having energies of 100's MeV/nucleon, as would be available from the proposed accelerator, are needed. There is currently great demand for this information in spacecraft design and in development of radiation-hardened circuitry.

II.E.10. References

- Ah82 S. P. Ahlen, G. Tarle, and P. B. Price, *Science* 217, 1139 (1982).
- Ar73 U. A. Arifov et al., *Sov. Phys.-Tech. Phys.* 18, 118 (1973).
- Ba85 A. B. Balantekin, C. Bottcher, M. R. Strayer, and S. J. Lee, *Phys. Rev. Lett.* 55, 461 (1985).
- Be82 H. H. Beyer, R. Mann, and F. Folkmann, *J. Phys.* B15, 1083 (1982).
- Be85 H. F. Beyer, R. D. Deslattes, F. Folkmann, and R. E. LaVilla, *J. Phys.* B18, 207 (1985).
- Be85a C. E. Bemis, Jr. "Laser Optical Pumping in Nuclear Physics: Fission Isomers, Oriented Targets and Hyperfine Pumping in Single-electron Ions," *Hyperfine Interactions* 24, 139 (1985).
- Be86 C. E. Bemis, Jr., J. R. Beene, J. Gomez del Campo, C. R. Vane, H. Gould, C. Munger, J. Alonso, R. McDonald, and G. Drake, "Physics with One Electron, High-Z Ions: Preparations for Experiments at the Bevelac," Phys. Div. Ann. Prog. Rep. for Period Ending Dec. 30, 1985, Oak Ridge National Laboratory Report, ORNL-6233 (1986).
- Bo85 G. T. Bodwin, D. R. Yennie, and M. A. Gregorio, *Rev. Mod. Phys.* 57, 723 (1985).
- Bo85a C. Bottcher and M. R. Strayer, *Phys. Rev. Lett.* 54, 669 (1985).
- Bo85b C. Bottcher and M. R. Strayer, in Relativistic and QED Effects in Heavy Atoms, ed. Y.-K. Kim and H. P. Kelly (to be published by Gordon and Breach, New York, 1985).
- Br78 S. J. Brodsky and P. Mohr, "Quantum Electrodynamics in Strong and Supercritical Fields," in Topics in Current Physics: Structure and Collisions of Ions and Atoms, Vol. 5, ed. I. Sellin (Springer-Verlag, Berlin, 1978), p. 3.
- Cl68 D. D. Clayton, Principles of Stellar Evolution and Nucleosynthesis, McGraw-Hill, New York, 1968, p. 546.
- Cl84 M. Clemente, E. Berderman, P. Kienle, H. Tsertos, W. Wagner, C. Kozhuharov, F. Bosch, and W. Konig, *Phys. Lett.* 137B, 41 (1984).

- Co79 C. L. Cocke, Phys. Rev. A 20, 749 (1979).
- Co81 C. L. Cocke et al., Phys. Rev. A 24, 2953 (1981).
- Cr79 H. Crawford and R. H. Ritchie, Phys. Rev. A 20, 1848 (1979).
- De84 R. D. Delattes, H. F. Beyer, and F. Folkmann, J. Phys. B17, L689 (1984).
- De84a R. D. Delattes and E.G. Kessler, p. 165 in Proc. Int. Conf. on X-ray and Inner-Shell Processes in Atoms, Molecules, and Solids, ed. A. Meisel and J Finster (Leipzig, 1984).
- De85 R. D. Deslattes, Nucl. Instrum. Methods Phys. Res. B9, 668 (1985).
- De185 M. Delaunay et al., p. 477 in Abstracts of Contributed Papers, 14th Int. Conf. on the Physics of Electronic and Atomic Collisions, Palo Alto, CA, 1985.
- Di83 P. F. Dittner, S. Datz, P. D. Miller, C. D. Moak, P. H. Stelson, C. Bottcher, W. B. Dress, G. D. Alton, and N. Neskovic, Phys. Rev. Lett. 51, 31 (1983).
- Di84 N. S. Dikansky and D. V. Pestrikov, Proceedings of ECOOL Workshop (Karlsruhe, 1984).
- Do83 E. D. Donets, Physica Scripta T3, 11 (1983).
- Dr82 G.W.F. Drake, "QED Effects in Few-Electron Atomic Systems," in Advances in Atomic and Molecular Systems, Vol. 18, edited by D. R. Bates and B. Bederson (Academic Press, New York, 1982) pp.399-460.
- Ei85 J. Eichler, Phys. Rev. A 32, 112 (1985).
- Fi83 B. E. Fischer and R. Spohr, Rev. Mod. Phys. 55, 907 (1983).
- F175 R. L. Fleischer, P.B. Price, and R.M. Walker, Nuclear Tracks in Solids: Principles and Applications (University of California Press, Berkeley, California, 1975).
- Ge82 R. Geller and B. Jacquot, Nucl. Instrum. Methods 202, 399 (1982).
- Gi85 J. P. Giese et al., Abstracts of Contributed Papers, 14th Int. Conf. on the Physics of Electronic and Atomic Collisions, Palo Alto, CA, 1985, p.473.
- Go83 H. Gould and C. E. Bemis, Jr., "Polarized Hydrogenic Uranium", Bevalac Proposal 719H, October 1983, unpublished.

- Go84 H. Gould et al., Phys. Rev. Lett. 52, 180 (1984).
- Go85 H. Gould, "New Experiments on Few-Electron Very Heavy Atoms", Lawrence Berkeley Laboratory Report, LBL-19884, July 1985.
- Go85a LBL-19884, to appear in Relativistic and QED Effects in Heavy Atoms, ed. Y.-K. Kim and H. P. Kelly (to be published by Gordon and Breach, New York, 1985).
- Gr80 T. J. Gray, Phys. Rev. A 22, 849 (1980).
- Gr83 W. Greiner, ed., Quantum Electrodynamics of Strong Fields, (Plenum, New York, 1983).
- Gr84 D. C. Griffin, C. Bottcher, M. S. Pindzola, S. M. Younger, D.C.Gregory, and D. H. Crandall, Phys. Rev. A 29, 1729 (1984).
- Gr85 T. J. Gray, J. C. Legg, and V. Meedham, Nucl. Instrum. Methods B10/11, 253 (1985).
- Gr85a D. C. Griffin, M. S. Pindzola, and C. Bottcher, Phys. Rev. A 31, 568 (1985).
- Gr85b D. C. Griffin, M. S. Pindzola, and C. Bottcher, The Effect of External Electric Fields on the Dielectronic Recombination Cross Sections of Lithium and Sodium Like Ions, ORNL/TM-9478 (1985).
- Gr85c D. C. Griffin, M. S. Pindzola, and C. Bottcher, in Atomic Excitation and Recombination in External Fields, edited by M. Nayfeh and C. W. Clark (Gordon and Breach, New York, 1985).
- Ha54 H. D. Hagstrum, Phys. Rev. 96, 325 (1954).
- Ie84 IEEE Trans. Nucl. Sci. NS-31, 1190 (1984).
- Ie85 For example, IEEE 22nd Annual Conference on Nuclear and Space Radiation Effects, Monterey, CA, July 22-24, 1985.
- Jo84 W. R. Johnson and G. Soff, "The Lamb-Shift in Hydrogen-like Atoms, $1 < Z < 110$," Gesellschaft fur Schwerionenforschung Report, GSI-84-72; At. Data and Nucl. Data Tables (to be published).
- Le81 G. P. Lepage, "Theoretical Advances in Quantum Electrodynamics," in Atomic Physics 7, ed. D. Kleppner and F.M. Pipkin, (Plenum, New York, 1981), pp. 297 ff.
- Ma81 R. Mann, F. Folkmann, and H. F. Beyer, J. Phys. B14, 1161 (1981).

- Ma85 R. Mann et al., GSI Scientific Report 1984, ISSN0174-0814, March 1985, p. 188.
- Ma85a I. Martinson, p. 425 in Treatise on Heavy-Ion Science, Vol. 5 - High-Energy Atomic Physics, ed. D. A. Bromley (Plenum, New York, 1985).
- Mo79 C. D. Moak, S. Datz, O. H. Crawford, H. F. Krause, P. F. Dittner, J. Gomez del Campo, J. A. Biggerstaff, P. D. Miller, P. Hvelplund, and H. Knudsen, Phys. Rev. A 19, 977 (1979).
- Mo83 P. J. Mohr, "Energy Levels of Hydrogen-like Atoms Predicted by Quantum Electrodynamics, $10 < Z < 40$," At. Data and Nucl. Data Tables 29, 453 (1983).
- Mo85 P.J. Mohr, Phys. Rev. A 32, 1949 (1985).
- Mo86 C. D. Moak et al., to be published.
- Ne82 P. A. Neil, G. C. Angel, K. F. Dunn, and H. B. Gilbody, J. Phys. B15, 4219 (1982).
- Ni85 J. M. Nitschke, p. K-3 in Proceedings of the Workshop on Intermediate Energy Heavy Ion Physics, Oak Ridge, 1985, (ORNL internal report CONF-8509176).
- Ok65 V. V. Okorokov, JETP Lett. 2, 111 (1965).
- Ok66 V. V. Okorokov, Sov. J. Nucl. Phys. 2, 719 (1966).
- Ot84 E. W. Otten, "Laser Spectroscopy of Cooled Heavy Ions," Workshop on the Physics with Heavy Ion Cooler Rings, Max-Planck-Institut für Kernphysik, Heidelberg, May 1984 (unpublished), paper D8.
- Pi84 M. S. Pindzola, D. C. Griffin, C. Bottcher, D. H. Crandall, R. A. Phaneuf, and D. C. Gregory, Phys. Rev. A 29, 1749 (1984).
- Pr83 M. H. Prior, R. Marrus, and C. R. Vane, Phys. Rev. A 28, 141 (1983).
- Ri85 P. Richard, J. Ullrich, S. Kelbch, H. Schmidt-Bocking, R. Mann, and C. L. Cocke, Nucl. Instrum. and Methods A 240, 532 (1985).
- Si83 J. A. Simpson, Ann. Rev. Nucl. Part. Sci. 33, 323 (1983).
- Sm53 S. M. Smith and E. M. Purcell, Phys. Rev. 92, 1069 (1953).

- Sp84 G. Sprouse, "Hyperfine Experiments in Cooler Rings," Workshop on the Physics with Heavy Ion Cooler Rings, Max-Planck-Institut für Kernphysik, Heidelberg, May 1984 (unpublished), paper D7.
- We34 C. F. v. Weizsacker, Ann. Phys. 88, 612 (1934).
- Wi35 E. J. Williams, Kgl. Dansk. Vid. Selsk. 13, No.4 (1935),

III. THE PROPOSAL FOR OAK RIDGE AS A SITE

	<u>Page</u>
III.A. OVERVIEW	III-1
III.B. A TRADITION OF HEAVY ION RESEARCH — THE EARLY YEARS	III-2
III.C. TRANSITION TO A USERS COMMUNITY	III-6
III.E. THE HOLIFIELD FACILITY	III-8
III.D. A TRADITION OF EQUIPMENT DEVELOPMENT	III-10
III.E. STATE AND UNIVERSITY ROLES	III-12

III.A. OVERVIEW

ORNL has established a long tradition in nuclear physics, including over three decades of building and operating accelerator facilities for heavy-ion research. The research performed on these facilities has made important contributions to scientific knowledge in nuclear and atomic physics. ORNL has proven its capability in development of accelerators, of ion sources, of experimental apparatus, and of computer systems, which are all essential to the operation of a large research facility.

A facility of the magnitude proposed here requires a commitment to a large users community. We have demonstrated such commitment in our interaction with and support of the users of the Holifield Facility. This support has been strongly augmented by the State of Tennessee and universities with research interest in the area of heavy-ion physics. The long tradition in heavy-ion research, the experience in accelerator and equipment design and construction, and a very active research climate helped by state and university support make the Holifield Facility an ideal location for the proposed new research facility.

III.B. A TRADITION OF HEAVY-ION RESEARCH - THE EARLY YEARS

The heavy-ion program at Oak Ridge traces its origins from 1953 when the 63-inch cyclotron was brought into operation. This accelerator was the world's first cyclotron built for the acceleration of particles with mass greater than that of the alpha particle. The original accelerating "dee" structure of the 63-inch cyclotron is now prominently displayed at the entrance to the permanent exhibit on accelerators at the Smithsonian Institute in Washington, D.C.

The research program at the 63-inch cyclotron provided some of the first experimental data on the behavior of fast multicharged ions in matter. Measurements on range-energy relations, charge state distributions, and electron capture and loss cross sections set the stage for a much broader program in atomic physics utilizing ORNL's Van de Graaff accelerators. Much of the early nuclear physics research at the 63-inch cyclotron involved the exposition of classical and semi-classical descriptions of the heavy-ion reaction process.

Accelerator and ion source development have always played an important role in the Oak Ridge program. The ion sources developed for the 63-inch cyclotron served for over three decades as models for multiply-charged ion sources used for all heavy-ion cyclotrons and linacs. Only in the past few years have more effective ion source concepts been developed. The early work on negative ion sources and pulsed positive sources for Van de Graaff machines produced source designs that were widely copied by laboratories throughout the world.

A major part of the research program at the ORNL EN tandem, which became operational in 1962, has been devoted to studies utilizing heavy-ion projectiles in both nuclear and atomic physics. In nuclear physics significant contributions were made in the investigation of Coulomb excitation, high-spin states as observed through in-beam γ -ray spectroscopy, fusion-fission cross sections, hexadecapole deformations of rare-earth and actinide nuclei, and high-resolution charged particle studies of transfer reactions. In atomic physics, areas of study included investigation of channeling in crystals, radiation damage, charge-state distributions, and interaction processes of highly stripped ions.

Some of the earliest theoretical work on the ideas for sector-focusing cyclotrons was done by the Oak Ridge group. These studies culminated with the construction of the Oak Ridge Isochronous Cyclotron (ORIC) which became operational in 1963. Intended as both a light- and heavy-ion accelerator, ORIC was designed with the flexibility to accelerate a wide range of ions with variable energy.

The heavy-ion research program on ORIC, and later the Holifield Facility, has had a long and distinguished history. A selection of notable highlights from this program includes:

- Systematic use and exploration of heavy-ion Coulomb excitation for precision nuclear structure research.

- Exploration of heavy-ion reactions in light systems with emphasis on critical angular momenta, limitations to fusion, and reaction systematics.

III-4

Systematic investigations of heavy-ion induced fission, of fission barriers, and of angular momentum effects.

Production, definitive identification, and study of nuclides of the transuranium elements, $Z = 102, 103, 104, \text{ and } 105$.

Precision elastic and inelastic heavy-ion scattering for determination of global optical-model potential parameters and investigation of Coulomb-nuclear interference mechanisms.

Study of nonequilibrium decay processes in heavy-ion collisions from observation of energetic light particles and the use of fermion correlations to deduce size of the localized reaction zone.

Channeling and blocking of heavy ions with applications in atomic physics and in the determination of compound nuclear lifetimes.

Demonstration of "shape co-existence" in neutron deficient Tl and Hg isotopes as a general phenomenon in this mass region.

Determination and systematization of alpha-decay properties for neutron-deficient, medium-weight nuclei.

Lifetime measurements of high-spin states produced in heavy-ion Coulomb excitation and in (HI, xn) reactions, with emphasis on nuclear structure, "backbending," and "shape evolution."

Quantitative studies of heavy-ion compound nucleus reactions, entry state populations, decay pathways, continuum states, etc., that made use of gamma-ray techniques and the Spin Spectrometer.

Exploration of giant resonance phenomena, excitations, and systematics.

Measurement of the photon decay properties of the giant quadrupole resonance.

Measurement of subthreshold pion production in heavy-ion reactions and studies of the related high-energy, gamma-ray production.

III-5

Accompanying these experimental programs were supporting efforts in theory. Most widely used were the large computer programs developed for optical-model calculations, for the prediction of direct reaction angular distributions, for calculation of the shell-model structure of nuclei, and for studies of collision processes with time-dependent Hartree-Fock calculations.

III.C. TRANSITION TO A USERS COMMUNITY

The Physics Division of ORNL has a long tradition of making its facilities available to the research community dating back to the 1960's for both the ORNL EN tandem accelerator and the ORIC. The first step in formalizing outside user participation came in April 1969, when an information meeting was held at Vanderbilt University to discuss a proposed new heavy-ion facility at Oak Ridge. Faculty from two dozen universities from the Southeastern area were present for these discussions with representatives from ORNL. In addition to discussions on new facilities, there were discussions on increasing university participation in the nuclear physics facilities at Oak Ridge, and these evoked considerable interest. From this meeting evolved the steering group that led to the formation, in 1971, of the UNISOR consortium. This group of 11 universities provided funds for the purchase and installation of an on-line isotope separator at the ORIC laboratory. The UNISOR consortium, still a major research presence at Oak Ridge, is viewed as a model for cooperative participation of federal agencies, state governments, and state and private universities.

As the national need for a major new facility for heavy-ion research became more pressing, a special Heavy Ion Advisory Board was formed at ORNL to provide guidance and to represent the interests of a much broader-based user community. The members of this committee

were: D. A. Bromley (chairman), J. H. Hamilton, J. A. Huizenga, A. K. Kerman, R. B. Leachman, R. A. Naumann, and R. Vandenbosch. This committee played a significant role in providing guidance to the planning efforts which were to follow. It is envisioned that a similar board would be formed to guide the development of the facility which is proposed in this document.

III.D. THE HOLIFIELD FACILITY

In 1975, ORNL received funding for a major addition to its heavy-ion capabilities. These funds provided for construction of a 25-MV tandem electrostatic accelerator and for conversion of the ORIC to serve as an energy booster. Designated the Holifield Heavy Ion Research Facility, in honor of retired Congressman Chet Holifield, the HHIRF first operated in May 1980. Among the most notable achievements of this project were the rapid implementation of coupled operation and the ability to provide the user community very quickly with a wide variety of ions from the ORIC booster accelerator.

Parallel with the beginning of the HHIRF project, a formal users organization was founded. Now numbering over 400 members, this group has participated actively, through its Executive Committee, in establishing priorities for experimental apparatus, establishment of design criteria and layout of the experimental facilities, and in some cases, in the design and fabrication of experimental devices. Prime examples of this latter category are the design and construction of the Spin Spectrometer at Washington University; construction assistance with the gas-jet target at the University of Virginia and the helium-jet target at Louisiana State University; and the design and construction of the velocity filter at MIT.

Since the start of regular operation of the Holifield Facility, the available beam time, as allocated by the Program Advisory Committee, has been utilized nearly equally by resident and non-resident research staff. Providing technical support to users has become an important task in the operation of the HHIRF.

There is an Experimental Support Group whose members assist all users in setting up and running at the HHIRF. This group contains technicians with expertise in the areas of experimental apparatus, electronics, and computers. Another group maintains and develops data acquisition/reduction computer systems and assists the researcher in the use of these systems. Just prior to and during an experiment, two technical staff members are assigned to each research group to serve as an interface between the group and the HHIRF staff and resources.

For each experimental device, there is a "mentor" who is a staff member of one of the resident research groups. The role of the mentors is to assure that the experimental apparatus are in good operating condition and that apparatus are appropriately developed. The mentors also assist the researchers in the use of the apparatus.

Thus, since the inception of the Holifield Users Group in 1975, the resident staff has developed substantial experience in operating a users facility. The staff has taken considerable effort to provide an environment which will enable researchers to carry out their research programs effectively and is committed to a users mode of operation.

III.E. A TRADITION OF EQUIPMENT DEVELOPMENT

An essential ingredient to a successful user facility operation is having strong resident research and development groups. The resident research staff has initiated a significant number of equipment development projects. Included in this category are magnetic spectrographs, scattering chambers, a time-of-flight facility, and many advanced detector systems.

The complex task of design and interfacing of the Spin Spectrometer electronics to the data acquisition system is one particularly notable accomplishment of the resident staff. This device is comparable in complexity to a small, high-energy-physics-style experiment and has required special hardware and software development. A Compton-suppression spectrometer system is now being developed for integration into the Spin Spectrometer. This system will provide unique capabilities for the study of nuclei at high temperature and high spin. This upgrade, done in consultation with outside users of the device, is the responsibility of the in-house staff.

Another notable equipment development project was the focal plane detector system for the magnetic spectrograph. This system provides both spacial (0.2 mm) and angular (5 mrad) resolution unparalleled in previous heavy-ion detector systems. An overall experimental energy resolution of 1 part in 6000 has been demonstrated with this system.

At present, one large equipment project in progress is the design and construction of a beam calorimeter and an array of calorimeter towers that will be used during 1986 in an experiment on relativistic heavy-ion collisions at CERN. This activity illustrates the breadth of the staff involvement in equipment development.

One particularly strong development area at HHIRF has been data acquisition hardware and software. The fast "front-end" processors and the elaborate data acquisition software developed by the resident staff have made available to the users the most powerful system at any nuclear physics laboratory.

All of this activity in equipment design and development provides a strong background for developing the experimental devices and data acquisition systems that will be essential to the success of the proposed accelerator and physics program.

III.F. STATE AND UNIVERSITY ROLES

A major strength of the Holifield program in the last decade has been the strong support from universities and from the State of Tennessee, in terms of money and manpower. For example, the State of Tennessee, through the University of Tennessee, has contributed nearly \$900,000 to Holifield research equipment or construction in the last ten years, while Vanderbilt University has provided an additional \$250,000. In the early evolution of the UNISOR project, state funds were used to purchase the mass separator. More recently, the Department of Energy funds for addition of Compton suppression units to the Spin Spectrometer are being augmented by \$320,000 from the University of Tennessee and by \$120,000 from Vanderbilt University. The addition of a dilution refrigerator for low-temperature nuclear orientation at UNISOR is receiving financial support from the University of Tennessee, Oregon State University, Georgia Institute of Technology, Louisiana State University, the University of South Carolina, Vanderbilt University, and Oak Ridge Associated Universities.

Perhaps nowhere has the state and university participation been more evident than in the building and operation of the Joint Institute for Heavy Ion Research, a collaborative venture initiated by Vanderbilt University and the University of Tennessee with ORNL to support and strengthen HHIRF as a center for heavy-ion research.

At the beginning of the HHIRF project, one of the needs stressed most strongly by the newly formed Users Group was for on-site accommodations for visiting users. The first step in meeting this goal was taken in 1980 with the beginning of construction of the first building of the Joint Institute. This building, completed in 1981, contains short-term living accommodations, kitchen and lounge areas, and short- and long-term office accommodations. This effort could not have been accomplished without major efforts by both Vanderbilt University and the University of Tennessee, including contributions of \$100,000 from each institution. It is important to recognize the benefit of such a facility in "stretching" a university group's limited contract research funds and making it economically feasible for more students to participate in the experiments.

In 1984 a second building for the Joint Institute was completed. This building, which provides office and laboratory space and an auditorium, was built by the University of Tennessee through a special \$340,000 grant from the State of Tennessee and a \$54,000 appropriation from the UNISOR universities. This institute is operated on an annual budget of approximately \$250,000 and is administered by a Policy council composed of representatives from the University of Tennessee, Vanderbilt University, and ORNL. The major portion (\$175,000) of this operating budget is funded by the State of Tennessee as part of the large center-of-excellence grant (called the Science Alliance) to the University of Tennessee, Knoxville.

Now entering its second year of full operation, the Joint Institute has developed a strong visitors program. During the first fifteen months of operation, 49 visitors were supported; the average length of assignment was 2 1/2 months. This program has provided a significant addition to the climate of active experimental and theoretical participation in the research programs at the Holifield Facility. The opportunities for much broader interaction with visiting scientists have been enhanced by a series of meetings hosted by the Institute. During FY 1985 there were four small workshops: two theoretical, and one each on high-spin states and low-lying level properties. There were two larger meetings (attendance ~150) with topics of "Directions in Nuclear Structure Research," and "Intermediate Energy Heavy Ion Physics." The latter meeting was held to assess the interest in the physics addressed in this proposal and to identify the most exciting areas to be explored. Material from this meeting served as an important resource for the development of Chapter II of this proposal. The program of this workshop is included as Appendix I.

The ongoing support of heavy-ion research at ORNL by the State of Tennessee and the support and involvement of the university community has produced a stimulating research atmosphere in which the facility expansion to be proposed here can be uniquely exploited. It is anticipated that this tradition of financial support from the state and from the most active universities can be continued. The Science Alliance center-of-excellence project at the University of Tennessee

exists to promote programs of joint research between this university and ORNL. Nuclear physics has been one such area of close cooperation in the past and will continue to receive financial support through this state-funded program.

IV. ACCELERATOR SYSTEM

	<u>Page</u>
IV.A. REQUIRED BEAM PROPERTIES	IV-1
IV.B. SYSTEM DESCRIPTION	IV-7
IV.C. GENERAL SYNCHROTRON CONSIDERATIONS	IV-15
IV.D. INJECTION	IV-18
IV.D.1. References	IV-25
IV.E. SYNCHROTRON RING PARAMETERS	IV-26
IV.E.1. Lattice of the 4-Tm Booster	IV-26
IV.E.2. Aperture Considerations for the Booster	IV-30
IV.E.3. Lattice of the 15-Tm Main Ring	IV-31
IV.E.4. Aperture Considerations for the Main Ring	IV-38
IV.E.5. Lattice of the 10-Tm Cooling Ring	IV-39
IV.E.6. Aperture Considerations for the Cooling Ring	IV-45
IV.E.7. References	IV-49
IV.F. RING MAGNETS	IV-50
IV.F.1. References	IV-54
IV.G. RF ACCELERATING/DECELERATING SYSTEMS	IV-55
IV.H. VACUUM SYSTEM	IV-75
IV.H.1. References	IV-103
IV.I. ELECTRON COOLING SYSTEM REQUIREMENTS	IV-104
IV.J. STOCHASTIC COOLING SYSTEM REQUIREMENTS	IV-116
IV.J.1. References	IV-120

IV.A. REQUIRED BEAM PROPERTIES

The number, configuration, bending powers, apertures, and cycle rates of the proposed accelerators depend on the desired beam energy, intensity, and quality. These beam characteristics are determined by the needs of the research program that will be undertaken at the new facility.

In Tables IV.A.1 to IV.A.4 we summarize the beam parameters required to perform the physics program outlined in Chapter II. Table IV.A.1 shows the range of desired beam energies for various classes of experiments. Most of the experiments include 1000 MeV/nucleon in their desired energy range. The atomic physics program would require less energy, but many of the most interesting experiments involve the heavier beams. The baryonic resonance program would require the most beam energy. From this table a maximum main-ring magnetic rigidity of 15 Tm was chosen. This rigidity corresponds to a maximum energy of 1500 MeV/nucleon for beams with $Q/A = 1/2$. The maximum energy for very-heavy ions ranges from 500 to 900 MeV/nucleon, depending on the stripper foil configuration. The 900 MeV/nucleon beam has, of course, less intensity since an additional foil stripper is required. The maximum main-ring rigidity was chosen so that greater than 50% of an output uranium beam could be fully stripped.

Table IV.A.2 summarizes the intensity requirements which are given for both a typical light ion, ^{32}S , and a typical heavy ion, ^{197}Au . Beam intensities from about 5×10^9 to 1×10^{11} particles/sec

IV-2

Table IV.A.1. Desired Projectile Energy
(for various areas of research)

	Energy (MeV/nucleon)			
	10 ¹	10 ²	10 ³	10 ⁴
Equation of state studies		xxxxxxxxxxxx		
Kaon studies		xxxxxxxxxxxx		
Crystal blocking		xxxxxxxxxx		
Particle-particle correlations		xxxxxxxxxxxx		
Atomic physics	xxxxxxxxxxxxxxxxxxxx			
Giant resonance studies			xxxxx	
Charge exchange and inelastic reactions			xxx	
Production of exotic nuclei		xxxxxxxxxx		
Transfer reactions		xxxxxxxxxx		
Baryonic resonances			xxxxxxx	

Table IV.A.2. Desired Beam Intensities

	Intensity (particles/sec)							
	^{32}S				^{197}Au			
	10^9	10^{10}	10^{11}		10^8	10^9	10^{10}	10^{11}
Equation of state studies		xxxxx					xxxxx	
Kaon studies		xxxxxxx					xxxxx	
Crystal blocking							xxxxx	
Particle-particle correlations		xxxx					xxxxx	
Atomic physics					xxxxx			
Giant resonance studies		xxxxx						
Charge exchange and inelastic		xxxxx					xxxxx	
Production of exotic nuclei		xxxx					xxxx	
Transfer reactions		xxxxx						
Baryonic resonances		xxxxxxx					xxxxxxx	

Table IV.A.3. Desired Energy Resolution

	Energy Resolution $\Delta E/E$			
	10 ⁻²	10 ⁻³	10 ⁻⁴	10 ⁻⁵
Equation of state studies	xxxxxxxx			
Kaon studies	xxxxxxxxxxxxxx			
Crystal blocking			xxxxxxxxxx	
Particle-particle correlations	xxxxxxxxxxxxxx			
Atomic physics			xxxxxxx	
Giant resonance studies			xxxxxxxxxx	
Charge exchange and inelastic reactions			xxxxxxxxxx	
Production of exotic nuclei	xxxxxxxxxx			
Transfer reactions			xxxxxxx	
Baryonic resonances	xxxxxxx			

Table IV.A.4. Desired Emittance

	Emittance (π -mm mrad)		
	10	1	0.1
Equation of state studies	xxxxxxxxxx		
Kaon studies	xxxxxxxxxx		
Crystal blocking			xxxxxxx
Particle-particle correlations		xxxxxxxxxx	
Atomic physics			xxxxxxxxx
Giant resonance studies		xxxxxxxxxx	
Charge exchange and inelastic reactions		xxxxxxxxxx	
Production of exotic nuclei	xxxxxxxxx		
Transfer reaction		xxxxxxxxxx	
Baryonic resonances	xxxxxxxxxxxxx		

are required for most measurements. The production of exotic nuclei requires intensities in excess of 5×10^{10} particles/sec, whereas the beam intensity for the atomic physics program is rather modest.

Tables IV.A.3 and IV.A.4 present the beam quality requirements for the various experiments. The crystal blocking, giant resonances, charge exchange, and inelastic reaction studies require extremely good energy resolution. Crystal blocking, atomic physics, giant resonances, inelastic reactions, and transfer reaction studies require extremely good transverse emittances. These beam quality levels with reasonable intensities can be approached only by using an electron cooling system.

There are requirements not listed in Tables IV.A.1 to IV.A.4 that affect the accelerator system design. The optimum beam-on duty cycle for most experiments is 100%. A high duty cycle is not compatible with high-intensity operation of a single ring; consequently, a second ring is needed to stretch the duty cycle. Moreover, production of beams of exotic nuclei requires a second ring to catch the radioactive ions. This ring must have a stochastic cooling system and also an electron cooling system to meet the needs of the physics research program. All these functions are performed by a single stretcher/cooler/catcher ring in the proposed design.

IV.B. SYSTEM DESCRIPTION

In response to the requirements given in Tables IV.A.1-4, a chain of three accelerator rings is proposed: a fast-cycling 4-Tm "booster" synchrotron, a slow cycling 15-Tm synchrotron "main ring", and a dc 10-Tm "cooler" storage ring. The main properties of these rings are summarized in Table IV.B.1. The existing HHIRF tandem will inject heavy ions into the booster, which will then inject the main ring. Both the main ring and cooler will be able to transfer beam to each other and to provide beam to the existing Building 6000 experimental caves and also to a new experimental area (building S-2 in Fig. V.A.1).

To provide beams for the desired experiments all three rings are needed. The 15-Tm main ring provides most of the acceleration to produce the ion energy. This ring could be directly injected with the tandem. However, starting from this low injection energy, the main ring would then need a very large acceptance and a fast cycle rate to achieve an adequate beam current. It is more cost effective to span this energy increase with two accelerators: a small-circumference, fast-cycling, large-acceptance booster, which accelerates ions to an intermediate energy, and a large-circumference, slow-cycling, low-acceptance main ring, which continues the acceleration to the final energy.

Table IV.B.1. Accelerator System

	<u>Booster</u>	<u>Main Ring</u>	<u>Cooler</u>
Maximum $B\rho$ (Tm)	4	15	10
Cycle freq. (Hz)	30	1	dc
Acceptances			
Horizontal (π mm mrad)	200	70	30
Vertical (π mm mrad)	50	40	30
$\Delta P/P$ (%)	1.0	0.3	1.0

The maximum beam energy from the booster and main ring depends on the ion species and the location and number of stripping foils. Stripper foils are possible between the tandem and booster (Case I), between the booster and main ring (Case II), or in both locations (Case III). Figs. IV.B.1 and IV.B.2 show the expected ion energies and intensities for these cases, based on operation of the tandem at a terminal voltage of 25 MV with a 500 μ A pulsed negative-ion beam from the source. For these curves the most abundant charge state is used after each stripping. Over 10^{11} light ions per main-ring cycle will be available at 1500 MeV/nucleon. With a single stripper after the booster, 1×10^{10} ^{238}U ions per cycle will be available at 400 MeV/nucleon. These energies and intensities are sufficient for the experimental objectives outlined in Chapter II.

The acceleration cycle for Case II, for the ^{238}U beam, would have the following timing sequence. The tandem beam would fill the booster acceptance with 30 turns of 1.58-MeV/nucleon $^{238}\text{U}^{14+}$ ions. This filling would require about 100 μ s. The booster circumference is 1/8 of the main ring circumference, and the booster would accelerate and inject these bunches 8 times into equally spaced positions around the main ring circumference. These fillings would be done at a 30-Hz rate and so require 0.27 sec to complete. The foil stripper between the booster and main ring would strip the 2.7-MeV/nucleon ^{238}U ions from 14^+ to 50^+ . The main ring would then accelerate these 1×10^{10} ions

Fig. IV.B.1. Energy of beam from the 15-Tn synchrotron for a tandem terminal potential of 25 MV. Stripping foil locations for the three curves are given in the text.

Fig. IV.B.2. Currents of beams from the 15-Tm synchrotron for a tandem terminal potential of 25 MV, a source current of 500 μ A, and 30-turn injection into the booster followed by eight booster injections into the main ring.

to 400 MeV/nucleon in about 0.4 sec. This beam can then be either slowly ejected to the experimental areas or rapidly injected into the cooler. The maximum rate at which the above cycle can occur is about once per second.

Using the main ring to both accelerate and to slow extract gives a short duty cycle. A major function of the cooler ring is to stretch this duty cycle to nearly 100%. This is accomplished by having the cooler store the beam and provide a slow resonant-extraction beam spill to the experimental areas while the booster and main ring are accelerating another group of ions. The smaller bending power of the cooler requires that fully accelerated ions are stripped before injection. For the ^{238}U example, about half of the beam (5×10^9 ions) would be fully stripped and stored in the cooler. These ions, of course, could be reinjected into the main ring for further acceleration; however, the cooler would not be available to stretch the resulting pulse since its bending power is too low.

Another important function of the cooling ring is to reduce the beam energy spread and emittance and, increase phase space density with an electron cooling system. This improvement in beam quality is necessary for high resolution work and also for cycles involving deceleration. For example, the 5×10^9 fully stripped ^{238}U ions will be decelerated to lower energies for atomic physics studies and QED tests. The timing sequence, of course, would require lengthening to allow time for cooling. The third major function of the cooling ring

is to catch and cool secondary radioactive beams produced from fixed target collisions of the main-ring beam. For this capability the cooler needs both a large momentum acceptance and a stochastic cooling system.

Most of the system cost is for the main-ring accelerator. For the required beam intensities, this cost is in fact reduced with the addition of a booster. Since the cooler ring is both dc and shares tunnel, utilities, etc., with the main ring, its incremental system cost is small. Its addition allows important physics issues to be addressed. The system will produce 5×10^9 fully stripped, 400-MeV/nucleon ^{238}U ions per second with nearly a 100% duty factor. For the light ions, up to 1×10^{11} per second can be produced at 1500 MeV/nucleon with a 50% duty factor.

The three rings provide a great deal of flexibility in allowing other acceleration configurations. For example, a higher-intensity, low-energy beam can be obtained by using the main ring as a stretcher for the booster. In this configuration, the booster can accelerate 30 bunches per second, giving 1×10^{12} $^{12}\text{C}^{6+}$ particles/sec at 176 MeV/nucleon and 5×10^{10} $^{238}\text{U}^{3+}$ particles/sec at 25 MeV/nucleon. In another configuration, the booster and main ring could deliver ions to a second experiment while another experiment used stored ions in the cooler.

The intensities are sufficiently large that two or more experiments could run simultaneously, with the use of a split beam. This is especially true for large acceptance experiments which need only 10^6 to

10^7 ions per second. The splitting could be accomplished in two ways. The first is to use a conventional wire splitter. This introduces a background of fragmented ions which may be difficult or impossible to tune out of the experimental beam lines. A second method is to keep the beam rf-bunched in the cooler and use rf splitters in the external beam lines to deliver different rf bunches to different experiments.

Finally, the present design allows the introduction of a relatively complex beam line between the main ring and the cooler, allowing a line specifically designed for separation of secondary ions. Such a line needs a low β area for a production target, a dispersing section, a variable energy degrader, a momentum combining section, and a section matching the cooler acceptance.

The individual rings and hardware systems will be considered in detail in later sections.

IV.C. GENERAL SYNCHROTRON CONSIDERATIONS

A synchrotron consists of dipole and quadrupole (and sextupole) magnets arranged in a ring. This arrangement is called the lattice. Particles travel inside a vacuum chamber around the ring guided by the bending and focusing force of the magnets. To confine the particles in the vacuum chamber as they are accelerated or decelerated, the strength of the magnetic field (B) is varied according to the linear momentum (P) of the particle:

$$B = \frac{P}{Q\rho} ,$$

where ρ is the bending radius of the magnet and, Q is the charge of the particle. The acceleration (deceleration) is achieved by applying an alternating electric field whose frequency is synchronized with the revolution frequency of the particle. The maximum ion energy is determined by the maximum bending power of the dipole magnets and the mass and charge of the ion. For the proposed $B\rho = 15 \text{ Tm}$ main ring, the maximum energy of a light-ion beam is 1502 MeV/nucleon for light ions with $Q/A = 1/2$.

For a given magnetic field, the orbit of particles with the designed energy and no transverse velocity is a closed curve called the central orbit. Particles with the same energy but with non-zero transverse velocity oscillate around the central orbit as a result of the focusing magnetic forces. This transverse motion relative to the

central orbit is known as the betatron oscillation and is usually described in terms of a periodic amplitude $\beta(s)$ and a phase $\phi(s)$:

$$\begin{aligned}x &= \sqrt{\epsilon_x \beta_x(s)} \sin (\phi_x(s) + \phi_{x0}), \\y &= \sqrt{\epsilon_y \beta_y(s)} \sin (\phi_y(s) + \phi_{y0}),\end{aligned}\tag{IV.C.1}$$

and

$$\phi_{x,y}(s) = \int_0^s \frac{ds'}{\beta_{x,y}(s')} .$$

where x, y are the horizontal and vertical displacements from the central orbit, s is the distance along the central orbit, and ϵ_x and ϵ_y are the particle emittances. The number of oscillations in one revolution around the ring is the tune of the betatron motion and is given by

$$\nu_{x,y} = \frac{1}{2\pi} \int \frac{ds'}{\beta_{x,y}(s')} .\tag{IV.C.2}$$

For a given lattice design, the β -functions are obtained by solving the equations of motion. The maximum betatron motion is limited by the size of the vacuum chamber. The corresponding maximum emittance is the acceptance of the synchrotron. Usually, the injected beam has an emittance (ϵ) smaller than the acceptance (A) of the ring, and it is possible to inject several turns (A/ϵ) of beam before the full acceptance is filled. The number of particles (N) that can be injected in filling a ring is given by

$$N \approx \frac{A}{\epsilon} \cdot \frac{IC}{V} ,\tag{IV.C.3}$$

where I is the beam intensity, C is the ring circumference and, v is the beam velocity at injection. In principle, it is possible to fill both the horizontal and vertical phase space by multi-turn injection. However, only one dimension has been used in existing accelerators and some dilution is always encountered.

Particles with momentum to charge ratios (P/Q) different from the designed value will oscillate around a different central orbit. In general, the central orbit of particles with larger momentum or lower charge has a larger average radius. This deviation $\Delta x(s)$ is described by a dispersion function $\eta(s)$ from which the displacement of the central orbit can be obtained as

$$\Delta x(s) = \eta(s) \frac{\Delta(P/Q)}{P/Q} , \quad (\text{IV.C.4})$$

where $\Delta(P/Q)$ is the deviation of P/Q from the designed value. It is obvious that a small dispersion function is desirable because it increases the amount of deviation in P/Q that can be accommodated in the ring.

IV.D. INJECTION

The heavy-ion beams from the existing HIRF tandem will be injected into the 4-Tm booster. The energy per nucleon and the intensity of the tandem beam vary with the mass of the particle and are lower for the heavier ions. As shown in Table IV.D.1, the energy changes from 12.5 Mev/nucleon for ^{12}C to 1.58 MeV/nucleon for ^{238}U . The beams can either be injected directly into the booster or be stripped before injection. In the former case there is a lower charge state, higher intensity beam, and in the latter there is a higher charge state, lower intensity beam. In Table IV.D.1 the most abundant charge states are listed for both cases. The currents are calculated with a source current of 500 μA , which has been demonstrated recently in ORNL measurements [A186], and with the charge state fraction obtained from an empirical formula [Sa77] based on the systematics of measured values.

To increase the number of injected particles, we plan to use multi-turn injection, in the horizontal plane, into the 4-Tm booster. The emittance of the tandem beam is about $\epsilon_x = \epsilon_y = 2-3 \pi \text{ mm-mrad}$. With a design horizontal acceptance of $A_x = 200 \pi \text{ mm-mrad}$ for the booster, it is possible to inject at least 30 turns, even with a factor of two dilution of the phase space. The number of particles that can be injected is

$$N_{inj} = \frac{nIC}{v} , \quad (\text{IV.D.1})$$

Table IV.D.1 Properties of beams from the tandem with a 25-MV terminal voltage and 500- μ A source current. No beam loss in the tandem is assumed for this table. The dominant charge state and the beam current before and after stripping at the exit of the tandem are shown.

Beam	E/A (MeV/nucleon)	Before Stripping		After Stripping	
		Charge State	Current (μ A)	Charge State	Current (μ A)
^{12}C	12.5	5	260	6	250
^{16}O	12.5	7	260	8	230
^{32}S	8.6	10	170	15	85
^{40}Ca	7.5	11	150	19	65
^{58}Ni	6.0	13	130	25	41
^{79}Br	4.8	14	120	28	31
^{127}I	3.4	16	104	36	21.6
^{150}Nd	2.84	16	99	38	18.7
^{197}Au	2.16	16	93	42	15.5
^{238}U	1.58	14	91	43	14.2

where n is the number of turns, I is the intensity of the beam (particles/sec), C is the circumference of the synchrotron, and v the velocity of the beam at injection. In principle, it is possible to fill both the horizontal and vertical phase space by multi-turn injection; however, so far only one-dimension has been used in existing accelerators. The injection and the subsequent rf capture of the beam are not accomplished with 100% efficiency. We have calculated the number of injected particles N_{inj} for 30-turn injection using equation (IV.D.1) and the beam energy and current from Table IV.D.1. A 50% transmission loss in the tandem, a 20% loss in injection and a rf capture efficiency ranging from 90% for ^{12}C to 75% for ^{197}Au are used in these calculations. The results for the stripped and non-stripped cases are shown in Figs. IV.D.1 and IV.D.2, respectively.

In addition to the limit on the number of injected particles due to the synchrotron acceptance, beam intensity and emittance, there are limits due to the electric and magnetic fields produced by the beam itself. The repulsive space-charge force introduces a defocusing effect and reduces the tune of the betatron motion. Since the strength of this force varies according to the radial position of the particles in the beam, it produces a distribution of tune reduction. The number of particles corresponding to the space charge limit of (N_{SC}) needed to produce a tune shift $\Delta\nu$ is

$$N_{SC} = \epsilon_y (1 + \sqrt{\epsilon_x/\epsilon_y}) \beta^2 \gamma^3 \frac{A}{Q^2} B_f \Delta\nu \cdot 2.72 \times 10^{18} , \quad (\text{IV.D.2})$$

Fig. IV.D.1. The number of particles per booster cycle N_{inj} injected from the tandem into the 4-Tm booster, the space charge limit N_{sc} and the Keil-Schnell limit N_{KS} as a function of particle mass for the case where the beams are stripped before injection into the booster.

Fig. IV.D.2. The number of particles N_{inj} injected from the tandem into the 4-Tm booster, the space charge limit N_{SC} and the Keil-Schnell limit N_{KS} as function of the particle mass for the case where the beams are not stripped between the tandem and the booster.

where ϵ_x and ϵ_y are the horizontal and vertical emittance of the synchrotron beam, $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$ is the Lorentz factor, B_f is the bunching factor, and A and Q are the mass number and charge state of the beam. Notice that for injection at low energy, N_{sc} is proportional to energy. As the beam is accelerated, $\epsilon\beta\gamma$, the normalized emittance, is invariant, and thus N_{sc} increases with the velocity. The A/Q^2 dependence means that particles with higher charge state experience a larger tune shift. If the tune shifts to a value which corresponds to a resonance value, the transverse motion will be unstable. To avoid resonances, the Δv value is usually limited to less than 0.1. The space charge limit of the number of particles for injection is also shown in Figs. IV.D.1 and IV.D.2. The calculation is carried out using $\epsilon_x = 200 \pi$ mm-mrad, $\epsilon_y = 50 \pi$ mm-mrad, $B_f = 0.5$, and $\Delta v = 0.08$.

Another collective effect, the microwave instability, is caused by the coherent interaction of the beam with the beam pipe. The limit on the number of particles, the Keil-Schnell limit, is given by

$$N_{ks} = \left(\frac{\Delta P}{P}\right)^2 \beta^2 \gamma^3 \frac{A}{Q^2} \frac{R |\eta|}{g} 6.65 \times 10^{17}, \quad (\text{IV.D.3})$$

where ΔP is the FWHM of the momentum spread, R is the mean radius of the ring, $\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_T^2}$, and g is a geometric factor. Notice that the same $\beta^2 \gamma^3 \frac{A}{Q^2}$ factor appears as in the space charge limit. The $\Delta P/P$ values resulting from the straggling in a $200 \mu\text{g}/\text{cm}^2$ carbon foil for the stripping case and $\Delta P/P = 10^{-4}$ for the nonstripping case are used in

the calculations. The results, as shown in Figs. IV.D.1 and IV.D.2., indicate that the number of injected particles exceed the Keil-Schnell limit. Theoretical studies [Ho83] indicate that the condition $N > N_{KS}$ may not result in a catastrophic loss of beam; instead, a tail will be developed in the momentum distribution, and this can stabilize the beam.

In order to increase $\Delta P/P$ for injection into the rings, a fixed frequency cavity operating at 100 or 200 MHz can be inserted just before the entrance to the booster. A momentum spread of $\Delta P/P = \pm 0.2\%$ is sufficient to place the Keil-Schell limit well above the N_{inj} line in Figs. IV.D.1 and IV.D.2. The cavity voltages needed are quite modest. They are 98 kV for $^{12}C^{6+}$, 95 kV for $^{238}U^{16+}$, and 35 kV for $^{238}U^{3+}$. These are easily obtained in a double gap, fixed frequency, 1/4 wave resonator, as it can be built with a rather high Q. The resonator is placed after the beam transport from the tandem to the 4-Tm booster. This avoids having to increase the momentum acceptance of this line to $\pm 0.4\%$ and, instead, allows designing for $\Delta P/P = \pm 0.1\%$. The stripper foil can then be made just thick enough to reach the equilibrium charge state for the ion being used, thus minimizing its contribution to the emittance growth.

IV.D.1. References

- A186 G.D. Alton and C.M. Jones, Nucl. Instr. Methods, to be published.
- Ho83 I. Hofmann, I. Bozsik, and A. Jahnke, IEEE Trans. Nucl. Sci. NS-30, No. 4, 2546 (1983).
- Sa77 R.O. Sayer, Revue de Physique Appliquée 12, 1543 (1977) and private communication.

IV.E. SYNCHROTRON RING PARAMETERS

IV.E.1. Lattice of the 4-Tm Booster

The booster will be injected by the HHIRF tandem. For intensity considerations, the booster is designed to accept multi-turn injection and will be a fast cycling (30 Hz) synchrotron. The maximum bending power of 4 Tm is chosen so that a uranium beam from the booster, after being stripped and accelerated by the 15-Tm main ring, will have an intensity of 1×10^{10} particles per second and an energy of 500 MeV/nucleon. At this energy the fraction of fully stripped ions is better than 50%.

The rf system contributes significantly to the capital and operating cost of a fast cycling synchrotron. Since the voltage is proportional to the square of the circumference for a given peak magnetic field, a combined function lattice is chosen to minimize the circumference. In addition, the length of the straight sections is kept to a minimum. The lattice, as shown in Fig. IV.E.1, has 6-fold symmetry. Each sextant consists of an arrangement of horizontal focusing (F) - defocusing (D) - defocusing (D) - focusing (F) combined function dipoles with a 2-m straight section between the F magnets. The circumference is 38.45 m. The tune is chosen to be $\nu_x = 1.704$ and $\nu_y = 1.698$, which gives approximately 100° of betatron phase advance per sextant. The parameters of the booster are listed in Table IV.E.1, and the lattice functions are shown in Fig. IV.E.2.

Fig. IV.E.1. The lattice of the 4-Tm booster.

Table IV.E.1. Parameters for the 4-Tm Booster

RING - 6-fold symmetry

24 combined function magnets and 6 straights	
circumference	$C = 38.45 \text{ m}$
distance arc-arc	$D_{aa} = 12.39 \text{ m}$
distance straight-straight	$D_{ss} = 11.91 \text{ m}$
tune	$\nu_x/\nu_y = 1.704/1.698$
chromaticity	$\xi_x/\xi_y = -1.2177/-2.1791$
transition γ	$\gamma_T = 1.714$

LATTICE CELL - Combined function FDDF

length of cell	$L_{cell} = 6.408 \text{ m}$
phase advance/cell	$\mu_x/\mu_y = 102.24^\circ/101.88^\circ$
length of dipole	$L_B = 0.952 \text{ m}$
length of straight	$L_S = 2.0 \text{ m}$
beta function ^a	$\hat{\beta}_x/\check{\beta}_x = 5.70/1.89 \text{ m}$
	$\hat{\beta}_y/\check{\beta}_y = 9.82/2.06 \text{ m}$
dispersion function	$\hat{\eta}_x/\check{\eta}_x = 2.59/1.59 \text{ m}$

MAGNET

length of magnet	$L_B = 0.952 \text{ m}$
magnetic field	$B = 1.1 \text{ T}$
bending radius	$\rho = 3.636 \text{ m}$
bending angle	$\phi = 15^\circ$
gradient	$G_F = 1.64 \text{ T/m}$
	$G_D = -1.79 \text{ T/m}$

BEAM APERTURE

focusing magnet	$\Delta x = \pm 6.1 \text{ cm}$	$\Delta y = \pm 1.7 \text{ cm}$
defocusing magnet	$\Delta x = \pm 4.7 \text{ cm}$	$\Delta y = \pm 1.9 \text{ cm}$
acceptance	$A_x/A_y = 200/50 \pi \text{ mm-mrad}$	
momentum spread	$\Delta P/P = 0.01$	
closed orbit error	$\sigma \Delta x_{eq} = 6.0 \times 10^{-4} (\beta_x)^{1/2} \text{ m}$	
	$\sigma \Delta y_{eq} = 4.3 \times 10^{-4} (\beta_y)^{1/2} \text{ m}$	

a) $\hat{\beta}$ and $\check{\beta}$ are, respectively, the maximum and minimum beta function values.

4 Tm BOOSTER

Fig. IV.E.2. Vertical beta function β_y , horizontal beta function β_x , and dispersion function η_x in one sextant of the 4-Tm booster.

IV.E.2. Aperture Considerations for the Booster

The acceptance of the booster is 200 and 50 π mm-mrad in the horizontal and vertical planes, respectively. The larger horizontal acceptance is needed for the multi-turn injection. The maximum spread in momentum during the acceleration is estimated to be $\Delta P/P = 0.01$. The horizontal and vertical closed orbit errors (root mean square) are calculated by using a magnet field error of $\sigma \Delta B/B = 5 \times 10^{-4}$ (where $\sigma \Delta B/B$ is the root mean square error of $\Delta B/B$), a magnet rotation error of $\sigma \Delta \theta = 2 \times 10^{-4}$ rad, and a magnet position error $\sigma \Delta x = \sigma \Delta y = 1.5 \times 10^{-4}$ m. The results are:

$$\sigma \Delta x_{eq} = 6.0 \times 10^{-4} (\beta_x)^{1/2} \text{ m}$$

$$\sigma \Delta y_{eq} = 4.3 \times 10^{-4} (\beta_y)^{1/2} \text{ m}$$

where β_x and β_y are the horizontal and vertical beta functions.

Values of the aperture (i.e., the minimum vacuum chamber size needed to accommodate the betatron motion, momentum dispersion, and closed orbit errors for this booster lattice) are $\Delta x = \pm 6.1$ cm, $\Delta y = \pm 1.7$ cm for the focusing magnet, B_f , and $\Delta x = \pm 4.7$ cm, $\Delta y = \pm 1.9$ cm for the defocusing magnet, B_d .

As shown in Fig. IV.E.1, the straight sections are occupied by injection and extraction septa, two each injection and extraction bump magnets, an extraction kicker, and an rf cavity. The 4-Tm booster is situated near the end of a long straight section of the 15-Tm main ring. Beam from the booster is injected into a dispersion suppressor cell in the 15 Tm ring (see the following subsection).

IV.E.3. Lattice of the 15-Tm Main Ring

The main synchrotron has a maximum bending power of 15 Tm with a race-track lattice consisting of two 180° arcs connected by two long straight sections. Fig. IV.E.3 shows one quadrant of the ring lattice. Each of the arc sections contains eight FODO cells each of which consists of a horizontally focusing quadrupole, two dipoles, and a horizontally defocusing quadrupole. The phase advance per cell is 90° in both the x and y planes. Such an arrangement, called a second order achromat, can be corrected for chromatic effects up to second order with two families of sextupole magnets [Br79]. A two-cell dispersion suppressor is placed between the arc sections and the long straights. These cells are identical to the regular bending cells except they contain half-length dipole magnets. All the bending cells are 8.4168 m in length; thus the 24 cells have a total length of 202 m. In order to transfer several beam bunches from the booster to the main ring with the same rf frequency, the circumference of the main ring has to be an integer multiple of the circumference of the booster. The circumference chosen was 307.584 m (8×38.45 m) and thus each long straight section has a length of 52.792 m.

The beta functions of the straight sections must smoothly match those of the arc cells at their boundaries. Since the straight section is nondispersive, the quantities to be matched are the β_x functions

Fig. IV.E.3. The lattice of one quadrant of the 15-Tm main ring.

and their derivatives, β_x , α_x , β_y , and α_y . Together with the two tune values of the straight sections there are six parameters to be controlled. Thus, six independent lattice variables (such as quadrupole strength) are needed to satisfy these six conditions.

The present design of the long straight section consists of six FODO cells with identical physical dimensions. Each straight section is magnetically symmetrical about its midpoint. The six pairs of quadrupole magnets and the center quadrupole are physically the same as the arc quadrupoles but they are powered independently. Their strength is adjusted to obtain the specific tune values and to match the beta functions while minimizing the maximum value of the beta functions.

The parameters of the 15-Tm ring are listed in Table IV.E.2 and the lattice functions for one quadrant of the ring are shown in Fig. IV.E.4. Equipment for fast injection from the 4-Tm booster, fast extraction to the 10-Tm cooler, slow extraction to two experimental areas and fast injection from the cooler is placed in the straight sections. Also space for rf cavities and possibly electron cooling equipment is needed. Fig. IV.E.5 shows schematically a possible arrangement of these devices. Only one of the several rf cavities is shown.

Table IV.E.2. Parameters of the 15-Tm Ring

RING - race track

Each arc has 8 regular cells and 4 dispersion suppressor cells with half length bending magnets. Each long straight has 6 FODO cells.

180° arc sections	$L_{\text{arc}} = 101 \text{ m}$
long straights	$L_s = 52.79 \text{ m}$
circumference	$C = 307.58 \text{ m} = 8 C_{4Tm}$
distance arc-arc	$D_{aa} = 122.87 \text{ m}$
distance straight-straight	$D_{ss} = 56.14 \text{ m}$
tune	$\nu_x/\nu_y = 9.36/9.45$
chromaticity	$\xi_x/\xi_y = -12.2/-12.0$
transition γ	$\gamma_T = 6.722$

ARC CELL - FODO structure

length of cell	$L_{\text{cell}} = 8.4168 \text{ m}$
phase advance/cell	$\mu_x/\mu_y = 90^\circ/90^\circ$
length of dipole	$L_B = 1.5708 \text{ m regular}$ $= 0.7854 \text{ m dispersion suppressor}$
length of quadrupole	$L_Q = 0.65 \text{ m}$
length of straight	$L_s = 0.9938 \text{ m}$
beta function	$\hat{\beta}_x/\check{\beta}_x = 13.8/2.55 \text{ m}$ $\hat{\beta}_y/\check{\beta}_y = 13.6/2.42 \text{ m}$
dispersion function	$\hat{\eta}_x/\check{\eta}_x = 1.76/0.87 \text{ m}$

LONG STRAIGHT SECTION - FODO STRUCTURE

length of cell	$L_{\text{cell}} = 8.7984 \text{ m}$
tune/straight	$\nu_x/\nu_y = 1.68/1.76$
length of straight	$L_s = 3.7492 \text{ m}$
beta function	$\hat{\beta}_x/\check{\beta}_y = 17.3/1.97 \text{ m}$ $\hat{\beta}_y/\check{\beta}_y = 15.4/1.71 \text{ m}$
dispersion function	$\eta_x = 0$

Table IV.E.2. Parameters of the 15-Tm Ring (Cont'd)

DIPOLE MAGNET - rectangular

length of dipole	L_B	= 1.5708 m regular = 0.7854 m half
magnetic field	B	= 1.5 T
bending radius	ρ	= 10 m
bending angle	ϕ	= 9° regular 4.5° half

QUADRUPOLE MAGNET

length of quadrupole	L_Q	= 0.65 m
gradient	G_F	= 8.13 T/m
	G_D	= -7.82 T/m
	G_{FA}	= 8.98 T/m
	G_{DA}	= -8.31 T/m
	G_{FS}	= 8.71 T/m
	G_{DS}	= -8.91 T/m
	G_{FB}	= 8.43 T/m
	G_{DB}	= -9.07 T/m
	G_{FC}	= 8.0 T/m

BEAM APERTURE

acceptance	A_x/A_y	= 70/40 π mm mrad
momentum spread	$\Delta P/P$	= 0.003
closed orbit error	$\sigma \Delta x_{eq}$	= $6.97 \times 10^{-4} (\beta_x)^{1/2}$ m
	$\sigma \Delta y_{eq}$	= $4.96 \times 10^{-4} (\beta_y)^{1/2}$ m
extraction β	β_x	= β_y = 12 m
extraction displacement	x_{ext}	= 2.0 cm
dipole aperture	Δx	= ± 4.8 cm Δy = ± 2.0 cm
quadrupole aperture	R_Q	= 6.1 cm

15 Tm Quadrant

Fig. IV.E.4. Vertical beta function β_y , horizontal beta function β_x , and dispersion function η_x in one quadrant of the 15-Tm synchrotron.

Fig. IV.E.5. The arrangement of injection and extraction elements in the straight sections of the 15-Tm synchrotron.

IV.E.4. Aperture Considerations for the Main Ring

This ring is designed to have an acceptance of 70 and 40 π mm-mrad in the horizontal and vertical planes, respectively, and it can accommodate a momentum spread of $\Delta P/P = \pm 0.3\%$. The closed orbit error due to assumed uncertainties in the dipole magnetic field $\sigma \Delta B/B$ of 5×10^{-4} , in the dipole magnet rotation $\sigma \Delta \theta$ of 2×10^{-4} rad and in the quadrupole position $\sigma \Delta x = \sigma \Delta y$ of 1.5×10^{-4} m are calculated to be

$$\sigma \Delta x_{eq} = 6.97 \times 10^{-4} (\beta_x)^{1/2} \text{ m}$$

$$\sigma \Delta y_{eq} = 4.96 \times 10^{-4} (\beta_y)^{1/2} \text{ m.}$$

Aperture has been allowed for the extraction in the x plane at a point with a beta function of ~ 12 m and a displacement of 2 cm. The beam aperture requirements are then determined to be $\Delta x = \pm 4.8$ cm and $\Delta y = \pm 2.0$ cm for the dipole magnets. A radius of 6.1 cm for the good field region is sufficient for all the quadrupoles.

IV.E.5. Lattice of the 10-Tm Cooling Ring

The cooling ring has a maximum bending power of 10 Tm which can hold fully stripped light ions, $Z/A = 1/2$, with an energy of 833 MeV/nucleon and fully stripped U ions of 555 MeV/nucleon. The lattice properties of this ring are determined mainly by the requirement of collection and cooling of secondary particles produced by the beam from the 15-Tm main ring. The large momentum spread of such secondary particles requires a large horizontal aperture. Stochastic cooling (see Section IV.I.) is needed to reduce this large momentum spread.

The stochastic cooling requires:

- (1) The pickup for longitudinal momentum cooling must be in a dispersive region with a small horizontal beta-function. The kicker must be placed in a nondispersive section.
- (2) For horizontal (vertical) betatron cooling, the pickup must be in a nondispersive region and near a horizontal (vertical) focusing quadrupole magnet where the beta function is large. The kicker must be in a nondispersive section, and the betatron phase difference between the pickup and the corresponding kicker must be an odd multiple of 90 degrees.

Therefore, the lattice must have both dispersive and nondispersive straights. The requirements on phase differences between the straight sections and the desire to use third integer resonance extraction limit the possible tunes of the machine to a few values. The proposed cooling ring has six-fold symmetry as shown in Fig. IV.E.6. Each sextant is symmetrical about its center. There are four dipole magnets and seven quadrupole magnets in each sextant; they form an achromatic bend. At the center of the bend, there is a dispersive straight with a length of 2 m. At each end of the bend, there are two nondispersive straights with lengths of 3.18 m. The circumference of the 10-Tm ring is 153.792 m, which is half that of the main ring. The lattice parameters are listed in Table IV.E.3 and the lattice functions for 1/12 of the ring are shown in Fig. IV.E.7.

Fig. IV.E.6. The lattice of the 10-Tm cooling ring. The horizontal (H), vertical (V), and momentum (P) pickups and kickers for stochastic cooling are shown.

Table IV.E.3. Parameters for 10-Tm Cooling Ring

RING - 6 fold symmetry

24 dipole and 42 quadrupole magnets
6 dispersive and 12 non-dispersive straights

circumference	C	= 153.792 m = 1/2 C _{15Tm}
distance-dispersive straights	D _{DD}	= 49.036 m
distance-nondispersive straight	D _{NN}	= 47.736 m
tune	ν_x/ν_y	= 5.31/5.274

LATTICE CELL - 60° achromatic bend

length of cell	L _{cell}	= 26.632 m
phase advance/cell	μ_x/μ_y	= 318.60°/316.44°
length of straights		
1 dispersive	L _{DS}	= 2 m
2 nondispersive	L _{NS}	= 3.1754 m
beta function	$\hat{\beta}_x/\hat{\beta}_y$	= 22.8/1.0 m
	$\hat{\beta}_y/\hat{\beta}_y$	= 22.6/1.79 m
dispersion function	$\hat{n}_x/\hat{n}_x$	= 2.72/0 m
chromaticity	ξ_x/ξ_y	= -10.0/-7.94
transition γ	γ_T	= 5.886

DIPOLE MAGNET - rectangular

length of dipole magnet	L _B	= 1.7453 m
magnetic field	B	= 1.5 T
bending radius	ρ	= 6.6667 m
bending angle	ϕ	= 15°

Table IV.E.3. Parameters for 10-Tm Cooling Ring (Cont'd)

QUADRUPOLE MAGNET

length of magnet	L_Q	= 0.5 m
gradient	G_A	= 5.208 T/m
	G_D	= -6.796 T/m
	G_F	= 7.609 T/m
	G_B	= -10.0 T/m

BEAM APERTURE

acceptance	A_x	= A_y = 30 π mm-mrad
momentum spread	$\Delta P/P$	= 0.01
extraction β	β_{ext}	= 18 m
extraction displacement	x_{ext}	= 2.0 cm
closed orbit error	$\sigma \Delta x_{eq}$	= $8.10 \times 10^{-4} (\beta_x)^{1/2}$ m
	$\sigma \Delta y_{eq}$	= $6.38 \times 10^{-4} (\beta_y)^{1/2}$ m
dipole aperture	Δx	= ± 4.8 cm Δy = ± 2.5 cm
quadrupole aperture	R_{QA}	= 7.0 cm
	R_{QD}	= 2.9 cm
	R_{QF}	= 5.3 cm
	R_{QB}	= 2.8 cm

10 Tm COOLER

Fig. IV.E.7. Vertical beta function β_y , horizontal beta function β_x , and dispersion function η_x in $1/12$ of the 10-Tm cooling ring.

IV.E.6. Aperture Considerations for the Cooling Ring

The momentum acceptance of the cooling ring in the two transverse directions and in the longitudinal direction must be large enough to collect an appreciable fraction of the secondary particles. The momentum spread of the secondary particles produced in the projectile fragmentation reaction has been measured [Gr75] [Vi79] and a model [Go74] based on Fermi motion can reproduce the results successfully. Figs. IV.E.8 and IV.E.9 show the emittance and the longitudinal momentum spread from this model for secondary particles with mass m_f produced by fragmentation of a ^{48}Ca beam. The beam is assumed to have an emittance of $10 \pi \text{ mm-mrad}$ and the beam spot on the production target is assumed to be $\pm 1 \text{ mm}$ ($\beta_x = \beta_y = 0.1 \text{ m}$). A momentum acceptance $\Delta P/P = 0.01$ and a transverse acceptance $E_x = E_y = 30 \pi \text{ mm mrad}$ was chosen for the cooling ring. It can be seen that these acceptances are needed in order to collect significant fractions of the secondary particles.

The closed orbit errors, from a dipole field error $\sigma \Delta B/B = 5 \times 10^{-4}$, a dipole rotational error $\sigma \Delta \theta = 2 \times 10^{-4} \text{ rad}$ and a quadrupole position error $\Delta x = \Delta y = 0.15 \text{ mm}$, are calculated to be

$$\sigma \Delta x_{\text{eq}} = 8.10 \times 10^{-4} (\beta_x)^{1/2} \text{ m and}$$

$$\sigma \Delta y_{\text{eq}} = 6.38 \times 10^{-4} (\beta_y)^{1/2} \text{ m.}$$

Slow extraction will take place in the x-plane at points in the non-dispersive straight with a beta function $\beta_x \approx 18 \text{ m}$. A 2-cm displacement is assumed for this extraction. The aperture requirements, as based on the above discussion, are $\Delta x = \pm 4.8 \text{ cm}$ and $\Delta y = \pm 2.5 \text{ cm}$ for

Fig. IV.E.8. Emittance of secondary beam produced by fragmentation of a ^{48}Ca beam as a function of the fragment mass for several beam energies. The beam is assumed to have an emittance $\epsilon = 10 \pi \text{ mm-mrad}$ and a beta function $\beta = 0.1 \text{ m}$ at the target.

Fig. IV.E.9. Longitudinal momentum spread of secondary beams produced by fragmentation of a ^{48}Ca beam as a function of the fragment mass for several beam energies.

the dipole. The radii for the quadrupole magnets are $R_{QA} = 7.0$ cm, $R_{QD} = 2.9$ cm, $R_{QF} = 5.3$ cm, and $R_{QB} = 2.8$ cm. Thus, three types of quadrupole magnets with beam aperture radii of 7.0 cm, 5.3 cm and 2.9 cm, respectively, may be used.

IV.E.7. References

- Br79 K. L. Brown, IEEE Trans. Nucl. Sci. NS-26, No.3, 3490 (1979).
- Go74 A. S. Goldhaber, Phys. Letters 53B, 306 (1974).
- Gr75 D. E. Greiner, P. J. Lindstrom, H. H. Heckman, Bruce Cork,
and F. S. Biesser, Phys. Rev. Lett. 35, 152 (1975).
- Vi79 Y. P. Viyogi, T. J. M. Symons, P. Doll, D. E. Greiner,
H. H. Heckman, D. L. Hendrie, P. J. Lindstrom, J. Mahoney,
D. K. Scott, K. Van Bibber, G. D. Westfall, H. Wieman, H. J.
Crawford, C. McParland, and C. K. Gelbke, Phys. Rev. Lett. 42,
33 (1979).

IV.F. RING MAGNETS

Some details of the main dipole and quadrupole magnets required for the three rings are listed in Tables IV.F.1 and IV.F.2, respectively. Five different kinds of dipoles are required: 9.0° and 4.5° bends for the 15-Tm main ring; 15.0° bends for the 10-Tm cooler; and both focussing and defocussing combined function 15.0° bends for the 4-Tm booster. All dipoles will be laminated H-frame construction, split at the horizontal midplane for vacuum pipe insertion. Laminations for the 15-Tm and 10-Tm low frequency and dc magnets will be 1.5-mm thick, whereas laminations for the 30-Hz booster dipoles will be much thinner in order to minimize core eddy current losses. All the dipole magnets will be stacked on a curved form so that the magnet center always follows the equilibrium orbit. This will eliminate extra field width for sagitta.

The 15-Tm and 10-Tm dipole gaps allow a total of 1.2 cm of space for vacuum pipe, bakeout heaters, and insulation and shims. These low-frequency booster dipoles will follow rather conventional design and construction procedures. The high-frequency booster dipoles will be very similar to those constructed for the KEK proton booster [Sa75]. A total space of 2.0 cm has been allowed in the center of the gap for a thin-walled, carbon fiber vacuum pipe with 150°C bakeout ability. The dipole core dimensions are listed in Table IV.F.1.

Table IV.F.1. Ring Dipole Parameters

Ring (Tm)	15	15	10	4	4
Cycle frequency (Hz)	1	1	dc	30	30
Number	32	16	24	12-Fa	12-Db
Bend angle (deg)	9.0	4.5	15	15	15
Max. field (T)	1.5	1.5	1.5	1.1	1.1
Path length (cm)	157.1	78.5	174.5	95.2	95.2
Gap (cm)	6.6	6.6	6.2	6.0	6.0
Good field width (cm)	10.0	10.0	10.0	12.0	12.0
Sagitta ^c (cm)	3.1	0.8	5.7	3.1	3.1
Pole width (cm)	22	22	22	26	26
Core height (cm)	58	58	62	53	53
Core width (cm)	88	88	86	73	73
Core length (cm)	148	70	163	86	86
Core mass (kg)	4740	2470	5730	2410	2410
NI (kA)	89	89	83	54	54
Max I ² R loss (kW)	32	22	33	14	14
Max. stored energy (kJ)	42	21	37	11	11
Total coil mass (kg)	693	441	550	350	350

- a. Combined function focusing $G = 1.64 \text{ T/m}$
b. Combined function defocusing $G = -1.79 \text{ T/m}$
c. The maximum distance between the path followed by a beam through a magnet and a straight line path.

Table IV.F.2. Ring Quadrupole Parameters

Ring (Tm)	15	10	10	10
Cycle frequency (Hz)	1	dc	dc	dc
Number	72	12	12	18
Good field radius (cm)	5.8	6.9	5.1	2.8
Field length (cm)	65	50	50	50
Max. gradient (T/m)	9.1	5.2	7.6	10.0
Inscribed diameter (cm)	14.0	16.0	12.0	8.0
Poletip field (T)	0.64	0.42	0.46	0.40
Core length (cm)	58	42	44	46
Core mass (kg)	1840	980	580	280
NI/pole (kA)	19.5	14.6	12.0	7.0
Max I ² R loss (kW)	13.8	9.0	6.8	3.6
Max. stored energy (kJ)	4.2	1.81	1.22	0.41
Total coil mass (kg)	270	180	130	70

The electrical parameters have been calculated for a peak current density of 5 A/mm^2 , which is roughly optimum for magnets of this kind. A higher current density gives a smaller capital cost with a higher power cost, whereas the opposite is true for a smaller current density. Ohmic losses and stored energies are listed in Tables IV.F.1-2 for the magnets operating at full excitation. The details of the coil construction will depend strongly on the magnet cycle frequency.

No more than four different kinds of quadrupoles seem to be required. All the quadrupole requirements for the 15-Tm ring are met with a single design: a high-field, 14-cm-bore magnet with a core length of 58 cm. These 72 quadrupoles will be constructed from 1.5-mm-thick laminations. The cooler quadrupoles could be of solid core construction. To minimize both operating and construction cost, magnets with 16-, 12- and 8-cm bores will probably be used. The quadrupole electrical parameters of Table IV.F.2 have also been calculated for a current density of 5 A/mm^2 .

Altogether, the three rings have a total of 96 dipoles and 114 quadrupoles. These magnets require 545 metric tons of steel for cores and 75 metric tons of copper for coils.

IV . i. References

- Sa75 H. Sasaki, K. Takikawa, M. Kumada, Y. Miyahara, T. Kurosawa,
and H. Someya, p.68, Proceedings of 5th International
Conference on Magnet Technology, Rome 1975.

IV.G. RF ACCELERATING/DECELERATING SYSTEMS

The radio frequency acceleration/deceleration systems used in the various rings operate over a wide range of frequencies and accelerating voltages. This is especially true for the 4-Tm booster system since beams may be injected from the tandem electrostatic accelerator in a variety of charge-to-mass ratios and kinetic energies per nucleon. The longitudinal phase-space area occupied by the injected beam will also depend upon its mass and kinetic energy per nucleon. This is particularly the case for beams post-stripped after the tandem where the stripper foil thickness, and hence energy spread, depends on ion species. Beams post-stripped after the 4-Tm machine will also have their longitudinal phase space diluted by the stripper. Moreover, for the case of very heavy beams being fully stripped after the 15-Tm ring, the possibility of severe dilution arises because of the thick (100-mg/cm² Cu) strippers that must be used.

Because the proposed system involves bunch-to-bucket beam transfers, knowledge of the bunch shape is essential in order to set up the holding buckets in the next ring properly. A few of the relevant equations for sizing an rf system to handle multiple charge-to-mass ratios are:

$$\Delta E/\text{turn} = (Q/A) V_{\text{cav}} \sin \phi_s = \rho C \dot{\beta} , \quad (\text{IV.G.1})$$

where

$\Delta E/\text{turn}$ is the energy gain per nucleon per turn,

Q and A are the ion charge state and mass number,

V_{cav} is the total rf cavity voltage (volts),

ϕ_s is the rf phase angle with respect to the beam,

ρ is the dipole bend radius (meters),

C is the ring circumference (meters), and

$\dot{B}$ is the rate of rise of the dipole field (tesla/second).

$$A_{1b}(\Gamma) = \frac{16N}{h\omega_0} \alpha(\Gamma) \sqrt{\frac{e V_{cav} E_s Q}{2\pi h |\eta| A}} \quad , \quad (IV.G.2)$$

where

A_{1b} is the the area of one bunch (eV·sec/A),

h is the harmonic number,

$\omega_0 = c/R$ is the radian frequency for a particle with $\beta = v/c = 1$,

c = speed of light,

$R = C/2\pi$ = mean radius of ring,

$\alpha(\Gamma)$ is the usual Symon-Sessler moving bucket factor (Bo70),

E_s is the current synchronous total energy per nucleon,

$\eta = \gamma_T^{-2} - \gamma^{-2}$ is the frequency slip factor,

γ_T is the lattice transition γ ,

γ is the usual Lorentz factor,

$N < 1$ is the fraction of the rf bucket occupied by the bunch, and

$\Gamma = \sin\phi_s$.

$$\frac{\Delta P}{P} = \frac{1}{\beta} \gamma(\Gamma) \sqrt{\frac{e V_{cav} Q}{\pi h |\eta| E_s A}} \quad , \quad (IV.G.3)$$

where

$\frac{\Delta P}{P}$ is the fractional momentum spread of the beam, and

$$Y(r) = \sqrt{2} [\cos\phi_s + (\sin\phi_s)(\phi_s - \pi/2)]^{1/2} .$$

The rf system will operate on harmonic one in the 4-Tm booster, on harmonic eight in the 15-Tm main ring, and on harmonic four in the 10-Tm storage ring when needed. This requires a tuning range of 9.32 to 1 in the booster and 10.089 in the two larger rings. Deceleration below 4 MeV/nucleon in the large rings would require more tuning range which would have to be met by installing additional cavities.

The $1/\beta$ dependence in Eq. IV.G.3 can cause a large aperture requirement via the dispersion during deceleration. For example, at kinetic energies of 1 MeV/nucleon, $\beta = 0.0463 = 1/21.6$. It is thus planned to cool an ion beam (using the electron cooling gun) before decelerating it, in order to reduce its longitudinal phase-space area and thus the needed V_{cav} and magnet aperture. Such deceleration is needed for slowing fully ionized ^{238}U to energies of interest for atomic physics experiments.

A number of beam bunching (capture) and acceleration simulations have been carried out to investigate the behavior of the longitudinal phase space for beams of the type that we expect to inject into the

4-Tm booster. Since this is a rapid-cycling machine, the most important problem is to capture as much beam as possible without introducing excessive energy spread. Following capture, the objective is to choose a cavity-voltage (or stable-phase-angle) program such that the rf-bucket contains the beam and that the required accelerating voltage is provided throughout the accelerating part of the magnet cycle. The conditions used in two such simulations, which are presented in this document, are listed in Table IV.G.1.

Figures IV.G.1 and IV.G.2 show the cavity voltage (VC), stable phase angle (ϕ_s), synchrotron frequency (ν_s) and the energy gain per nucleon per turn (DE/T) throughout the accelerating part of the magnet cycle for $^{12}\text{C}^{6+}$ and $^{197}\text{Au}^{40+}$, respectively. Figures IV.G.3 through IV.G.6 present several longitudinal phase diagrams which illustrate the capture and acceleration of these two beams. Beam particles which lie outside the separatrix (denoted by the solid curve) are lost. In general, more beam is captured into the rf bucket by using larger cavity voltages and smaller stable phase angles, but this introduces more energy spread into the beam so that one must compromise. The greater capture efficiency (90%) for the ^{12}C beam versus that (~5%) for the ^{197}Au beam is due mainly to the fact that at injection the velocity of the ^{12}C beam is 2.5 times that for ^{197}Au ; therefore, the capture can be more adiabatic.

Table IV.G.1. 4-Tm Accelerator Parameters Used for Simulations

Ion Species	^{12}C	^{197}Au
No. of Particles Tracked	801	801
Ring Circumference (m)	38.45	38.45
Transition Gamma	1.72	1.72
Harmonic Number	1	1
Max. Beam Energy Spread $\Delta E/E$ accepted	$\pm 2\%$	$\pm 2\%$
Ion charge	6+	40+
Initial Beam Energy Spread ($\sigma(\Delta E/E)$)	0.10%	0.15%
Injection Energy (MeV/nucleon)	12.0	1.9
Extraction Energy (MeV/nucleon)	176.3	31.3
Cavity Frequency (MHz)	1.24 to 4.24	0.50 to 1.97
Magnet Cycle (30 Hz sinusoidal)	0.27 to 1.1	0.27 to 1.1 Tesla
Energy-Gain/Turn (eV/nucleon) (max.)	5450	2210
Fraction of Beam Captured	90%	75%

Fig. IV.G.1. Cavity voltage (VC), stable phase angle (ϕ_s), synchrotron frequency (ν_s) and energy gain per nucleon per turn (DE/T) vs time after injection for capture and acceleration simulation for $^{12}\text{C}^{6+}$. (See text for simulation conditions.)

Fig. IV.G.2. Cavity voltage (VC), stable phase angle (ϕs), synchrotron frequency (νs) and energy gain per nucleon per turn (DE/T) vs time after injection for capture and acceleration simulation for $^{197}\text{Au}^{40+}$. (See text for simulation conditions.)

ORNL-DWG 86-7540

Fig. IV.G.3. Capture and acceleration simulation for $^{12}\text{C}^{6+}$ with energy spread at injection $\sigma(\Delta E/E) = 0.10\%$. (See text for symbol definitions.) (Continued in Fig. IV.G.4.)

ORNL-DWG 86-7541

Fig. IV.G.4. Capture and acceleration simulation for $^{12}\text{C}^{6+}$ with energy spread at injection $\sigma(\Delta E/E) = 0.10\%$. (See text for symbol definitions.) (Continuation of process from Fig. IV.G.3.)

ORNL-DRL 86-7342

Fig. IV.G.5. Capture and acceleration simulation for $^{197}\text{Au}^{40+}$ with energy spread at injection $\sigma(\Delta E/E) = 0.15\%$. (See text for symbol definitions.) (Continued in Fig. IV.G.6.)

ORNL-DWG 86-7543

Fig. IV.G.6. Capture and acceleration simulation for $^{197}\text{Au}^{40+}$ with energy spread at injection $\sigma(\Delta E/E) = 0.15\%$. (See text for symbol definitions.) (Continuation of process from Fig. IV.G.5.)

The cavity voltage programs shown in Figs. IV.G.1 and IV.G.2 are probably not optimum. We will continue to study the problem with special emphasis given to improving the capture efficiency as we evolve the design of the machines.

The symbol definitions used in Fig. IV.G.3 through Fig. IV.G.6 are:

NT = number of turns (trips around the ring)

VC = rf-cavity amplitude in volts

T = time from injection in milliseconds

ϕ_s = stable phase angle in degrees

E0 = MeV/nucleon for phase-stable particle (kinetic)

F = cavity frequency in megahertz.

The voltage requirements for the rf system in the 15-Tm main ring are dictated by the need to provide a matched, or nearly matched, bucket for transfer of single bunches from the 4-Tm booster. Provision of a fully matched bucket was found to require cavity voltages in excess of 150 kV for the lightest ions. Allowing a small amount of longitudinal phase space dilution would reduce this to 100 kV or less while keeping the phase spread of a bunch less than 240° . Even in the most demanding case, that for $Z/A = 1/2$ ions, this still allows 80 nsec for the injection kicker to fire. Since a 1-m long injection kicker needs to develop 120 G or less, this is an adequate rise/fall time. Table IV.G.2 lists various rf quantities for the case in which beams are stripped after the tandem but

Table IV.G.2. Injection with Stripping after the Tandem

Ion species	^{12}C	^{32}S	^{40}Ca	^{58}Ni	^{79}Br	^{127}I	^{197}Au	^{238}U
Charge state	6^+	15^+	18^+	24^+	27^+	36^+	40^+	43^+
Acceleration in 15-Tm Ring								
Injection energy (kinetic) (MeV/nucleon)	176.	156.	145.	124.	86.2	60.1	31.3	24.9
Final energy (kinetic) (MeV/nucleon)	1500.	1370.	1300.	1150.	866.	647.	373.	305.
Harmonic number	8	8	8	8	8	8	8	8
Injection f_{rf} (MHz)	4.22	4.03	3.91	3.67	3.14	2.67	1.97	1.77
Final f_{rf} (MHz)	7.20	7.13	7.08	6.97	6.67	6.30	5.46	5.13
Ratio $(f_{rf})_{\text{final}}/(f_{rf})_{\text{injection}}$	1.71	1.77	1.81	1.90	2.12	2.36	2.77	2.90
$(\Delta P/P)_{\text{injected}}$ ($\times 10^{-3}$)	3.24	3.22	3.20	3.17	3.12	3.08	3.03	3.02
Bunch area injected (eV·s/A) ($\times 10^{-1}$)	1.61	1.49	1.43	1.30	1.06	8.65	6.11	5.42
Bunch area accelerated (eV·s/A) ($\times 10^{-1}$)	2.51	2.33	2.23	2.03	1.65	1.35	0.952	0.845
n (injection)	-0.685	-0.711	-0.727	-0.757	-0.816	-0.860	-0.914	-0.927
V_{cavity} (coasting) (kV)	76.4	74.5	73.1	70.2	62.6	54.8	41.7	37.6
V_{cavity} (start of ramp) (kV)	105.	103.	101.	97.2	89.2	81.1	66.7	62.3
ϕ_s (start of ramp) (degrees)	4.04	4.14	4.20	4.36	4.75	5.22	6.35	6.81

Table IV.G.2. Injection with Stripping after the Tandem (Continued)

Ion species	^{12}C	^{32}S	^{40}Ca	^{58}Ni	^{79}Br	^{127}I	^{197}Au	^{238}U
Charge state	6^+	15^+	18^+	24^+	27^+	36^+	40^+	43^+
Deceleration								
v_s (start of ramp) ($\times 10^{-2}$)	1.68	1.78	1.85	2.00	2.37	2.76	3.54	3.85
$r_x \cdot \Delta P/P$ (start of ramp) (cm)	0.60	0.59	0.59	0.59	0.58	0.58	0.59	0.59
V_{cavity} (end of ramp) (kV)	23.3	24.3	25.0	26.4	29.7	32.9	37.2	39.2
θ_s (end of ramp) (degrees)	18.5	17.7	17.2	16.2	14.4	13.0	11.4	11.2
v_s (end of ramp) ($\times 10^{-3}$)	1.3	1.47	1.59	1.86	2.62	3.59	5.95	6.98
$r_x(\Delta P/P)$ (end of ramp) (cm)	0.21	0.20	0.20	0.19	0.18	0.18	0.17	0.17
V_{cavity} (10 Tm matched bucket) (kV)	9.26	9.81	10.2	10.9	12.6	14.2	16.3	16.8

before acceleration in the 4-Tm booster. Table IV.G.3 lists corresponding values for the case in which ions are not stripped after the tandem, but rather are stripped after the 4-Tm booster. Tandem operation at 22 MV was assumed.

The acceleration requirement in the 15-Tm ring is $V \sin \phi_s = 7.3819$ kV for a magnetic-field ramp rate of 2.4 T/sec. Given the larger bucket requirements at injection, the initial stable phase values are rather small. During acceleration it would be advantageous to decrease the cavity voltage while increasing ϕ_s to reduce power dissipation in the cavity ferrite at the higher frequencies where the biasing current is largest. Values are given for V_{cavity} at the beginning and end of a ramp from 4 Tm to 15 Tm for a fixed bunch area to bucket area ratio.

The tables also list values of the required rf voltage in the 10-Tm ring for a transfer to matched buckets if the beam were accelerated to 15 Tm in the main ring. Obviously, for the light ions the acceleration in the main ring would have to stop at 10 Tm for this to be possible, whereas, for the heavy ions, a stripping between the two rings would allow transferring a full rigidity beam from the 15-Tm ring. Since the 10-Tm ring runs at $h = 4$, it will need only about half the voltage for a coasting beam as would the 15-Tm ring, which runs at $h = 8$.

Table IV.G.3. Injection with Stripping after the 4-Tm Booster

Ion species	^{12}C	^{32}S	^{40}Ca	^{58}Ni	^{79}Br	^{127}I	^{197}Au	^{238}U
Charge state (after strip)	6^+	16^+	20^+	28^+	34^+	42^+	50^+	54^+
Injection energy (kinetic) (MeV/nucleon)	126.	72.6	56.6	38.0	20.7	10.7	5.08	3.93
Final energy (kinetic) (MeV/nucleon)	1500.	1500.	1500.	1430.	1220.	623.	542.	450.
Harmonic number	8	8	8	8	8	8	8	8
Injection f_{rf} (MHz)	3.69	2.91	2.60	2.16	1.62	1.17	0.81	0.71
Final f_{rf} (MHz)	7.20	7.20	7.20	7.17	7.03	6.61	6.04	5.76
Ratio $(f_{rf})_{\text{final}} / (f_{rf})_{\text{injection}}$	1.95	2.48	2.77	3.31	4.35	5.65	7.45	8.06
$(\Delta P/P)_{\text{injected}} (\times 10^{-3})$	3.17	3.10	3.07	3.04	3.02	3.00	2.99	2.99
Bunch area injected ($\text{eV}\cdot\text{s}/\text{A}$) ($\times 10^{-2}$)	13.1	9.60	8.38	6.77	4.92	3.52	2.41	2.12
Bunch area accelerated ($\text{eV}\cdot\text{s}/\text{A}$) ($\times 10^{-1}$)	2.04	1.50	1.31	1.05	0.768	0.548	0.376	0.330
n (injection)	-0.754	-0.839	-0.867	-0.901	-0.935	-0.955	-0.967	-0.969
V_{cavity} (coasting) (kV)	58.7	36.8	29.4	21.1	13.2	9.1	5.7	4.9
V_{cavity} (start of ramp) (kV)	85.6	61.4	53.1	43.0	33.1	27.4	22.3	21.0
ϕ_s (start of ramp) (degrees)	4.9	6.9	8.0	9.9	12.9	15.6	19.4	20.5

Table IV.G.3. Injection with Stripping after the 4-Tm Booster (Continued)

Ion species	^{12}C	^{32}S	^{40}Ca	^{58}Ni	^{79}Br	^{127}I	^{197}Au	^{238}U
Charge state (after strip)	6^+	16^+	20^+	28^+	34^+	42^+	50^+	54^+
v_s (start of ramp) ($\times 10^{-2}$)	1.86	2.16	2.30	2.55	3.07	3.88	5.05	5.57
$n_x \cdot \Delta P/P$ (start of ramp) (cm)	0.60	0.60	0.61	0.63	0.65	0.68	0.73	0.74
V_{cavity} (end of ramp) (kV)	19.9	16.1	14.9	13.9	13.2	14.0	14.2	14.4
θ_s (end of ramp) (degrees)	21.8	27.2	29.6	32.2	34.0	31.9	31.4	30.9
v_s (end of ramp) ($\times 10^{-3}$)	1.19	1.05	0.995	1.00	1.15	1.76	2.51	3.00
$n_x \cdot \Delta P/P$ (end of ramp) (cm)	0.18	0.14	0.13	0.12	0.10	0.09	0.08	0.07
V_{cavity} (10 Tm matched bucket) (kV)	7.62	5.82	5.22	4.69	4.40	4.87	5.02	5.14

It can also be seen that there are advantages, from the standpoint of required rf voltage, to defer stripping till after the 4-Tm ring. Both the voltage to hold a coasting beam and the voltage to accelerate it are markedly lower in this case. In fact, it is possible to provide matched buckets with less than 100 kV for all but the lightest ions. This will be the preferred procedure during operation, as it maintains the smallest phase extent of the bunches. Upon transfer to the 10-Tm ring, advantage can be taken of this during adiabatic debunching in order to decrease the $\Delta P/P$ spread of the beam as much as possible before needing to resort to the cooling systems. This phase compression also eases ejection kicker requirements. However, even in the worst case of 15-Tm $Z/A = 1/2$ ions, the phase spread of the bunches corresponds to about 73 nsec of free space. This is adequate for the ejection kickers (a total length of 2-m, developing about 210 G) to operate with conservative values of B .

The cavities in the large rings must cover a frequency range from 714.0 kHz to 7.203 MHz, a range of 10.0%. Since a ferrite such as MnNi is needed to cover the upper end of this range, and since such ferrites do not easily exhibit permeability ranges of 100:1, it appears advantageous to have two sets of cavities, each covering a range of 3.2:1 (or slightly more) in frequency. The cavities in the booster must be able to operate between 465.4 kHz and 4.22 MHz and develop 22 kV (see Fig. IV.G.3). A single cavity could cover this range but at the cost of considerable power dissipation in the ferrite

at high frequencies. This tuning range of 9.07:1 could also be split between two cavities having a tuning range of 3.01:1. Should this prove the best solution, the booster lattice would have to be changed to 7-fold or 8-fold to accommodate the second cavity. This poses no particular problems or circumference penalties.

Double-gap cavities have been selected. They will be loaded with MnNi or similar ferrite, chosen due to its reasonably large permeability range and good μQ_f values in the required frequency range. By using water cooling for the ferrite, it is planned to develop up to 18 kV on each of the two gaps in one cavity for the main ring. This requirement is relaxed to 12 kV for the booster and 14 kV for the stretcher/cooler ring. Thus, for the booster, one cavity is required (two if it proves advantageous) to split the tuning range. In the main ring, three cavities are required (six if the tuning range is divided). In the cooler two cavities are required (four if the tuning range is divided). The large tuning range in the cooler is needed in order to be able to synchronously capture a beam ejected at any rigidity from the 15-Tm ring. Adequate straight sections exist for these cavities in either scenario, with the exception of the booster as discussed above. Power dissipation in the ferrite will not pose a problem since water cooling will be used.

All components of the rf system involve well-developed technology. As with any resonant structure, care must be taken with the

cavities to suppress unwanted modes of oscillation. The impedance match between driver and cavities may not be optimal. Care will be taken to minimize this mismatch.

The rf systems must track the dipole magnetic field, with the voltage, frequency, and phase all following predetermined programs as a function of the dipole field. The systems will also follow the short-term behavior of the beam and provide appropriate feedback to keep the beam centered in the vacuum chamber as the magnetic field rises.

Commissioning of the rf system will include study of the rf capture efficiency as a function of ion species, injection energy, and voltage program chosen. The longitudinal emittance of the beam before and after cooling and before and after acceleration or deceleration will be studied to learn the optimal rf parameters for the various cycles desired by the experimentalists. The rf structure of stored or extracted beams will be measured and the debunching program varied in order to obtain nearly dc beam where that is desired.

Attention will be given to careful preprogramming of the rf parameters so that the cavity can be run in "open loop" mode for very weak beams. This will entail careful attention to error signals generated during acceleration of strong beams and inclusion of the information from these error signals in the generation of the primary rf programs.

IV.H. VACUUM SYSTEM

The ions to be accelerated, decelerated, and stored in the various rings will typically have from one-sixth up to all of their electrons removed. They will have kinetic energies anywhere from 1 MeV/nucleon up to 900 MeV/nucleon for very heavy ions and up to 1500 MeV/nucleon for light ions. Such ions, upon passing through the residual gas in the vacuum chambers, can either capture electrons from the gas molecules or lose electrons by colliding with the gas molecules. These charge-changing collisions change the magnetic rigidity of an ion, causing it to strike the chamber wall. The ions may also undergo multiple small-angle Coulomb collisions with the gas molecules, causing an increase in beam emittance and eventual loss of beam nuclei.

To ameliorate these beam-loss processes, ultrahigh vacuum systems will be installed in all three rings to maintain pressures of 10^{-10} to 10^{-11} torr. These ultrahigh vacuum systems must interface to both injection lines and extraction lines. In order to minimize costs, most of the booster injection beam line will be built, following present practice at the HHIRF, to attain a pressure of 10^{-8} torr. A transition region, consisting of the beam path covered by the last two quadrupole doublets, will separate the injection line vacuum of 10^{-8} torr from the booster vacuum of 10^{-10} torr. Likewise, the ejection lines will have similar transition regions before connection to the main experimental beam lines maintained at 10^{-8} torr.

The greatest beam loss arises from charge-changing collisions of partially-stripped heavy ions with residual gas. The differential loss rate for a beam of N ions can be written as

$$dN = -nPN\sigma dx, \quad (\text{IV.H.1})$$

where

$$n = 3.27 \times 10^{16} \text{ molecules/cm}^3/\text{torr},$$

$$P = \text{residual gas pressure},$$

$$\sigma = \text{total cross section causing loss of particles, and}$$

$$dx = \beta c dt.$$

It is understood that the gas densities are to be evaluated at $T = 20^\circ\text{C}$. Here σ is taken to be the sum of the electron-capture, electron-loss, and nuclear reaction cross sections for beam ions colliding with residual gas. These three cross sections are several orders of magnitude larger than those from other effects at energies below 50 MeV/nucleon. It is the need to operate the rings for ions with such energies that leads to the most stringent requirements on the vacuum. Thus, other cross sections will not be dealt with here.

For a coasting beam as in the 10-Tm storage ring, P , σ , and β are time independent and the solution of Eq. IV.H.1 is simply

$$N = N_0 e^{-nP\beta c \sigma \Delta t}, \quad (\text{IV.H.2})$$

where N_0 is the original number of ions and Δt is the beam coasting time. For the acceleration case, Eq. IV.H.1 has the formal solution

$$N = N_0 e^{-\int n\beta c P \sigma dt}, \quad (\text{IV.H.3})$$

where there are explicit dependences of β on t and σ on β .

For a ring with a constant magnetic-field ramp rate (as in the 15-Tm ring), this equation can be conveniently written as

$$N = N_0 e^{-\chi} , \quad (\text{IV.H.4})$$

where

$$\chi = n c P_{\text{at}} \frac{\int \beta \sigma_T^3 d\beta}{(\beta_T)_{\text{final}} - (\beta_T)_{\text{initial}}} . \quad (\text{IV.H.5})$$

This form is convenient if σ can be expanded in a power series in $(1/\beta)$. The integral can also be calculated numerically. For the case of a sinusoidally varying magnetic field as in the 4-Tm booster, the solution is most conveniently written as

$$N = N_0 e^{-n P c \xi} , \quad (\text{IV.H.6})$$

where $\xi = \int \beta \sigma dt$ must be evaluated numerically from a knowledge of the time variation of the magnetic field, and thus the time variation of β and σ .

The total cross section was evaluated numerically using the partial cross sections described below. The capture cross sections are taken from Schlachter (Sc84) who defines

$$\tilde{E} = E/Z_T^{1.25}/Q^{0.7} , \text{ and}$$

$$\tilde{\sigma} = (\sigma_C/Q^{0.5}) Z_T^{1.8} ,$$

where $\tilde{E}$ is the ion kinetic energy in keV/nucleon, Z_T is the nuclear charge of the gas atom, Q is the ion charge state, and σ_C is the capture cross section in cm^2 . With these variables the following scaling law is valid:

$$\tilde{\sigma} = (1.1 \times 10^{-8}/\tilde{E}^{4.8})(1 - e^{-0.037 \tilde{E}^{2.2}})(1 - e^{-2.44 \times 10^{-5} \tilde{E}^{2.6}}) \quad (\text{IV.H.7})$$

for $1 < \tilde{E} < 1000$, which covers the present kinetic energies of interest for very heavy ions. The cross sections are largest for the highest charge states.

The electron loss cross sections are calculated following Alonso and Gould (A182), who give the following equation based on Bohr's formula:

$$\sigma_L = 2\pi a_0^2 \alpha^2 Z_S^2 (\alpha/\beta)^2 \sum_{p=Q}^{Z_I} \left(\frac{1}{I_p} - \frac{1}{2\beta^2} \right), \quad (\text{IV.H.8})$$

where

$a_0 = 0.5292 \times 10^{-8}$ cm is the Bohr radius,

$\alpha = 1/137$ is the fine structure constant,

$Z_S = (Z_I^{1/3} + Z_T^{1/3})$; Z_I = ion's nuclear charge, Z_T = target gas molecule's nuclear charge, and

I_p = the ionization potential (in units of the electron mass) for the ion in charge state p .

The sum runs over all ionization states for which $I_p < 2\beta^2$. The needed ionization potentials were taken from the calculations of Carlson, Nestor, Wasserman, and McDowell (Ca70).

The total nuclear cross sections were estimated from the simple geometrical equation

$$\sigma_N = \pi R^2, \quad (\text{IV.H.9})$$

where

$R = 1.25(A_I^{1/3} + A_T^{1/3}) \times 10^{-13}$ cm,

A_I = mass number of ion, and

A_T = mass number of target gas molecule.

Below the Coulomb barrier, this cross section was set to zero. At the highest energies, especially for fully stripped ions, this cross section can dominate.

The residual gas in the vacuum system was taken to be 90% H₂ and 10% N₂. The N₂ component is assumed to be representative of all the heavy gases found in such a system. The total cross section is obtained from the equation

$$\sigma = 0.9 \times 2x\sigma(H) + 0.1 \times 2x\sigma(N) , \quad (IV.H.10)$$

where

$\sigma(H)$ is the total cross section on hydrogen atoms, and

$\sigma(N)$ is the total cross section on nitrogen atoms.

Since the cross sections are largest for very heavy ions at low energies, values are shown in Fig. IV.H.1 for uranium ions. The figure gives capture and loss cross sections on atomic hydrogen for $^{238}\text{U}^{43+}$ ions injected from the tandem with post stripping and for $^{238}\text{U}^{17+}$ ions injected from the tandem without post stripping. Also shown are values for U^{61+} , obtained by post stripping U^{17+} accelerated in the booster and for U^{61+} , obtained by post stripping U^{43+} accelerated in the booster.

Shown in Figs. IV.H.2 - Fig. IV.H.10 are ratios N/N_0 , called the "surviving fraction," as a function of pressure (in torr) of the residual gas. As there are a large number of ways in which the accelerator can be operated, examples are given in the figures for those modes for the various rings which lead to the most severe restrictions on the vacuum pressure. Each figure has a panel showing the surviving fraction

Fig. IV.H.1a. Single-electron capture and loss cross sections for ^{238}U in charge states of 17^+ and 43^+ colliding with atomic hydrogen, calculated as described in the text.

Fig. IV.H.1b. Single-electron capture and loss cross sections for ^{238}U in charge states of 51^+ and 81^+ colliding with atomic hydrogen, calculated as described in the text.

STRIPPED AT TANDEM EXIT, ENERGY DOUBLED IN 4 Tm BOOSTER

Fig. IV.H.2. The surviving fraction N/N_0 (see Eq. IV.H.2 to IV.H.6) for ions post-stripped after the tandem, injected into the 4-Tm booster; and doubled in energy. N/N_0 is calculated for the loss during the booster cycle.

STRIPPED AT TANDEM EXIT, ACCELERATED TO 4 Tm

Fig. IV.H.3. As Fig. IV.H.2, but for ion accelerated to full rigidity in the booster.

UNSTRIPPED AT TANDEM EXIT, ENERGY DOUBLED IN 4Tm BOOSTER

Fig. IV.H.4. As Fig. IV.H.2, but for ions not post-stripped after the tandem.

UNSTRIPPED AT TANDEM EXT. ACCELERATE TO 4 Tm

Fig. IV.H.5. As Fig. IV.H.3, but for ions not post-stripped after the tandem.

STRIPPED AT T⁺ DEM EXIT, ACCELERATED TO 4 Tm, ACCELERATED TO 15 Tm

Fig. IV.H.6. For ions post-stripped at the tandem exit, accelerated at 4-Tm, injected into the 15-Tm ring and accelerated to full rigidity there. N/N_0 is for the acceleration cycle in the 15-Tm ring.

STRIPPED AT TANDEM EXIT, ACCELERATED TO 4 Tm, STORED FOR 1 SECOND

Fig. IV.H.7. N/N_0 for ions coasting for one second. The ions are assumed to be post-stripped after the tandem and boosted to 4 Tm, then stored.

**STRIPPED AT TANDEM EXIT, ACCELERATED TO 4 Tm.
STRIPPED, STORED FOR 1 SECOND**

Fig. IV.H.8. As Fig. IV.H.7, except including a stripping after acceleration to 4 Tm.

UNSTRIPPED AFTER TANDEM, ACCELERATED TO 4 Tm, STORED FOR 1 SECOND

Fig. IV.H.9. As Fig. IV.H.7, except for beams not post-stripped after the tandem.

**UNSTRIPPED AFTER TANDEM, ACCELERATED TO 4 Tm,
STRIPPED, STORED FOR 1 SECOND**

Fig. IV.H.10. As Fig. IV.H.9, except including a post-stripping after acceleration to 4 Tm.

versus pressure for ^{12}C , ^{32}S , ^{58}Ni , ^{79}Br , ^{127}I and ^{238}U . In Fig. IV.H.2 are shown curves for the 4-Tm fast-cycling booster for the case where ions are post-stripped after the tandem and then only doubled in kinetic energy. Fig. IV.H.3 gives the results for the same stripping but for acceleration to full energy in the 4-Tm booster. More than 95% of the beam survives if the pressure is 10^{-9} torr. In Fig. IV.H.4 is shown the results for the more demanding case (refer to Fig. IV.H.1) where the beam is not stripped after the tandem and its kinetic energy is doubled in the 4 Tm booster. Fig. IV.H.5 gives results again for no stripping after the tandem but for acceleration to full rigidity in the 4-Tm ring. In both of these cases a pressure of 5×10^{-10} torr is needed for 95% of the beam to survive. Thus, the design pressure for the 4-Tm ring has been put at 10^{-10} torr, to have a margin of safety.

The vacuum requirements for acceleration in the 15-Tm ring, at a ramp rate of 2.4 T/sec in the magnets, can be determined from the results shown in Fig. IV.H.6. Shown there are surviving fractions versus pressure for beams which have been post-stripped after the tandem, accelerated to 4-Tm in the booster, transferred to the 15-Tm ring, and then accelerated to 15Tm. A pressure of 4×10^{-10} torr is needed to assure 95% survival of $^{238}\text{U}^{43+}$. If the beams were stripped after the 4-Tm machine also, the pressure requirement would be relaxed but there would be less beam current because of the stripping losses.

As an example of the situation when either the 15-Tm accelerator or the 10-Tm storage ring hold a coasting beam, Fig. IV.H.7 shows the surviving fractions for beams stripped at the tandem exit, accelerated to 4 Tm in the fast cycling booster and then stored for one second in either the 15-Tm or 10-Tm rings. It can be seen in Fig. IV.H.7 that a pressure of 9×10^{-11} torr is needed for 95% survival of $^{238}\text{U}^{43+}$ at 24.9 MeV/nucleon. If the ions are also stripped after the 4-Tm booster, the vacuum requirements ease somewhat as can be seen in Fig. IV.H.8. In that case, a pressure of 1×10^{-9} torr yields 95% survival of $^{238}\text{U}^{81+}$, the equilibrium charge state at 24.9 MeV/nucleon.

The most severe requirements for storage in the 15-Tm or 10-Tm rings arise for the case where the beam is not post-stripped after the tandem before acceleration to 4 Tm and subsequent transferral to one of the larger rings. Fig. IV.H.9 shows results for ions not stripped after ejection from the 4-Tm ring and Fig. IV.H.10 gives results for beams that are stripped after ejection from the 4-Tm ring (with the associated beam current loss due to charge state fractionation). A pressure of 9×10^{-12} torr in the former case and 3×10^{-11} torr in the latter case are needed for 95% survival of U^{17+} and $^{238}\text{U}^{51+}$, respectively. If these beams were just to be extracted to a target, then the extraction could be made to take place over 1/30 of a second, to match the 4-Tm repetition rate. The vacuum requirements could then be relaxed by a factor of thirty, to 3×10^{-10} torr and 9×10^{-10} torr, respectively. If such beams had to be stored for the requirements of a particular experiment,

it would improve things (from the standpoint of vacuum needs) first to produce fully stripped nuclei at the necessary high energies and then to decelerate these nuclei to the energy required for experiments. Note that the vacuum requirements are troublesome only for the heaviest nuclei, i.e., $A \gtrsim 200$. A goal of future studies will be to identify experiments (such as atomic physics experiments) which must store partly ionized heavy nuclei for long periods. It may be necessary in the final design for the storage ring to reach a pressure lower than 10^{-11} torr. This will require an expensive upgrade of the vacuum bakeout and insulation hardware. It will also require an increase in magnet aperture and an increase in magnet power supply ratings and power consumption over the values presently foreseen.

It is planned to use the 15-Tm ring for acceleration, for slow spills of beams which can be accelerated to sufficiently high energies in the 4-Tm booster alone, and for storage of beams which are too rigid for the 10-Tm ring. For very heavy ions accelerated to 15 Tm, three cases exist: (1) If ^{238}U is accelerated to 15 Tm in charge state 43^+ , it can be transferred to the 10-Tm ring after passing through a stripper to increase its charge state to $q = 90, 91$ or 92^+ . (2) If ^{238}U is not poststripped after the tandem but is post stripped after the 4-Tm booster, it will be in charge state $q \approx 51^+$. (3) If it is accelerated to $E_p > 10$ Tm in the 15-Tm ring and must be stored, it can be fully stripped upon transfer to the 10-Tm ring. In the third case, if ^{238}U is post-stripped after the tandem and the 4-Tm booster, it will be in

charge state $q = 81^+$ in the 15-Tm ring. It can then be stored there for 60 seconds at a pressure of 10^{-10} torr with 95% survival of the ions, assuming it has been accelerated to $B_p > 11.4$ Tm, at which point it could no longer be transferred to and stored in the 10-Tm ring.

Thus, the design pressure for the 15-Tm ring is also taken as 10^{-10} torr. For the case of the 10-Tm storage ring, several proposed experiments require storing medium-and low-energy, partly stripped ions. The design pressure for that ring has thus been taken as 10^{-11} torr.

Pressures in the 10^{-10} to 10^{-11} torr range can be produced in synchrotron vacuum systems by pumping with liquid helium and liquid nitrogen cooled cryogenic pumps or with various combinations of titanium sublimation pumps, magnetic sputter ion pumps, and nonevaporable getter pumps. The extremely low outgassing rate requirements limit the major materials of construction to aluminum, stainless steel, and alumina ceramic. Beam line valves must be "all-metal," including the gate seal. In situ conditioning at 150°C for 24 to 36 hours requires that all vacuum components be suitable for such service. Glow discharge conditioning in low pressure argon (90%) and oxygen (10%) may be required, either in situ or before assembly to obtain satisfactory outgassing rates. The X-ray limit of the standard Bayard-Alpert ionization gauge is 1×10^{-11} torr. Thus, if an ability to measure any lower pressure is desired, a Bayard-Alpert gauge with modulator or an extractor type gauge must be used. A modulator-type gauge requires that the modulator electrodes be switched between the anode potential and the ion collector potential to overcome the X-ray limits.

The liquid-cooled cryogenic pumps provide a single type of pump for all gas species in the beam lines but require a complicated liquefaction plant and control system. Also, it is very expensive to do distributed cryogenic pumping where lumped pumping is not suitable. When titanium sublimation pumping or nonevaporable getter pumping is used, a magnetic sputter ion pump is required to pump the inert gasses and methane.

Complete synchrotron vacuum systems have been fabricated of aluminum. However, most such components are made by only a few manufacturers and none are made by U.S. manufacturers. Since stainless steel contains a small contamination of hydrogen, a high temperature (950°C) vacuum bake is required before fabrication. The resistivity of stainless steel is much larger than that of aluminum. This, coupled with the fact that stainless steel can be made with thinner walls, means the eddy currents induced in the chambers by the pulsed magnets will be smaller for stainless steel chambers than for aluminum chambers.

The magnet chambers for the 4-Tm, fast-cycling booster pose a special problem arising from the cycling rates in this machine. An all-metal, smooth-surface chamber cannot be used in this machine because of the magnitude of the eddy currents arising from the high magnetic field ramp rate ($\dot{B} \sim 78 \text{ T/sec}$ at the peak ramp rate). Solutions to this problem include use of ceramic vacuum chambers (Rutherford SNS), use of thin, ribbed aluminum chambers (DESY), use of corrugated "bellows-like" stainless steel chambers (KEK booster), and avoidance of any chamber at

all by encasing the entire magnet in a stainless steel box and potting the yoke and coils (FNAL booster). The solution proposed here is to use the new carbon fiber beam pipes developed for use at CERN in the heavy-ion and LEP programs. These can be made with 1 to 2 mm thick walls and can be evacuated to 10^{-11} torr. The resistivity for graphite is $1375 \mu\Omega\text{-cm}$, whereas that for aluminum is $2.65 \mu\Omega\text{-cm}$, and that for stainless steel is $73.8 \mu\Omega\text{-cm}$. The increase of a factor of ~ 20 of the value for graphite over the value for stainless steel causes a corresponding drop in the perturbing magnetic fields due to eddy currents, causing them to decrease to an acceptable value. In order to provide a conductive surface to be seen by the beam, a thin coating of aluminum will be evaporated onto the inside of the graphite beam pipe.

A listing of principal components to be used in the ring vacuum system is given in Table IV.H.1. The entire system uses ultrahigh vacuum (UHV) technology only, due to the desired base pressure of 10^{-10} to 10^{-11} torr. Surface treatment must be attended to in great detail. Provisions are made for vacuum baking all steel components at 950°C before assembly and for in situ argon glow-discharge cleaning of the entire system.

Each magnet in the two large rings will have a stainless steel vacuum chamber designed to match its specific gap geometry. The steel will be approximately 0.05-in. thick and will be baked in a vacuum furnace at 950°C to drive out hydrogen trapped during manufacture. Chambers will be wrapped with heater tape and wrapped in several layers of aluminized Kapton film. The film is needed to minimize convective and radiative heat loss during baking. A thermocouple will be inserted

Table IV.H.1. Vacuum System Components

Design pressure:	10 ⁻¹⁰ torr in 4 Tm booster and 15 Tm main ring 10 ⁻¹¹ torr in the 10 Tm storage ring All pressures are nitrogen equivalent.		
Design specific outgassing:	10 ⁻¹³ torr L/s cm ²		
Baking temperature:	150°C		
Major material of construction:	304/316 SS vacuum prebaked at 950°C for the 15-Tm and 10-Tm rings Carbon fiber with aluminized inner wall for 4-Tm booster.		
	<u>4-Tm Ring</u>	<u>15-Tm Ring</u>	<u>10-Tm Ring</u>
Magnetic sputter ion pumps 60 L/s	6	24	24
Titanium sublimation pumps	6	24	24
Distributed nonevaporable getter strip in all sections where possible			
2 turbo/cryogenic rough pump carts for entire facility			
All metal beamline valves, 6-in.-ID	6	24	12
All metal right angle valves, 4-in.-ID	6	24	12
Ionization gauges	6	24	12
Residual gas analyzer gauges	1	8	8

to monitor chamber temperature during bakeout. All steel chambers will be electropolished before installation. They will be stored in a clean room, sealed by noncontaminating materials, and kept under high vacuum before installation. All insulators will be of alumina ceramic. High-voltage and signal penetrations through the chamber will be kept to a minimum. All components will be designed and tested to withstand a 150°C bakeout of 24- to 36-hours duration.

Field welds will be used where possible. All flanges will be of the Conflat type with a metal seal. Six-inch gate valves are provided to isolate the various ring sectors from one another. A 4-in. roughing valve is provided in each of the sectors. All valves must have a metal seal and be of all-metal composition.

Each section will be leak checked in a clean room. Assembly into one sector of each machine will be done, and a second leak check will be performed. Contamination with hydrocarbon or helium must be scrupulously avoided. After pump-down to ultrahigh vacuum range, a final check with argon will be done by controlled spraying about the chamber and observation of the chamber pressure.

Special liners will be constructed for use with the injection septa and ejection septa. The ultrahigh vacuum system must extend along the injection and ejection lines to points at which the beam has a double waist. At those points a vacuum baffle will be installed in order to separate the ring vacuum from beam line vacuum, which is normally maintained at 10^{-8} torr.

The vacuum chambers for the rf systems and electron beam cooling system are an integral part of these devices. These will be handled in the clean room also and must also withstand an extended 150°C bakeout.

Due to the different thermal conductivities expected for the various chamber configurations, a microprocessor-based controller will be needed to monitor bakeout temperatures around the rings and to adjust heater currents of different elements so as to maintain an even temperature distribution. This is required to ensure that gas desorbed from one section of pipe does not readsorb on another section at a lower temperature, but rather enters a pump.

Each sector of the rings will be equipped with a magnetic 60-L/sec sputter ion pump, a titanium sublimator pump, and a distributed system of nonevaporable getter strips, the latter to provide distributed pumping in the low conductance areas such as the dipole chambers. Twice as many pumps per sector will be used in the 10-Tm storage ring due to the lower required pressure. The pumps are located in special chambers attached to the ring chambers. In the arcs these are located near the dipole ends. They are distributed relative to the valves so that any arc or any straight section can be evacuated to ultrahigh vacuum without disturbing the vacuum in adjacent sections. Each ion pump and sublimation pump will have its own power supply. The chambers for the pumps are themselves equipped with heater tapes and thermocouples and will be baked out with the rest of the ring. One ion gauge of Bayard-Alpert type will be included for each pumping station.

To analyze the contents of the chamber, residual gas analyzers will be used. Their gauge tubes will be made a permanent part of the ring vacuum system. One tube will be located approximately every 40 meters along the ring circumference.

The roughing system will consist of an oil-free turbomolecular pump and a 6-in. cryogenic pump. The turbopump will be of the magnetically levitated type, with dry lubricant only, and will be equipped with a large foreline trap. The use of sorption pumps instead of rotary pumps for rough-down from atmosphere is being studied as a means to eliminate all hydrocarbons from anywhere in the vacuum system. The roughing system also can be baked out and will use only all-metal hoses.

The surface outgassing rate for the vacuum system materials will determine the system pressure, since outgassing is the major source of gas to be pumped and the pumping speed of the pipes and pumps is more or less constant and independent of pressure. The outgassing rate for stainless steel appears to depend on many factors, including processing history and surface condition. Therefore, the exact outgassing rate to be obtained may be somewhat uncertain. Development testing will be required to confirm the processes.

The requirements for cleanliness dictate that special procedures must be followed to prevent contamination, which can easily keep the vacuum system from pumping down to the 10^{-10} to 10^{-11} torr level. All vacuum system components must be stored in almost "clean room" conditions with all openings covered or closed with noncontaminating

material. Assembly personnel must be specially trained in ultrahigh vacuum techniques and must be supervised much more closely than is standard practice.

Leak checking with an ultrasensitive helium mass spectrometer detector must be done on each section of the vacuum system as it is assembled. Carefully prepared leak checking procedures will be required and must be followed to prevent contamination with hydrocarbons or with helium, which can complicate further leak checking. The final leak checking can be done by spraying Ar around suspected leak areas and watching for pressure changes on the ionization gauges.

An initial pump-down cycle should consist of rough pumping each section of the ring with the turbopump of the roughing cart to about 10^{-5} torr, then switching to the cryopump and starting the bakeout procedure. The temperature should be raised uniformly on all components of the section to 150°C and held there for approximately 24 hours. During the last 25% of the baking cycle, the sputter ion pumps are cycled on for 1 min/h for conditioning, and the titanium sublimators are outgassed and kept warm until the end of the cycle. The cryogenic roughing pump is then valved off, the sublimators flashed at high current, the sputter ion pumps turned on, and baking is stopped.

Any time a section of the ring must be returned to atmospheric pressure for maintenance or change of experimental apparatus, that section shall be isolated by closing the all-metal beam-line gate valves on

each side of the section, with the remainder of the ring left on the pumps. Dry nitrogen only shall be used to let up to air. Prior planning shall be made to minimize the length of time any component is open to the atmosphere, and dry nitrogen shall be left flowing out of all openings, if possible. The pump-down will be the same as initial pump-down.

IV.H.1. References

- A182 Jose Alonso and Harvey Gould, Phys. Rev. A 26, 1134 (1982).
- Ca70 Thomas A. Carlson, C. W. Nestor, Jr., Neil Wasserman, and
J. D. McDowell, Atomic Data 2, 63-99 (1970).
- Sc84 Alfred S. Schlachter, Tenth International Conference on
Cyclotrons and Their Applications, MSU, 29 April-3 May, 1984,
ed. F. Marti, IEEE Catalog No. 84CH11963, pp. 563-70.

IV.1. ELECTRON COOLING SYSTEM REQUIREMENTS

Studies of ways to improve charged-particle beam quality in storage rings recently have received a great deal of attention. The fundamental quality parameter which describes the beam is phase-space density. In an ideal situation this density is conserved (Liouville's theorem), but in reality, it decreases due to diffusionlike heating processes such as residual gas scattering. In order to increase storage times and reduce emittances, phase-space density must be increased. This increase of phase-space density is called "cooling." Cooling is also required prior to deceleration of ions, since deceleration decreases phase space density and increases aperture requirements. Space must be left in the lattice to allow for the cooling systems.

Heavy-ion cooling can be done with either stochastic or electron beam methods. Electron beam cooling is accomplished by merging the circulating ion beam with an intense monoenergetic electron beam in a straight section of the storage ring. When the electron velocity is adjusted to be equal to the mean ion velocity, a situation is created in which, in the common rest frame of the two beams, a recurrent mixing of the "hot ion gas" with the "cold electron gas" takes place. After some cooling time, τ_c , this mixing reduces the temperature of the ion gas and the phase-space density of the ion beam is increased. The theoretical explanation of electron beam cooling has been discussed by several authors (Po84, Bu76, Be81), and only the resulting equations will be given here.

The cooling time, τ_c in seconds, is given by

$$\tau_c = \frac{kAL\beta^4\gamma^5(\theta_e^2 + \theta_i^2)^{3/2}}{\lambda jQ^2}, \quad (\text{IV.I.1})$$

where

k is a constant approximately equal to 1.4×10^{12} (SI units),

A and Q are the ion mass and charge numbers,

L is the ring circumference,

β and γ are the ion relativistic velocity and mass,

θ_e and θ_i are the electron and ion beam divergences,

j is the electron beam current density in A/m^2 , and

λ is the cooling path length.

The divergence of the electron beam is directly related to the temperature of the electron gun, which is about 800°C . Thus the transverse temperature, T , of the electron beam equals 800°C , or 0.1 eV, and the divergence is given by

$$\theta_e = \left(\frac{2T}{m}\right)^{1/2} / c\beta\gamma, \quad (\text{IV.I.2})$$

where m is the electron mass and c is the velocity of light. The divergence of the ion beam is determined by the device injecting into the ring.

From Eq. IV.I.1, it can be seen that τ_c increases linearly with the mass and decreases as the square of the charge of the ion. The cooling time also decreases linearly when j or the fraction λ/L is increased, so that a long cooling section having a high-current density produces the

shortest cooling times. The explicit velocity dependence of $\tau_c \propto \beta^4$ in Eq. IV.I.2 is deceptive, since for a space-charge-limited electron gun, $j \propto \beta^3$. Once $\theta_i < \theta_e$, from Eq. IV.I.2, $(\theta_e^2 + \theta_i^2)^{3/2} \propto \beta^{-3}$, which leads to a β^{-2} velocity dependence. Furthermore, the velocity dependence introduced via γ is not negligible for the energies of the heavy ions from the proposed accelerator; $\gamma^5 = 8.57$ for 500 MeV/nucleon. Thus, for the partly relativistic heavy-ion beams considered here, the cooling time does not always decrease with increasing ion kinetic energies.

To first order, the cooling can be thought of as achieving equal temperatures for the two beams, a condition which may be written as

$$\theta_i = \left(\frac{m}{A}\right)^{1/2} \theta_e . \quad (\text{IV.I.3})$$

In practice, the equilibrium ion divergence will be higher because heating mechanisms, such as residual gas scattering, intra beam scattering, power supply ripple, misalignment of the ion and electron beams, etc., are present. As an example, consider a 500-MeV/nucleon Ca^{20+} beam with $\theta_i = 0.3 \times 10^{-3}$ and a 274-keV electron beam with a temperature of 0.1 eV ($\theta_e = 5.4 \times 10^{-4}$) and with $j = 35,000 \text{ A}/\text{m}^2$. Then for a 1-meter-long cooling section in the 154-m circumference cooling ring, Eq. IV.I.1 predicts a cooling time of 0.42 seconds and Eq. IV.I.3 predicts an ion divergence of 2.0 microradians.

The stochastic method of cooling involves sensing the beam position and applying corrective "kicks" to the beam at appropriate places in the lattice. A separate set of pickups and kickers is required for

each degree of freedom: longitudinal, horizontal, and vertical. Stochastic cooling works best for hot, diffuse beams. The cooling time increases with an increasing number of ions. Given present technology, which allows operation with ~GHz bandwidths, cooling times will exceed one second when there are more than 10^9 ions. Electron cooling works best for initially cool, low emittance beams. As several amperes of electrons can be generated easily, a weak beam (ions)-strong beam (electrons) regime is realized, and the cooling rate is independent of the number of ions being cooled, certainly up to 10^{11} ions. At present the ultimate increase in phase-space density of an ion beam is greater with electron cooling.

Given that the primary heavy-ion beams are initially rather cool and have numbers of ions well in excess of 10^9 , the electron beam method was selected for cooling. The exception to this is for secondary radioactive beams, where the initial momentum spread is $\geq 2\%$ and the number of ions is 10^7 to 10^8 . In this case an additional stochastic system is needed, and is proposed (see Sect. IV-J).

Design of the resonant focussing anode structure, design of high homogeneity solenoids, reduction of power consumption by the electron beam, and attainment of low-background gas pressure are the main areas of uncertainty for the electron cooling system. An ORNL staff member is spending a year at CERN collaborating on the design and construction of the electron cooling system for the Low Energy Antiproton Ring (LEAR) at CERN. However, this system is designed for 60-keV electron operation.

Consultation with FNAL, IUCF, and GSI (where $\sim 250\text{--}300$ keV systems exist or are being built) is planned. Most of the technical issues for these systems have been resolved, and it is anticipated that knowledge gained there will be directly applicable to the design, construction, and operation of the electron cooling system for intermediate-energy heavy ions.

The gun assembly, collector assembly, and solenoid/toroid structures would be brought into operation initially independent of the ring. Field maps will be made, gun operation tested, and vacuum performance studied at various gun currents in an off-line setup. Initial tests of the gun's operation with beam will be made in a single pass setup on an existing MHIRF beam line. After installation into the ring, a series of tests will be made. These include the effect of the electron beam on the machine tune and lattice functions, the rate of beam loss due to electron capture by ions passing through the beam, the ability of the gun's power supplies to track the main ring dipole field, and the effect of the gun on ring vacuum. After these tests, the cooling performance of the system will be measured for various beams at various energies. Cooling rates and ultimate emittance reached would be measured for a variety of operating conditions.

The electron beam cooling (EBC) apparatus, shown in Fig. IV.1.1 consists of three major components: the electron gun, the drift region, and the collector. All three are immersed in a solenoidal magnetic field. The 1-meter-long drift region is where the cooling of the ions

Fig. IV.1.1. The electron beam cooling system showing the location of: 1. electron gun, 2. NEG pumps, 3. pick-up station, 4. toroid, 5. central drift tube or interaction region, 6. solenoid, 7. toroid chamber, 8. collector drift tube, 9. collector, 10. pump port, 11. valve, 12. correction dipole, and 13. pumping station.

takes place. Two identical toroidal magnets with deflection angles of 48 degrees deflect the electron beam onto and away from the ion beam axis. To compensate for the unwanted deflection of the ion beam due to the dipole components of the toroids, correction dipoles are placed before and after the cooling region. The EBC region is terminated by two UHV valves in order to isolate the remainder of the storage ring, either during maintenance of the EBC apparatus or during startup and testing of the electron gun.

The electron gun (see Fig. IV.I.2) will consist of a flat dispenser-type cathode, a Pierce shield, and a multicomponent anode structure. In the acceleration region of an arbitrary electron gun, the electrons are given transverse velocities because of the focussing action of the anode opening. Since it is desired to have an electron beam in the drift region with minimum transverse velocities, an anode structure is built which produces "resonant focussing," i.e., where the transit time through the anode lens equals exactly one accelerator period (Ru77). This procedure can eliminate the transverse velocity spread caused by acceleration, although the transverse velocity spread caused by the thermal effects of the cathode remains. The cathode and the Pierce shield structure are attached to a bellows so that the position of the structure can be adjusted relative to that of the anode.

Fig. IV.I.2. The electron gun (LEAR-CERN design) showing the location of:
 1. cathode, 2. Pierce shield, 3. heat sink, 4. gas cooled base, 5. cathode feedthrough,
 6. anode feedthrough, 7. bellows, 8. and 9. anodes, and 10. anode support.

Contiguous with the electron gun chamber is a section of beam pipe containing an assembly of six nonevaporative getter pumps (NEG) and a pickup station to monitor the electron beam. This pickup station consists of a sectioned cylinder (4 quadrants) coaxial with the electron beam axis. The pickups determine the position of the beam and, with the appropriate microwave diagnostics, the transverse velocity spread of the electrons.

The fields in the toroids are adjusted so that, on the axis of the electron beam, the field is the same as in the solenoidal regions. Small trim coils are necessary at the toroid-solenoid interfaces in order to make the fields as continuous as possible.

The drift region requires a very uniform (50 ppm in space and time) solenoidal magnetic field in order to produce the shortest cooling times and the lowest ultimate divergences of the ion beam. After construction and assembly of the solenoid and vacuum chamber, the field will be mapped and any inhomogeneities eliminated by the installation of trim coils. The drift region also contains two pickup stations and a grounded coaxial cylinder, which surrounds the electron beam. After all the power supplies for the magnets (three solenoids, two toroids, and trim coils) are adjusted to produce the desired field, the power supplies will be computer controlled and ramped together. The magnetic field and the electron energy will be programmed to track each other and to track the energy of the ion beam.

After being deflected from the ion axis by the second toroid, the electron beam enters the collector region. Here the electrons are decelerated by electric fields, and the magnetic field is decreased to allow the electron beam to blow up and strike the surface of the collector. The electrons are decelerated to an energy of 3 keV or less, and thus the power requirements of the high-voltage power supply are greatly reduced (see Fig. IV.I.3). In addition, lowering the energy of the electrons decreases the rate of outgassing that occurs when they strike the collector surface. This section also provides pumping access for a 400-L/sec sputter-ion pump and a roughing port.

The vacuum in the EBC system will be $\sim 10^{-11}$ torr, which is the same order of magnitude as the vacuum in the storage ring. There are two main sources of outgassing: (1) the gun region due to the operation of a heated cathode and (2) the collector region due to electrons striking the surfaces. To compensate for the first source, an assembly of six NEG pumps, having a total surface area of 0.15 m² and a pumping speed of 3000 L/sec, is placed in a chamber adjacent to the gun region. To minimize the second source, the electrons are decelerated, and a 400 L/sec sputter-ion pump is attached to the collector region. Four NEG pumps (2000 L/sec) are placed in each toroid vacuum chamber. The entire system will be bakeable to 150°C.

Parameters for the electron cooling system are listed in Table IV.I.1.

Fig. IV.I.3. The collector assembly (LEAR-CERN design) showing the location of:
 1. magnetic shunt, 2. collector, 3. repeller, 4. mesh, 5. tungsten spike, 6. feedthrough,
 7. feedthroughs, 8. collector cooling, 9. solenoid, 10. collector correction coil,
 11. flux return, and 12. and 13. alumina stand-offs.

Table IV.I.1. Parameters of the Electron Cooling System

Length of the cooling region	1.00 m
Cathode diameter	4 cm
Electron beam diameter	4 cm
Acceleration	resonant
Deceleration in collector	nonresonant
Electron energy, maximum (minimum)	270 keV (10 keV)
Electron current loss	< 1%
Beam current, maximum (minimum)	22 A (40 mA)
Magnetic field, maximum (minimum)	0.2 T (0.02 T)
Magnetic field stability, dB/B	5×10^{-5}
High voltage stability, dV/V	5×10^{-6}
Toroid deflection angle	48 degrees
Toroid bending radius	0.5 m
Alignment of the magnetic field with the ion axis	$< 2 \times 10^{-4}$ rad

IV.J. STOCHASTIC COOLING SYSTEM REQUIREMENTS

The stochastic cooling process is effective for beams of low intensity, large emittance, and large momentum spread. In the 10-Tm ring, the stochastic method will be used to cool secondary beams. The cooling ring has an acceptance of $A_x = A_y = 30 \pi$ mm-mrad and $\Delta P/P = 1\%$. As has been discussed in subsection IV.E.6, this acceptance is large enough to collect a large fraction of the secondary particles produced in fragmentation reactions. In such reactions, it is possible to produce up to 10^7 secondary particles of one isotope from 10^{11} primary particles.

The principle of stochastic cooling was first proposed by Van der Meer [Va72]. This method uses an electronic feedback mechanism to correct the deviations of the motions of the particles from the ideal orbit. The deviations in a given coordinate are sensed by pickup electrodes in the ring. The amplified signals from the pickups are applied to the kickers for the same coordinate, and give the particle a correction impulse proportional to its deviation. As discussed in subsection IV.E.5, the positions of the pickups and the kicker are important and should satisfy the following conditions:

- (1) The pickup for the longitudinal momentum cooling must be in a dispersive region having a small horizontal beta function. The corresponding kicker must be placed in a nondispersive section.

- (2) For horizontal (vertical) betatron cooling, the pickup must be in a nondispersive region and near a horizontal (vertical) focusing quadrupole magnet where the corresponding beta function is large. The kicker must be in a nondispersive section, and the betatron phase difference between the pickup and the corresponding kicker must be an odd multiple of 90 degrees.

A practical electronic system has a finite bandwidth, W . If there are N particles in the ring with a revolution frequency, f , then there are Nf particles which pass through the pickup every second. Usually, Nf is greater than W . Thus, the signal from an individual particle cannot be resolved by the electronic system. The cooling is carried out on samples of particles with particle number

$$N_s = \frac{Nf}{2W} . \quad (IV.J.1)$$

The necessary statistical nature of this sampling process is the origin of the term "stochastic cooling". An analysis including the effect of the degree of randomness (mixing) of the sampling process and the noise of the system, gives the formula [Sa78] for the cooling rate (inverse cooling time)

$$\frac{1}{\tau} = \frac{W}{2N} (2g - g^2(M + U)) , \quad (IV.J.2)$$

where g is the gain of the system, M is the mixing factor and is greater than one ($M = 1$ for perfect mixing, meaning that the particles are completely randomized in one revolution), and U is the ratio of the noise power to the signal power.

By optimizing the gain ($g_{\text{opt}} = \frac{1}{M+U} < 1$), we have the maximum cooling rate

$$\left(\frac{1}{\tau}\right)_{\text{max}} = \frac{W}{2N(M+U)} \quad (\text{IV.J.3})$$

This result indicates that the cooling rate is reduced as the number of particles is increased. Thus, for fast stochastic cooling, the system should have a wide band width, good mixing, and low noise. A more refined analysis in the frequency domain gives similar results, but the value of the optimal gain is frequency dependent.

The pickups consist of an array of elements from which signals are added in phase with the passage of the particle. A carefully designed combiner circuit with proper impedance matching and time delay must be used. Summing of the signals improves the signal-to-noise ratio of the system. To reduce the noise further, the front end components, from the pickups to the preamplifiers, will be cooled to liquid nitrogen temperature (80°K).

The structure of the pickup is essentially the same as that of the kicker, except that the kicker is constructed to handle higher power. Ferrite core pickups and kickers can have a bandwidth of up to 500 MHz. For transverse cooling, gigahertz bandwidths are needed.

Slotted waveguide pickups with bandwidths greater than one GHz have been used at CERN [Fa78]. Recently, pickups with bandwidths of two to four GHz have been constructed [Go85]; these use directional coupler-loop pairs. These devices with minor modification will be used in the present ring.

Commercially available low-noise wideband preamplifiers and power amplifiers will be used to drive the kickers. Similar to the pickups, the kickers will consist of many electrodes driven by separate amplifiers. This arrangement reduces the total power requirement.

IV.J.1. References

- Fa78 L. Faltin, Nucl. Instrum. and Methods 145, 449 (1978).
- Go85 P.A. Goldberg, G.R. Lambertson, F. Voelker and Loren Shalz, IEEE Trans. Nucl. Sci. NS-32, No. 5, 2168 (1985).
- Sa78 F. Sacherer, Stochastic Cooling Theory, CERN-ISR-TH/78-11 (1978).
- Va72 S. Van der Meer, Stochastic Damping of Betatron Oscillations in the ISR, CERN-ISR-po/72-31 (1972).

V. FACILITIES

	<u>Page</u>
V.A. SITE	V-1
V.B. BUILDINGS	V-3
V.C. BEAM TRANSPORT	V-10
V.D. SHIELDING	V-12
V.D.1. References	V-18
V.E. EXPERIMENTAL FACILITIES OVERVIEW	V-19
V.E.1. General Considerations	V-20
V.E.2. Target Areas	V-21
V.E.2.1. Low-Rigidity-Beam Target Areas	V-21
V.E.2.2 Full Rigidity, Low Intensity-Beam Target Areas	V-24
V.E.2.3 High Rigidity, High Intensity-Beam Target Area	V-27
V.E.3. Cost Estimates	V-33
V.E.4. References	V-35

V.A. SITE

Figure V.A.1 shows a site plan for the facility housing the synchrotron rings and the associated buildings. Existing buildings in Fig. V.A.1 are marked with 6000-series numbers. Buildings with numbers having the prefix S are included as part of this proposal. Tunnels and other earth shielded areas are indicated by dotted lines.

The location of the synchrotron rings and beam transport network are denoted by lines in the figure. The site chosen for the synchrotron booster has the merits of being conveniently located in relation to the buildings accommodating the HHIRF and the ORNL Physics Division, of minimizing the length of the injection beamline from the 25 MV tandem accelerator and extraction beam line to existing target rooms in building 6000, and of being on relatively flat terrain (the elevation ranges from 807 to 815 ft). Also, the site requires few unusual preparations. These are rerouting of a creek, relocating a 16-in. waterline, and removing the 200-m time-of-flight station of the ORELA accelerator. Bed rock in the general area of the site indicates that the floor of the tunnel housing the synchrotron rings should be around an elevation of 807.5 ft (the same elevation as of the ground floor of the HHIRF). This elevation will also give a reasonable balance between excavated earth and earth used for fill.

Fig. V.A.1. Site plan for the synchrotron facility. Existing buildings are denoted by cross hatching. (North is toward the top of the figure.)

V.B. BUILDINGS

The accelerator and storage synchrotron rings will be housed in tunnels with usually only adequate width to allow necessary repairs and replacement of machine components. Most of the shielding of the tunnels will be provided by earth fill sloped at a one foot drop in every two feet. The earthen mound on the outside of the ring will merge with the existing terrain at an elevation of about 815 ft on the north side and 810 ft on the south. Excess excavated dirt and rocks will be placed within the space surrounded by the synchrotron rings resulting in a final elevation of near 815 ft. Examples of sectional cuts of the tunnels are shown in Figs. V.B.1 and V.B.2.

A tunnel between building 6000 and the 15-Tm ring will house extraction lines from both the 15-Tm and 10-Tm synchrotrons (these two extraction lines join in this tunnel), and the injection line from the tandem accelerator. Because of the height of the injection line as it leaves building 6000 ($E_1 = 816.25$ ft.), the floor of this tunnel will be at 809.5 ft.

The building within the accelerator ring (building S-1) will house the 4-Tm booster ring and power supplies for all three rings. Building S-1 will be a one story structure of prefabricated construction except for the basement area containing the booster. A sectional view of the buildings, which will have an area of about 8000 ft², is

SECTION A-A

Fig. V.B.1. Sectional view of the 10-Tm and 15-Tm tunnel on the east side. This is marked AA in Fig. V.A.1.

SECTION C-C

Fig. V.B.2. Sectional view of the tunnel between building 6000 and the 15-Tm ring. This is marked CC in Fig. V.A.1.

shown in Fig. V.B.3. There will be tunnels between this building and both the 15-Tm and 10-Tm rings for power leads and personnel access. Above the area occupied by the 4-Tm booster will be a 40-ft-long traveling crane with 10-ton capacity.

Building S-2 will have a large single room (180 ft x 100 ft) for experimental target stations for beams extracted from both the 15-Tm and 10-Tm rings. Shielding will be provided around experimental stations by stacked concrete blocks and roof planks supplemented by iron slabs and blocks placed around high radiation sources. There will be a traveling crane with a span of 100 ft and capacity of 20 tons. The elevation of the floor, like that of the tunnels for the rings will be 807.5 ft. The height of the building will be about 50 ft. Future space for additional target stations could be made available by extending the building to the east.

Building S-2A, a one-floor prefabricated structure, will be for a counting room, laboratories, and shops, as needed for support of activities in the adjoining target room. Provisions will also be made for portable counting trailers placed next to the experimental equipment outside of the shielding.

The control room for the synchrotrons will be located in Building 6000 along with four existing target rooms as illustrated in Fig. V.B.4. Target areas A, B, and C have 7-foot-thick permanent concrete walls and roofs. Interior heights of these areas are 20 ft and their total area is 4300 ft². The fourth area, marked D, has a ceiling height of 30 ft and no permanent shielding. There is a

SECTION B-B

Fig. V.B.3. Sectional view (marked CC in Fig. V.A.1) of building S1, the 4-Tm booster, and the tunnel to the north of the 4-Tm booster.

Fig. V.B.4. Floor plan of building 6000 with a possible configuration of the beam transport lines. The dashed lines to the right indicate the tunnel to the synchrotron rings.

traveling 12-ton crane. In area D, stacked block and portable roof planks will be placed around beam lines and target stations as required for shielding. The area, excluding the stacked-block shielding illustrated in the figure, is 3600 ft². Two existing counting rooms for target rooms A-D will continue to be used.

An access route between the synchrotron control room in Building 6000 and the accelerator ring will follow the beam transport tunnel between the accelerator ring tunnel and Building 6000. A labyrinth entering the west end of the tunnel is shown in Fig. V.B.4.

V.C. BEAM TRANSPORT

Beam lines in all target rooms will be 7 ft above the floor (E1 = 814.5 ft) to allow for reasonable space to place large experimental apparatus. The elevations of the rings are 813.5 ft for the 4-Tm and 10-Tm rings and 811.5 ft for the 15-Tm ring. The injection line from the tandem to the 4-Tm ring is at an elevation of 816.25 ft (8.75 ft above the floor in Building 6000).

Figure V.B.4 shows a possible configuration of beam lines in the target rooms in Building 6000. However, the final configuration will depend on type and size of experimental devices chosen for the facility. The illustrated layout can accommodate on the order of nine target stations on the four beam lines. Beam lines into areas D and A would handle a beam with full rigidity of 15 Tm. However, the beam line into area C, because of the larger bend, will probably be able to handle only a 5- to 10-Tm beam. Most of the vacuum components, vacuum controls, and beam line elements (beam pipes, bellows, multiported boxes, etc.) for these lines will be provided by disassembly of existing beam lines. Present patch panels should offer sufficient signal cables from these stations to the two counting rooms. Power supplies for these lines and also for the injection line will be housed in space now occupied by ORIC power supplies on the third floor of Building 6000.

Major components for area D will be brought in through the roof shield with the assistance of the overhead traveling crane. There is a loading area at the northeast corner of room D (see Fig. V.B.4).

Beams in the injection line from the tandem accelerator to the 4-Tm booster will have a maximum rigidity of 1.0 Tm. Thus, the line can be constructed entirely out of components from existing lines which are designed for rigidity of 2.6 Tm.

The beam transport lines to building S-2 (see Fig. V.A.1) will be constructed out of new components. Power supplies for these lines will be located in building S-2A.

The configuration of beamlines to target stations will use bending magnets with bends of 4.5° and 9.0° . These will be identical to magnets in the 15-Tm synchrotron ring.

V.D. SHIELDING

For estimates of shielding, the worst situation was taken as that produced by a 1.5-GeV/nucleon ^{12}C beam with intensity of 7×10^{10} particles/sec. To limit exposure to permissible levels (5 rem/yr for radiation workers), radiation levels are to be no more than 2.5 mrem/hr in continuously occupied areas. For shielding of the accelerator ring we assumed that 1% of the beam is lost, losses being distributed evenly around the ring. The radiation was then calculated from the relation given in Ref. [Ag84]:

$$t = 230 \log_{10} (L/R) - 610,$$

where

t = shielding thickness in gm/cm^2 ,

L = uniform energy loss in GeV/cm-sec , and

R = radiation level at outer surface of shielding in mrem/hr.

For $R = 2.5$ mrem/hr, the required thickness t is 590 gm/cm^2 . The shielding will be provided by one foot of concrete (density = 2.4 gm/cm^3) in the tunnel walls and roof, and by earth. If the density of earth is taken as $\rho = 2.0 \text{ gm/cm}^3$, the required thickness is about $8\frac{1}{2}$ ft. Local shielding will be placed around beam dumps and other points regularly struck by the beam.

The intensity of the extracted beam from the synchrotron rings to Building 6000 will be limited to $\sim 10^4$ particles/sec. Thus, for this section of beam transport, the thickness of the earth shield will be only 5 ft.

For shielding calculations for radiation produced by a fully stopped beam, we followed the procedure outlined in Ref. [Om66]. This approach is based on experimental measurements which show that shielding designs can be reasonably approximated by calculating the shielding necessary for 150-MeV neutrons. The number of fast (150 MeV) neutrons per proton was obtained from a linear extrapolation of 8 neutrons per 6.3 GeV/nucleon proton. We assumed that, at energies of the proposed accelerator, a heavy-ion projectile of mass A_{proj} will give the same fast neutron flux as A_{proj} number of protons. Then the flux of fast neutrons after passing through the shield is:

$$\psi_n = \frac{i A_{proj} K e^{-x/\lambda} g(\theta)}{r^2},$$

where

ψ_n = fast neutrons/sec-cm²,

i = particles/sec of the beam,

A_{proj} = atomic number of projectile,

K = normalization constant,

λ = attenuation length (cm),

x = thickness of shield along direction of emitted neutron (cm),

$g(\theta)$ = angular distribution of fast neutrons, and

r = distance in cm between the target and point at which radiation is measured.

The dependence of $g(\theta)$ on θ was taken from Fig. X1-3 in Ref. [Om66]. Values used for several angles are given in Table V.D.1. The value of K is obtained from

$$2\pi K \int g(\theta) \sin \theta d\theta = \text{number of neutrons produced per nucleon in projectile.}$$

For the case considered here, $K = 1.2$.

The attenuation length was taken to be

$$\lambda = \frac{(130 \text{ gm/cm}^2)}{\rho},$$

where ρ is the density of the shielding material in gm/cm^3 [Om66].

The factor for converting from neutron flux to radiation R in mrem/hr which was taken from Ref. [Nr71] is,

$$R = 0.19 \phi_n.$$

Table V.D.2 shows some examples of the radiation levels for various amounts of shielding. These values are calculated for a fully stopped 1.5-GeV/amu ^{12}C beam with maximum beam intensity of 7×10^{10} particles/sec.

In the target rooms denoted by A, B, and C of the existing building, there is 7 ft of permanent concrete shielding. The stacked block walls and ceiling in area D typically will be 7 ft and 4 ft thick, respectively. We propose to use up to about 2 feet of iron shielding directly around the beam stops. Thus, for the maximum energy beam of ^{12}C , the radiation level outside the shield will be acceptable for beam intensities to $\sim 10^9$ particles/sec. This will

Table V.D.1. Values of the relative angular distribution of fast neutrons from a thick target bombarded with 6-GeV protons as read from Fig. XI-3 in Ref. [Om66].

<u>θ (deg)</u>	<u>$g(\theta)$</u>	<u>θ</u>	<u>$g(\theta)$</u>
0	1.00	100	0.032
20	0.70	120	0.018
40	0.37	140	0.012
60	0.15	160	0.009
80	0.062		

Table. V.D.2. Radiation levels for various conditions of shielding for a fully stopped beam of 1.5-GeV/nucleon ^{12}C with intensity of 7×10^{10} particles/sec.

$\theta^a(\text{deg})$	$g(\theta)$	$x(\text{ft})^b$		$r^c(\text{ft})$	$R(\text{mrem/hr})$
		Iron	Concrete		
0	1.000	0	7	15	1.8×10^4
0	1.000	2	7	15	440
0	1.000	3	7	15	69
90	0.044	0	4	11	7.9×10^3
90	0.044	2	4	11	195
90	0.044	3	4	11	114
0	1.000	0	20	20	6.7
0	1.000	4	10	14	2.4

a) Angle between emitted neutrons and beam direction.

b) Thickness of shield along direction of emitted neutrons.

c) Distance between beam stop and point at which radiation is measured.

be adequate for experiments utilizing large solid-angle detectors or having large cross sections such as for atomic processes. Experiments producing higher levels of radiation would normally be carried out in the new experimental hall in building S-2.

V.D.1. References

- Ag84 Proposal II for Heavy Ion/Proton Accumulator Booster, BNL
Report 32949-R (1984).
- Om66 Proposal for the Omnitron, A Multipurpose Accelerator at
Lawrence Berkeley Laboratory (1966).
- Nr71 Protection against Neutron Radiation, NCRP Report No. 38
(1971).

V.E. EXPERIMENTAL FACILITIES OVERVIEW

The proposed accelerator complex will be a major U.S. facility for nuclear physics research with intermediate-energy heavy-ion beams. The unprecedented variety of high quality beam type/beam energy combinations available from the facility provides for a wide range of experimental studies. This fact has been well documented by the suggestions for research presented in Chapter II of this proposal. The experimental facilities must include a wide variety of devices that can address a large range of nuclear physics problems and accommodate as large a number of users as possible. The expense of building major research apparatus requires a major commitment of funds and resources after the facility is funded. Several workshops of potential users will be held to develop detailed plans for major pieces of equipment. The following brief discussion of experimental facilities, although very preliminary, should serve as an indication of the scope of the experimental devices envisioned.

V.E.1. General Considerations

Detection methods for nuclei with energies below a few hundred MeV/nucleon differ from those appropriate at energies in the GeV/nucleon regime. The stopping of charged particles at lower energies proceeds mostly via atomic processes and as a result the deposition of charged particle energy is localized around the primary trajectory. At higher energies the probability of nuclear processes becomes large and energy deposition occurs via a cascade of nuclear reaction products. Thus, for high-energy measurements, large volumes of stopping materials are required to achieve containment and detection of all the energy of the primary particle. The proposed detection systems must be able to bridge the broad energy and ion range of beams available from the proposed accelerator.

V.E.2. Target Areas

The proposed facility will deliver beams to two major sites as shown on Fig. V.A.1. Primarily lower-energy beams will be directed to the existing areas A, B, and C in building 6000 (Fig. V.B.4) where available apparatus presently suitable for beams with energies of a few tens of MeV/nucleon will be upgraded for use at higher energies. The experimental annex, area D, in Building 6000 will accept full rigidity but lower intensity beams ($< 10^9$ particles/sec). This area will house an assortment of segmented, large, solid-angle detector systems. Both full intensity and full rigidity beams will be delivered to a newly constructed experimental area in building S-2 (Fig. V.A.1). Devices suitable for more exclusive high resolution measurements — a variety of charged particle and high-energy, gamma-ray spectrometers — are planned for that area.

V.E.2.1 Low-Rigidity-Beam Target Areas

The existing devices that will be used in this area will, to different degrees, have to be reconfigured and upgraded in order to take advantage of the higher energy beams available. These devices may include any or all of those facilities listed below.

- (1) The Spin Spectrometer (4π array of 72 NaI detectors) and the large array of BGO-shielded, Ge gamma-ray detectors will be used with the higher-energy beams. For event triggers based on discrete gamma rays, no modification of the existing array of Compton-suppressed, Ge detectors will be necessary.

In situations where event selection requires full energy deposition of a charged particle, a large trigger detector will be needed. The physical constraint of the size of the Spin Spectrometer cavity and the need to minimize γ -ray absorption and scattering might dictate the removal of one or more NaI elements to be replaced by a port to which a massive trigger particle detector can be attached.

- (2) A broad-range magnetic spectrometer (Q-D, 2.4-Tm, and $\Delta\Omega = 5 \text{ msr}$) is presently equipped with a detection system that measures the arrival time ($\Delta T \lesssim 500 \text{ ps}$), momentum ($\Delta p/p \lesssim 5 \times 10^{-4}$) and energy ($\lesssim 1\%$) of each detected particle [Ro80].
- (3) The UNISOR facility is designed to provide mass-separated samples or beams of stable or radioactive atoms. Intended primarily for studies of nuclei far from stability, it consists of an isotope separator on-line to the HHIRF accelerators. For on-line operation, the beam impinges on the target which is mounted in the ion source. Presently, targets must be relatively refractory and thin (several mg/cm^2). For experiments with beams from the proposed accelerator, targets can be 2 to 3 orders of magnitude thicker which will compensate for the effects of the lower beam intensity and lower cross sections. The UNISOR facility has three separate beam lines providing for three simultaneous on-line experiments. At each counting station,

"conventional" alpha, electron, or gamma-ray spectroscopy can be performed. For example, a laser facility is capable of measuring the atomic hyperfine structure yielding electromagnetic moments and changes in the mean squared charged nuclear radii. A helium dilution refrigerator will be installed at UNISOR in late 1986, making possible measurements on oriented nuclei.

- (4) A general purpose, 1.6-m-diameter, scattering chamber is equipped with an assortment of detector mounts (arms) that can be moved remotely. This chamber has enough room for moderate sized detectors. [Ro80].
- (5) A new, large area, segmented, logarithmic detector system (HILI) will provide simultaneous detection of several complex fragments and a large multiplicity of light particles emitted from a nuclear collision. With an angular acceptance of $\pm 20^\circ$ in plane and $\pm 16^\circ$ out of plane this detector is capable of detecting all the particles emitted in a collision if a heavy, fast-moving, projectile is used to bombard a light target. The version being built will be suitable for studies of nuclear reaction processes for projectile energies between 10 MeV/nucleon and 100 MeV/nucleon.
- (6) A spectrometer for studies of π^0 production at bombarding energies of a few tens of MeV/nucleon is available. It has 20 gamma-ray detector telescopes each with an absorber,

a Pb Glass converter, and a veto counter sandwich with the associated electronics. The converter can be removed for studies with higher energy beams where π^0 -production cross section are larger and background is less of a problem.

V.E.2.2 Full Rigidity, Low Intensity-Beam Target Areas

Area D of Building 6000 will house new devices which feature large solid-angle coverage with varying degrees of segmentation and resolution. Options considered are:

- (1) A streamer chamber with electronic readout (using charge coupled devices). Bending power of 2-3 Tm can be achieved over moderate distances (<1 m). Electronic track recording is expected to provide high sensitivity and a large dynamic range compared to the photographic track recording method. This should result in better densitometric measurements of particle charge. Image enhancement and pattern recognition techniques can be employed with electronic recording to speed up data analysis [An82], provided appropriate computer facilities are available. A few meters of free space in front and on the sides of the streamer chamber should be reserved for the possible addition of detection devices outside the streamer chamber region (for example, light particle hodoscopes). Such a device could be very useful in the study of light particles emitted at mid-rapidity in

central collisions. The enhanced capability of identifying and measuring the production of heavier fragments can be particularly useful in the study of liquid-gas phase transitions in hot nuclear matter.

- (2) A large spherical scattering chamber that can accommodate an assortment of detectors surrounding the target and an array of segmented, logarithmic, charged-particle detectors for the forward 30-degree cone around the beam direction.

Fig. V.E.1 provides a schematic drawing of such a system with several suggested components (see below for details). It would be desirable to allow for some reconfiguring and changing of the detector arrangement in the chamber when adapting the system to a particular experiment. The example shown in the figure considers the possibility of having a densely packed array of Si-strip detectors around the target. Two layers of such detectors could provide energy loss and position information as well as a start signal for time-of-flight measurements. The detectors at forward angles can be combinations of gas filled detectors backed by solid scintillation detectors. The large-angle coverage and the large dynamic range of the logarithmic detectors will make it possible to attain situations where all the outgoing products in a collision are detected. The walls of the spherical scattering chamber could provide mid- and low-

Fig. V.E.1. A large multidetector device with logarithmic detectors at forward angles.

rapidity and low-rapidity coverage for certain types of particles: for example, thin detectors for heavy recoils or BaF_2 plus plastic scintillator phoswiches for the detection of lighter particles. Such a device would be very suitable for the study of peripheral collisions and would complement measurements made with the steamer chamber.

- (3) A high resolution time projection chamber (TPC) surrounding the target with multiple sampling readout of the integrated charge for energy loss and multiple track measurements. Such a TPC can be augmented by surrounding it with total absorption devices for calorimetric measurements.

V.E.2.3 Full Rigidity, High Intensity-Beam Target Area

The magnetic separation of products is applicable at all energies; however, the higher energy beams require very long bending paths, or very strong magnetic fields. Ideally one would like to have a choice of magnetic detection systems suitable for the detection of products having rigidity ranging from that of the projectile to that of the target. Two magnetic devices are listed below that are suitable for measurement of low- and mid-rapidity charged particles.

- (1) A projectile fragment spectrometer. Such a spectrometer is suitable for momentum analysis of fragments moving with velocities near those of the projectile. A small angular range near zero degrees is desired. A configuration similar

to the SPES IV spectrometer at the SATURNE facility, Saclay, France [Ba80] would be desirable because it can operate in a low resolution mode with large acceptance or in a high-resolution mode. This device as shown in Fig. V.E.2, is a double focusing stationary spectrometer. The scattering angle is varied by directing the beam onto the target at different angles. The beam transport to the target can also be used to change the mode in which the spectrometer operates. The study of nuclear transitions to discrete levels or resonances (see Section II.D.2) requires good energy resolution. Studies of broad resonances (delta and nuclear giant resonances) may require a large momentum bite with $\Delta P/P$ up to 1.5%. A magnetic device can be designed to operate in modes that provide both of these desired features. Because of the high projectile energies available from the proposed accelerator and the physics to be addressed, the relevant data is focussed into a small forward cone. Therefore, the magnetic spectrometer does not need to be very large and can have a fairly small gap. This spectrometer could be provided with a large scattering chamber where detectors for low-rapidity fragments can be mounted for coincidence studies. The very long path of the detected fragments makes time-of-flight measurement a possibility. The velocity of the more energetic heavy ions can

Fig. V.E.2. Layout of the SPES IV spectrometer Q-Quadrupoles, D-dipoles and S-sextupoles. Beam is steered onto a target with elements D1, Q1, Q2 and D2. The arm with D1, Q1 and Q2 can be moved. The spectrometer arm does not move. A similar spectrometer at Berkeley [Am83] has no movable parts.

also be measured with Cherenkov detectors (using the dependence, near threshold, of the Cherenkov light intensity on ion velocity in different media). Energy loss and total energy measurements can be performed at the focal plane.

- (2) A large double-arm spectrometer for light fragments is a possibility. For the study of protons and charged pions with momenta near 1 GeV/c, a large magnetic (4- to 5-Tm) spectrometer like HISS [Gr85] may also be suitable.

Inclusive differential cross sections for pion and proton production can be measured by combining momentum (position) and velocity (TOF) measurements. The spectrometer would also be used for particle-particle correlation measurements. The momentum or energy resolution of such a device should be around a few percent for light particles.

- (3) A large momentum acceptance spectrometer will also be needed for subthreshold kaon production studies. Because of the large background due to pions, leptons, and protons produced in the reaction a multi-element spectrometer may be needed. Such a device might have a dispersive element and an intermediate, nondispersive focus followed by a high-dispersion element. The long path of the detected particles and the intermediate focus provide for multiple sampling of the detected products. Measurements of the kaon trajectories at

many points will allow k/π separation. Additional information from differential-Cherenkov counters placed at the intermediate focus will aid in the reduction of electron, muon, pion, and proton background. Following the second high-dispersion elements an array of tracking detectors and/or Ring Imaging Cherenkov counters can be used for final identification and momentum measurements. The device should be capable of attaining a k/π discrimination ratio of 1×10^6 .

- (4) For single-photon detection and neutral-pion detection a "wall" of lead glass modules will be assembled. Due to the high π^0 and gamma-ray multiplicities which are encountered in collisions of very heavy ions, this wall must be highly segmented. An arrangement similar to the CERN GAMS [Bi81] detector will be used. In that device approximately 2000 lead-glass blocks are arranged in a rectangular array. Single blocks are 3.5 cm x 3.5 cm x 37 cm. Glass such as Schott SF5 or F-2 could be used. The latter has a higher critical energy which has some advantages in rejecting background from low-energy (<10 MeV) photons. The wall would be placed at a short distance in order to subtend more than one steradian. Simulations of the response of a similar device show good π^0 identification above

$T_{\pi^0} = 50-100$ MeV. Single photon studies would have to correct for the fraction of π^0 decays in which only one decay photon reaches the detector. Such a glass wall would be of great usefulness in studies for example, of $\Delta \rightarrow \pi^0 N$ decays. In that case the π^0 is emitted with enough kinetic energy that its decay photons are emitted with a small opening angle.

For low-energy π^0 production reactions a spectrometer already exists. It could be supplemented with detectors from the large array, with the proviso that converters would be needed below about 80-MeV/nucleon bombarding energy because of the very small π^0 production cross sections (10 μb or less). The wall would provide an ideal device for single-photon studies and $\gamma\gamma$ studies at bombarding energies of a few hundred MeV/nucleon and below. At these energies the pion-production cross sections are still so low that the single-photon yield dominates.

V.E.3. Cost Estimates

The suggested list of new experimental apparatus has not undergone any optimization as far as details of function (specification) and cost effectiveness. The estimates presented in Table V.E.1 should therefore be viewed as very preliminary and serve mostly to indicate the magnitude of additional resources that will be required to carry out a vigorous research at the proposed facility.

Table V.E.1. Cost Estimates for Experimental Apparatus

<u>Device</u>	<u>Costs^a</u>	<u>Magnets</u>	<u>Other Hardware</u>	<u>Signal Processing</u>
Proj. fragment spectrometer	2600 ^b	1600	500	500
High energy γ -ray detectors	1400 ^c	--	500	800
Streamer chamber	800 ^d	400	200	200
Large array of detectors	1900	--	1200	700
Kaon spectrometer	1100 ^e	500	300	300

a) Cost in \$1000 units.

b) Based on SPES IV design but with smaller vertical acceptance ($\pm 1^\circ$).

c) Estimate based on Ref. [An82].

d) A Pb glass "wall" with 2000 units.

e) Cost estimate for single arm.

V.E.4. References

- An82 N. Anantaraman, H. Stocker, and G. D. Westfall, p. 18 in Workshop on Phase II Apparatus, NSCL, Dec. 1982, Rep. No. MSUCL-411.
- Am83 L. Anderson, W. Bruckner, E. Moeller, S. Nagamiya, S. Nissen-Meyer, L. Schroeder, G. Shapiro, and H. Steiner, Phys. Rev. C 28, 1224 (1983).
- Ba 81 Nucl. Instrum. Methods 188, 549 (1981).
- Bi81 F. Binon, C. Bricman, V. A. Davidov, S. V. Donskov, J. Dufournaud, P. Duteil, M. Gouanere, A. V. Inyakin, V. A. Kachanov, D. B. Kakauridze, G. V. Khaustov, A. V. Kulik, J. P. Lagnaux, A. A. Lendev, Yu. V. Mikhailov, J. P. Peigneux, Yu. D. Prokoshkin, Yu. V. Rodnov, R. Rossen, S. A. Sadovrky, D. Sillon, A. V. Starzev, J. P. Stroot, and V. P. Sugonyaev, Nucl. Instrum. Methods 188, 507 (1981).
- Gr85 D. E. Greiner, "The HISS Spectrometer", Proceedings of the Conference on Instrumentation for Heavy Ion Nuclear Research, Nucl. Sci. Res. Series, Vol. 7, ed. D. Shapira (Harwood Academic Publishers, 1985).
- Ro80 HHIRF User's Handbook, ed. R. I. Robinson (1980).

VI. COST ESTIMATE AND CONSTRUCTION SCHEDULE

VI. COST ESTIMATE AND CONSTRUCTION SCHEDULE

The cost estimate for the project (see Table VI.1) is based on preliminary designs for the principal components of the project. Cost estimates were derived from scaling previous conceptual designs made by the Holifield staff and by others. Building and utilities estimates include a new 13.8-KV transmission line to the site from the main ORNL substation, substations at the site, cooling towers, demineralized water pumps and distribution, and all heating, ventilating and air conditioning equipment. Cost estimates for the technical components include procurement and installation. Costs are given in FY 1986 dollars without escalation.

The project schedule, Table VI.2, shows design of the facility beginning in October 1988, which is consistent with FY 1989 funding of the project. The total time for completion of the project is six years. This schedule allows approximately three years for design and construction of the conventional facilities and for staggered design, procurement and installation of the technical components.

Operating costs for the project are given in Table VI.3. Significant increases in staff and associated costs are required because of the complexity of the facility. An estimate of electrical power requirements for the facility is given in Table VI.4.

Table VI.1. Project Cost Estimate

(Costs in \$1000)

Buildings, Tunnels, Utilities ^a		\$ 7,040
Accelerators		18,210
4-Tm Synchrotron	\$ 3,770	
15-Tm Synchrotron	\$14,440	
10-Tm Cooling Ring		7,920
Electron Cooling System		800
Stochastic Cooling System		2,000
Beam Transport Systems ^b		5,500
10-Tm/15-Tm to New Exp. Area	\$ 2,460	
10-Tm/15-Tm to Bldg. 6000	\$ 2,770	
Tandem to 4-Tm (reinstall existing equipment)	\$ 270	
Control System and Software		\$ 3,600
Radiation Safety System		<u>\$ 500</u>
Total		\$ 45,570
Engineering @ 20% of Const.		<u>\$ 9,110</u>
Total		\$ 54,680
Allowance for Contingencies @ 25%		<u>\$ 13,670</u>
TOTAL ESTIMATED COST		\$ 68,350

a) Building and tunnel locations are shown in Fig. V.A.1.

b) Location of beam transport lines are shown in Figs. V.A.1 and V.B.4.

Table VI.2. Schedule for Expansion of the Hollifield Facility

Calendar Years	1988				1989				1990				1991				1992				1993				1994				1995			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Building and Utilities						---	Design/Bld		----	Construction	----																					
4-Tm Synchrotron						---	Design/Bld		----	Fab/Deliver	----		---	Install/Test	---																	
15-Tm Synchrotron										---	Design/Bld		----	Fab/Deliver	----		---	Install/Test	---													
10-Tm Cooling Ring													---	Design/Bld		----	Fab/Deliver	----		---	Install/Test											
ORIC Exp. Area Disassembly													---	Plan		Const																
Control System						---	Design		----	Procurement/Software							---	Install/Test	----													
Beam Transport Systems								---	Design		----	Fab/Deliver		----	Install/Test	----																
Beam Cooling Systems										---	Design		----	Fab/Deliver	----		Install/Test															
Radiation Safety System								---	Design		----	Procure		----	Inst/Test																	
Install Exp. Equipment																	---	Install/Test	----													
ORIC Operation	-----				ORIC Operating				-----				ORIC Shut Down				-----															
Experimental Program																															Exp.	-----

Table VI.3. Estimated Incremental Operating Costs for
the Expanded Holifield Facility

<u>Category</u>	<u>Present Holifield Facility</u>	<u>Total for Expanded Holifield Facility</u>	<u>Increment for Expanded Holifield Facility</u>
Professional Staff (person year)	14.6 - \$1710 K	24.0 - \$2822 K	9.4 - \$1112 K
Technicians and Operations Staff (person year)	14.5 - \$ 847 K	36.0 - \$2110 K	21.5 - \$1263 K
Craft Support (person year)	9.0 - \$ 818 K	30.0 - \$2728 K	21.0 - \$1910 K
Exempt power (GWh)	13.8 - \$ 623 K	43.8 - \$1978 K	30.0 - \$1355 K
Other Costs (Materials, supplies, Health Physics, etc.)	<u>\$ 867 K</u>	<u>\$1762 K</u>	<u>\$ 895 K</u>
Total	\$4865 K	\$11,400 K	\$6535 K

Table VI.4. Electrical Power Requirements for the Expanded Facility

	Max. Avg. Power (MW)	Avg./Max. (%)	Up-Time (%)	Annual Avg. Power (MW)
New Accelerators	6.6	80	70	3.70
Beam Transport	0.6	20	70	0.10
Experiment Areas	1.0	50	70	0.4
New Facilities - Total				4.2
Tandem Accelerator and background power				0.8
Facility Total				5.0

APPENDIX A

WORKSHOP ON INTERMEDIATE ENERGY HEAVY ION PHYSICS

A Workshop on Intermediate Energy Heavy Ion Physics, jointly sponsored by the Physics Division of ORNL and the Joint Institute for Heavy Ion Research, was held at the Joint Institute on September 23-25, 1985. The purpose was twofold: (1) to examine the physics opportunities that might be made available by an intermediate energy heavy-ion facility and (2) to assess the interest of the physics community in the field of intermediate energy heavy-ion physics.

If the 134 attendees of the workshop can be viewed as a reasonable sounding board for the physics community, interest is high and it is time to move vigorously into this sparsely investigated area. The accelerator system being proposed in this document is in response to the message which emanated from that meeting.

The program for the workshop is shown on the following page. Proceedings of the workshop, consisting of copies of all viewgraphs and of any text the speakers wished to submit, were published as ORNL Report CONF - 8509176.

Workshop on Intermediate Energy Heavy Ion Physics

Oak Ridge, Tennessee

September 23-25, 1985

PROGRAM

MONDAY, SEPTEMBER 23

Session IA, 9:00 a.m. - Chairman, J. B. Ball,
Oak Ridge National Laboratory

Welcome, A. Zucker, Associate Director, Oak
Ridge National Laboratory

The MHIRF Plus R-Tm Synchrotron Facility,
G. R. Young, Oak Ridge National Laboratory

Session IB, 10:30 a.m. - Chairman, D. Brink,
Oxford University

Equation of State - Theory, P. Siemens, Texas
A & M University

Equation of State - Experiment, R. Stock,
University of Frankfurt/GSI Darmstadt

Session IIA, 1:30 p.m. - Chairman, J. Lynen,
GSI Darmstadt

Physics at 10-MeV Temperature, J. F. Bertach,
Michigan State University

Charged PIONeering with Heavy Ions,
J. O. Rasmussen, Lawrence Berkeley
Laboratory

Session IIB, 3:30 p.m. - Chairman, C. C. Wilke,
University of Liege

QED Experiments with Few-Electron Very Heavy
Ions, M. A. Gould, Lawrence Berkeley
Laboratory

Possible Effects of Nucleon Substructure in
Intermediate Energy Heavy-Ion Interactions,
J. P. Vary, Iowa State University

TUESDAY, SEPTEMBER 24

Session IIIA, 8:30 a.m., Chairman,
F. L. Petrovich, Florida State University

Direct Reactions of Heavy Ions up to Energies
of Several Hundred MeV/Nucleon,
W. von Oertzen, Hahn-Meitner Institut für
Kernforschung, Berlin

Using Nuclear Structure to Study the
Vaporization of Hot Nuclei, R. A. Broglia,
Joint Institute for Heavy Ion Research/Niels
Bohr Institute

Session IIIB, 10:30 a.m. - Chairman,
J. H. Hamilton, Vanderbilt University

Nuclear Structure Studies with an Intermediate
Energy Heavy Ion Accelerator, A. Faessler,
University of Tübingen

Secondary Beams and the Synthesis of Exotic
Nuclei, J. V. Mitache, Lawrence Berkeley
Laboratory

Production and Identification of New Isotopes,
F. Pougeon, Institut de Physique Nucléaire,
Orsay

Session IVA, 1:30 p.m. - Chairman, F. Videbæk,
Argonne National Laboratory

Compression and Expansion, H. G. Ritter,
Lawrence Berkeley Laboratory

Quantum (Statistical?) Effects in Light
Particle Correlations at Small Relative
Momenta, C. K. Gelboe, Michigan State
University

Session IVB, 3:30 p.m. - Chairman, H. C. Britt,
Los Alamos National Laboratory

Nuclear Reaction Studies Using Inverse
Kinematics, D. Shapira, Oak Ridge National
Laboratory

Intermediate Time Scale Phenomena between
10-100 eV/Nucleon, B. Tamain, University
of Caen

WEDNESDAY, SEPTEMBER 25

Session VA, 8:30 a.m. - Chairman, O. Hansen,
Brookhaven National Laboratory

Giant Resonances, F. E. Bertrand, Oak Ridge
National Laboratory

Probing Heavy Ion Collisions with
Bremsstrahlung, C. M. Ko, Joint Institute
for Heavy Ion Research/Texas A&M University

Session VB, 10:20 a.m., Panel Discussion

Moderator, D. K. Scott, Michigan State
University
W. Greiner, University of Frankfurt
A. K. Kerman, Massachusetts Institute of
Technology
S. Aoshin, California Institute of
Technology
U. Lynen, GSI Darmstadt

END
Date Filmed
06/05/86