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CYCLOTRON LABORATORY

EAST LANSING, MICHIGAN

Proposal for Operating Support
for setting up a
National Facility for
Research with Heavy Ions
using a
500 MeV Superconducting Cyclotron

June 1978

MSUCL-270

PROPOSAL
to the
NATIONAL SCIENCE FOUNDATION
for
OPERATING SUPPORT
for setting up a
NATIONAL FACILITY
for
RESEARCH WITH HEAVY IONS
Using a
500 MeV SUPERCONDUCTING CYCLOTRON

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I. Introduction

This proposal requests $6,585,000 for support of the MSU nuclear science program during an important two year transitional period in which

1) the nuclear research program will shift from the 50 MeV cyclotron to the 500 MeV superconducting cyclotron,
2) the operating style of the laboratory will change from serving a relatively homogeneous internal group to serving a broad community of inside and outsider users,
3) the MSU nuclear research program will shift from mostly light-ion to mostly heavy-ion studies, and
4) the accelerator research and development program will shift from design of details of the 500 MeV cyclotron to design of beam transport and experimental apparatus for using the 500 MeV beams while continuing (with an increasing level of effort) design studies for an 800 MeV superconducting cyclotron.

The program which we propose is part of an overall long range plan which has been described in a previous major proposal for a "Coupled Superconducting Cyclotron" facility. We attach this "CSC" proposal as an appendix to avoid rewriting material discussed therein, and to allow the present request to be viewed in the context of the long range program of which it is a part. In view of the relatively thorough account of the program contained in the appendix, we have adopted a briefer format in the main text than has normally been our custom. The main text then hopefully provides an easily readable overview of the program and moves in the direction of new guidelines from NSF which we understand will stipulate 15 pages as the appropriate maximum length for proposals.*

Our basic assumption in writing this proposal is that the soundest criterion for judging a long-range research program is the demonstrated creativity and productivity of the staff involved. As a national facility, the 500 MeV cyclotron will of course serve the broad nuclear science community; the effectiveness with which this is accomplished will nevertheless depend heavily on the skill of the local group. This proposal is then primarily a review of recent scientific accomplishments of the MSU group. The review of the nuclear physics program includes plans for use of the 50 MeV machine during its final two years, as well as plans for research activities using the 500 MeV cyclotron. The discussion of the accelerator development program is mainly in terms of the appendix material, since that material has been updated recently (in February of this year, for use of the Facilities Subcommittee of the Nuclear Science Advisory Committee--NUSAC).

The level of support requested for the two-year period follows the overall plan which we presented at the NUSAC facilitities hearings. The proposal thus requests $2,480,000 for operating expenses in the year 1979, and $3,260,000 for operating expenses in the year 1980 (with escalation estimated at 8% per year, these figures correspond approximately to 1978 dollar levels of $2,300,000

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*Private communication from M. Bardon.

for 1979 and $2,800,000 for 1980, the levels which we presented to NUSAC-see p. 212-iv of the appendix).

We also request $575,000 in 1979 and $270,000 in 1980 to provide additional experimental facilities for the 500 MeV cyclotron to supplement the limited facilities included in the existing 500 MeV cyclotron construction budget. The 500 MeV cyclotron will provide first access to major new areas of nuclear phenomena in the 20 to 80 MeV per nucleon range; the additional experimental equipment proposed here will allow a much more effective exploration of this important new region. (We also note that these additional facilities will be transferred to the coupled cyclotron program, if that program is ultimately funded, and will reduce funds requested for experimental equipment in that program.)

Table I summarizes funding requested for various program elements for each year.

TABLE I.--Budget Summary

	1979	1980
OPERATING EXPENSES:		
MSU Nuclear Research Group	970,000	1,165,000
Accelerator & Instrumentation R&D	1,240,000	1,515,000
Cyclotron Operation (50 MeV and 500 MeV)	270,000	580,000
SUBTOTAL	2,480,000	3,260,000
FACILITIES:		
Additional Experimental Equipment	575,000	270,000
	3,055,000	3,530,000
TOTAL	$6,585,000	

We feel that the requested level of support will provide an efficient and cost effective step into a major new area of nuclear science. We also feel that the program is tailored to be appropriately frugal, while at the same time providing sufficient support personnel to allow effective use of the 500 MeV cyclotron by interested outside scientists. (The funds requested will provide an operating staff for the 500 MeV cyclotron on a 20-shift per week basis, as well as liaison physicists to help outside users acquaint themselves with laboratory procedures and experimental apparatus--the facility management procedures described in Sec. II of the CSC Proposal are already in effect.) Summarizing, we believe that the funds requested will allow us to bring a major new heavy ion laboratory into operation and make its unique facilities conveniently available to the broad national community of nuclear scientists.

II. Nuclear Research with the 50 MeV and 500 MeV Cyclotrons

The nuclear research program is at present based largely on the use of the 50 MeV cyclotron. A few experiments also involve the use of other accelerators as dictated by the interests of the staff, and particularly an increasing involvement in heavy ion physics. Planning for experiments with the 500 MeV cyclotron is a growing program component as we anticipate the implementation of our long range plans which include phasing out research on the 50 MeV cyclotron when the 500 MeV machine reaches a state of reasonably routine operation.

As mentioned in the introduction, we are using a briefer format for this proposal than in past proposals. We have therefore not attempted a comprehensive review of the entire program but rather have selected a few examples of current research to discuss and indicated some of the research planned for the next few years. As well as being more readable, we hope that the overall thrust of the program is more clearly visible in the shortened presentation.

For brevity, we have also omitted the normal referencing to the scientific literature, including references only to our own publications. Readers interested in detail will find in these publications, references to other relevant work.

II.1. Precision Direct Reaction Measurements

An outstanding feature of the MSU cyclotron facility is the availability of precision beams of high energy light particles which, together with the Enge split-pole spectrograph and its unique focal plane detector system, permit high resolution experiments to be carried out at all available cyclotron energies. Recent studies have included inelastic scattering on nuclei in the N=82[1] and A=208[2] mass regions, (p,d) reactions on nuclei in the sd shell[3] and in the lead region[4] and extensive (p,t) and (p,^{3}He) studies in the fp shell.[5] In many cases, the theoretical interpretation or motivation for these experiments has come from the extensive shell model studies of Wildenthal and his collaborators. In addition to providing information about nuclear spins and parities, such experiments probe the single particle, collective, pairing and clustering properties of the nuclear wavefunctions in an exceptionally detailed and powerful fashion.

One ongoing program is the study of inelastic proton scattering from rare earth and actinide targets to obtain the matter distributions of these deformed nuclei.[6] Electron scattering and Coulomb excitation measurements determine their charge distributions, and a comparison with the proton measurements may provide information on the neutron distributions which is difficult to obtain by other means. The experiments carried out to date have yielded angular distributions of the ground state band up to the 10^+ state in ^{232}Th and ^{238}U, and coupled channel calculations have been used to obtain deformation parameters, β_2, β_4 and β_6 (see Fig. T1). Very similar multipole moments are obtained for the charge and matter distributions. This work is being extended to other targets to provide systematic information on these effects over a wide range of deformation parameters.

Other high resolution (p,p') work includes studies of the Pt isotopes 194, 196 and 198[7] which, together with (p,t) studies,

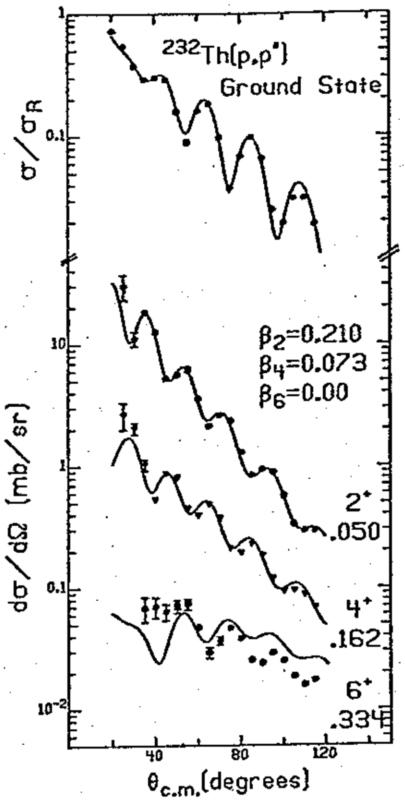


Fig. T1.--Angular distributions for ^{232}Th(p,p') at E_p=35 MeV.

test the interacting boson model of Iachello and Arima as it applies to this mass region. Another recent (p,p') experiment on ^{24}Mg,[8] provided a detailed test of the wavefunctions of Wildenthal and Chung[9] which were used to predict angular distributions for many states up to 10 MeV of excitation.

An extensive multinucleon transfer reaction program includes (p,t) reactions to comparatively unknown nuclei such as ^{104}Cd as well as to better studied nuclei such as ^{52}Fe, ^{48}Ti, and ^{63}Cu. For these latter cases, high quality data are being taken to test both reaction theories and nuclear models in this mass region. The (p,α) reaction has been extensively studied in medium mass nuclei[10] and is also being examined in the mass region near A=208,[11] where the high spin states populated in (p,α) reactions serve as a very useful test of nuclear models.

A number of nuclei in the sd shell which are difficult to study, and therefore are comparatively unknown are being explored using the three neutron transfer reaction ($(^3He,^6He)$). An example of a spectrum, showing the levels of ^{21}Mg, with a resolution of about 30 keV full width at half maximum is shown in Fig. T2. In the fp shell, the $^{48}Ca(^3He,^6He)^{45}Ca$ reaction was used to identify the $(f_{7/2})^{-3}$ states of ^{45}Ca and served as a stringent test of the validity of the $(f_{7/2})^n$ shell model description of nuclear spectra in this mass region.[12]

Studies of direct (p,n) reactions make use of the precise timing properties of the 50 MeV cyclotron and a magnetic beam

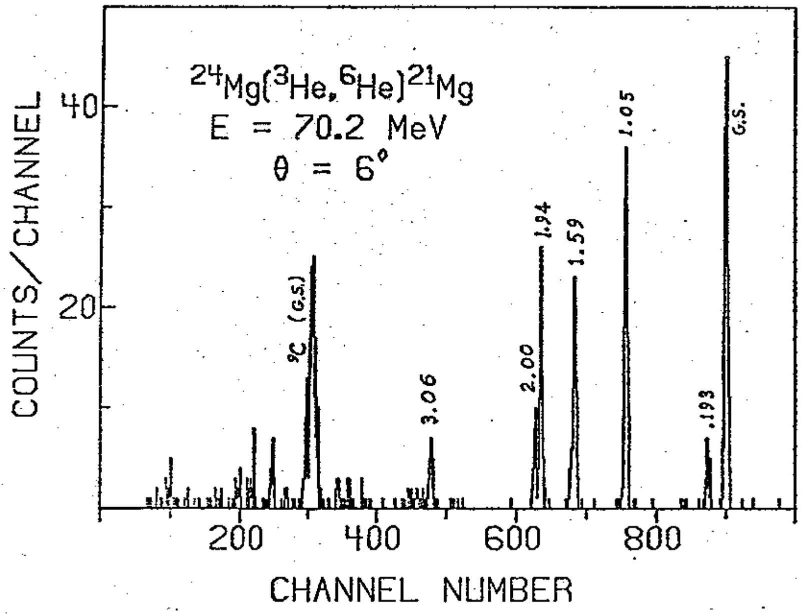


Fig. T2.--Spectrum of $^{24}Mg(^3He,^6He)^{21}Mg$. Resolution is approximately 30 keV FWHM.

swinger with flight paths up to 34 meters.[13] By studying the (p,n) reaction to the isobaric analog of the target ground state for a wide range of targets and bombarding energies, a global, energy-dependent, Lane-model potential was obtained.[14] A microscopic analysis of the same data yielded the strength of the isospin-flip part of the effective nucleon-nucleon interaction.[15] This interaction is, to a good approximation, independent of both bombarding energy and mass number and should be applicable to all nuclei in this energy region.

Since the operator mediating charge exchange reactions is identical in spin-isospin space to that mediating beta decay and to the spin dependent part of the M1 operator, one should be able to use these reactions to locate Gamow Teller (GT) and M1 strength in nuclei. Recently a large concentration of 1^+ strength was found[16] at the theoretically expected location for GT strength in the ^{90}Zr(p,n)^{90}Nb reaction. Some indication of the $T_>$ component of this 1^+ strength was also observed (Fig. T3). A similar concentration has been found more recently in the ^{58}Ni(p,n)^{58}Cu reaction. However, a detailed quantitative correspondence between (p,n) cross sections and the M1, GT matrix elements has not as yet been convincingly demonstrated.

A number of experiments are presently underway to elucidate this connection further. The first is a measurement of the ratio of cross sections for the ^{7}Li(p,n)^{7}Be reaction (Fig. T4) leading to the ground and first excited states of ^{7}Be.[17] These reactions should permit a relatively model independent measurement of $V_{\sigma\tau}$, the "coupling constant" for these (p,n) reactions. Secondly,

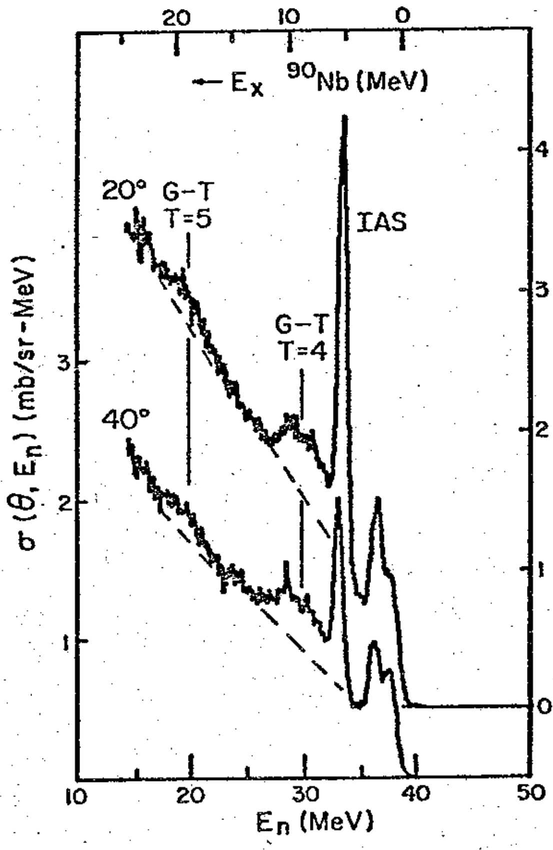
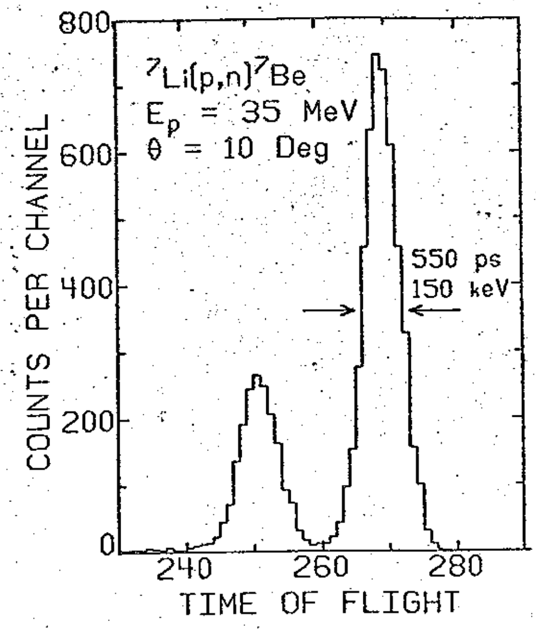


Fig. T3.--Spectrum of the ^{90}Zr(p,n)^{90}Nb reaction at E_p=45 MeV. Indications of Gamow-Teller strength for $T_<$=4 and $T_>$=5 are noted.

Fig. T4.--Time-of-flight spectrum from the ^{7}Li(p,n)^{7}Be reaction taken at a flight path of 19.18 m. The two peaks correspond to the ground state and the 429 keV state in ^{7}Be.



the ^{24,25,26}Mg(p,n)^{24,25,26}Al cross sections are being measured.[18] Much information is available on M1 and GT strengths in these nuclei and preliminary results show a strong correlation between σ(p,n) and the B(M1)'s. Correlations will also be made with the GT matrix elements, which can be reliably calculated from the Chung-Wildenthal wavefunctions.

Future studies will involve further measurements in the sd shell where correlations similar to those for the Mg isotopes can be made and a survey of a number of heavier nuclei.

II.2. Exotic Nuclei and Mass Measurements

Multinucleon transfer reactions have been used at MSU since 1970 to produce new nuclei far from stability and to measure their masses. The main reactions used are given in Table TI. While the Q-values of these reactions are strongly negative and the cross sections very small, techniques using sophisticated on-line counters in the Enge split-pole magnet[19] have permitted

ΔA	REACTION	ΔN	ΔP	ΔT_z	Q-values MeV	~$d\sigma/d\Omega$* μb/sr
3	(p, ^{4}He)	2	1	1/2	−7	50
	(^{3}He, ^{6}Li)	1	2	−1/2	−11	50
	(^{3}He, ^{6}He)	3	0	3/2	−27	1
4	(^{3}He, ^{7}Be)	2	2	0	−8	10
	(^{3}He, ^{7}Li)	3	1	1	−21	2
	(^{4}He, ^{8}He)	4	0	2	−60	0.01
5	(^{3}He, ^{8}B)	2	3	−1/2	−20	0.2
	(^{3}He, ^{8}Li)	4	1	3/2	−33	0.1
	(p, ^{6}He)	4	1	3/2	−37	0.1
	(^{3}He, ^{8}He)	5	0	5/2	−52	0.0002
6	(^{3}He, ^{9}Li)	5	1	2	−51	0.005
	(^{3}He, ^{9}C)	2	4	−1	−30	<0.002

*75 MeV ^{3}He
45 MeV p

Table T1.--Reactions used to produce exotic nuclei.

exceptionally precise mass measurements of many new nuclei. Approximately 50 exotic nuclei have been investigated, and in virtually every case the work resulted in the only or the most accurate mass measurement of the isotope in question. The work has expanded the number of complete isobaric quartets from 1 to 22 and has completed the first isobaric quintet.

Recent projects include the first mass measurements[20,21] of ^{15}F, ^{27}P, ^{31}Cl, and ^{35}K (see Fig. T5). This completes the first round of measurements for the T=3/2 nuclei in the p and sd shells, although the masses of some nuclei should be remeasured because advances in technique now permit a much improved accuracy. The T_z=-1/2 nuclei in the $f_{7/2}$ shell have also been completed,[22] and, as a result, the Garvey-Kelson mass relation has been extended to proton rich nuclei in that mass region. The (^{3}He,^{6}He) reaction has been observed on six heavier targets,[23] and the same proton rich targets will now be used for mass measurements with the (^{3}He,^{8}Li) reaction. Identical techniques have been used to

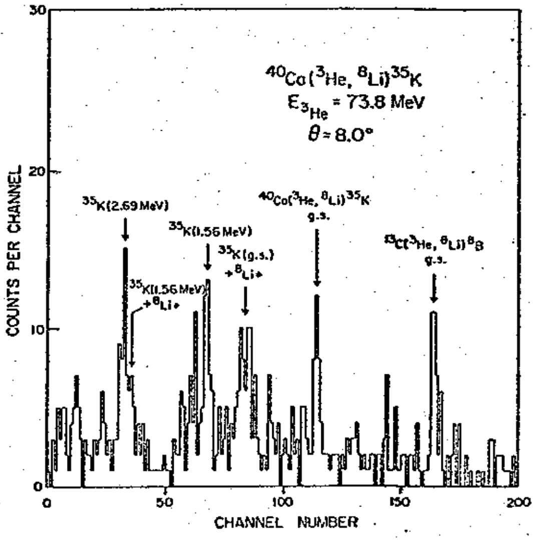


Fig. T5.--Spectrum of ^{8}Li from ^{40}Ca(^{3}He,^{8}Li)^{35}K. The largest peaks shown correspond to cross sections of about 35 nb/sr.

measure the masses of the neutron rich isotopes ^{43}Cl and ^{59}Mn in the 5 nucleon pickup reaction (^{3}He,^{8}B).[24]

A program to produce T_z=-2 isotopes has begun. A cryogenic helium jet will quickly transport cyclotron produced activities to a low background area. Delayed protons will be detected in coincidence with the recoil nuclei they eject. In this way each group in a high resolution proton spectrum is identified with the mass of its parent. The apparatus is being constructed with a view to its use with both the 50 MeV and 500 MeV cyclotrons.

Mass measurements carried out with heavy ions include the (^{12}C,^{10}Be) and (^{12}C,^{9}Be) reactions on ^{58}Ni and ^{64}Zn.[23,25] Recent improvements in the ion source are expected to make feasible additional measurements with heavy ions from the 50 MeV cyclotron. For example, the (^{6}Li,^{8}He), (^{7}Li,^{8}He) reactions and reactions induced by ^{18}O are now under investigation. The techniques developed in these experiments will also be valuable for mass measurements with the 500 MeV cyclotron.

To make sensitive tests of the Isobaric Mass Multiplet Equation (IMME), the masses of nuclei near the stability line must be known with high accuracy. Techniques which have been developed in the past few years allow extremely precise measurements to be made for such nuclei using the Enge split-pole spectrograph. Very negative Q-values, such as that of the $^{16}O(p,t)^{14}O$ reaction, have been determined with sub-keV uncertainties.[26] Excitation energies of states up to 8 MeV have been measured with uncertainties less than 200 eV.[27] These measurements have been done for a variety of purposes, e.g., to calculate ft-values in super allowed β decay,[26] to obtain astrophysical reaction rates[27] and of course, to test the IMME.[28]

An electrostatic deflector, recently installed in the split-pole spectrograph, makes possible the simultaneous exposure on photographic plates of separated bands of protons, deuterons and tritons. This system permitted a much improved determination of the mass of the lowest T=2 state in ^{12}C,[29] and will shortly be used for a new mass determination of ^{9}C to check the one known case where the IMME contains a significant cubic term.

II.3. Simple Excitations of the Nucleus

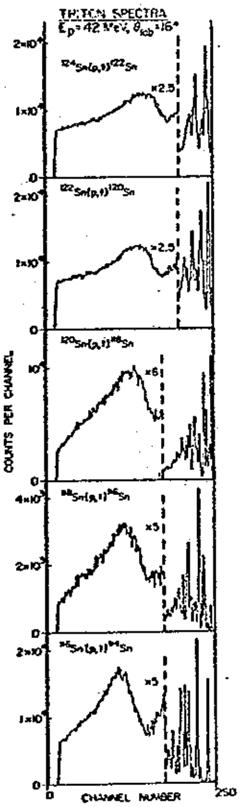
Earlier work at MSU on the giant quadrupole resonance used the 70 MeV ^{3}He beam to excite this state in a wide range of nuclei. More recent work has focussed on the excitation of the giant monopole resonance by proton scattering on ^{208}Pb[30] and the use of 74 MeV ^{6}Li beams to investigate giant multipole excitations in ^{90}Zr.[31] Further investigations, especially searches for higher multipole resonances, are expected with the higher energy, heavy ion beams from the 500 MeV machine. These beams bring in large amounts of angular momentum, and the background yield is expected to be lower.

Another simple mode is excitation of single hole states from deep shells. Currently these excitations are being investigated in heavy nuclei using the (^{3}He,α) reaction. For example, in ^{207}Pb centroid energies and widths have been obtained for not only the six lowest lying levels ($3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, $1i_{13/2}$, $2f_{7/2}$, and $1h_{9/2}$) but also for six additional states viz. $3s_{1/2}$, $2d_{3/2}$, $1h_{11/2}$, $2d_{5/2}$, $1g_{7/2}$, and $1g_{9/2}$.[32] In this same investigation the T=45/2 components of the $s_{1/2}$,$d_{3/2}$, $h_{11/2}$, $d_{5/2}$, and $g_{7/2}$ states were observed at an excitation energy of around 20 MeV.

The damping of single-particle motion at 5-8 MeV excitation is an important observable measured in this type of experiment. Understanding this damping is necessary to elucidate the damping of vibrational modes; a theoretical study of these questions using the framework of Bertsch and Tsai[33] is underway.

Gross structure, identified as arising from deep two hole states, has also been seen for the first time in (p,t) reactions at 42 MeV.[34] A peak about 2 MeV wide was observed at an excitation energy between 8 and 9 MeV in six even-even tin isotopes (Fig. T6) and at lower excitation in ^{104}Cd and ^{102}Pd. If the peak

Fig. T6.--Gross structure seen in Sn(p,t) reactions at E_p=42 MeV.



is assumed to arise from two neutron pickup from the $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$ levels, which lie below the valence levels, the angular distribution calculated using the program DWUCK is in good agreement with those observed for $^{122}Sn(p,t)$ and $^{116}Sn(p,t)$. This work is being extended both to other nuclei near A=90 and to heavier nuclei to help cast further light on this phenomenon.

II.4. β-and γ-ray Spectroscopy Studies

Over the past several years, substantial work has been carried out at MSU to investigate "yrast line spectroscopy", including the phenomenon of "backbending" of the yrast line itself. The emphasis has been on the mass region between the well deformed hafnium isotopes and the lead closed shell nuclei.[35] About 15 even-even nuclei in this mass region have been investigated, and further work on detailed aspects of particle-core interactions, nuclear shapes and non-yrast band structure in these and neighboring odd mass nuclei is continuing.

The single particle spectrum for nuclei in the region just below Z=78, N=108 is unique, because numerous high-Ω orbits cluster near the Fermi surface and can give rise to a different type of yrast structure where angular momentum is carried most efficiently not by collective or rotation-aligned motion but rather by the motion of many high-j particles approximately aligned with the nuclear symmetry axis. Such strongly coupled states are often isomeric and provide interesting physical analogs to the isomeric yrast traps thought to be possible at much higher spins. The most impressive example of such very high-K "deformation-aligned" isomerism encountered thus far, is in ^{176}Hf. Other such isomers in isotopes of W and Ta are currently under study. Similar work continues on high spin structures near the Pb closed shell with the 50 MeV α-particles that have already proved their utility for populating isomers up to 22h. The improved ^{12}C and ^{16}O source lifetimes anticipated in the near future will allow access to other regions, including the recently discovered "island" near N=82,[36] where isomers may permit the study of nuclear shapes under the influence of still higher centrifugal stress.

Another area of recent interest has been the study of high spin states in the odd-odd antimony nuclei. Recently Gaigalas et al. have identified a series of J=1 rotational bands based on deformed $9/2^+$ states in several odd mass antimony nuclei via the (^{6}Li,3nγ) reaction on even cadmium isotopes. This showed the co-existence of deformed and spherical structures in antimony. The low and high spin states of the adjacent odd-odd antimonies have been studied at MSU using the (p,xnγ), (α,3nγ), and (^{7}Li,3nγ) reactions. Recently a series of high spin rotational bands in the odd-odd ^{116}Sb and ^{118}Sb has been identified, again indicating shape co-existence. Preliminary indications are that these odd-odd bands are based on states that are formed by the addition of a neutron state to the same proton hole states as in the odd A antimonies. Further work including studies of ^{114}Sb is planned.

II.5. Studies of Fundamental Processes

A major effort to search for the presence of neutral currents in nuclei is presently underway. The question of whether neutral currents play a role in the purely hadronic weak interaction and, if so, whether they are parity-non-conserving, is an interesting one. One of the most successful modern weak interaction theories is that of Weinberg and Salam, which predicts substantial contributions from parity-violating neutral currents, whereas conventional Cabibbo theories do not. A sensitive indication of such currents is the size of T=1 parity-violating matrix elements in nuclei.

The α decay of the 0^+, T=1, 3.56 MeV state of ^{6}Li should provide a fundamental test of Weinberg-Salam theory. Using the inverse reaction, $^4\text{He}+{}^2\text{H}\rightarrow{}^6\text{Li}+\gamma$, and detecting the ^{6}Li rather than the γ ray, far higher sensitivity has been achieved than was obtained by previous workers. The non-resonant (direct) radiative capture process has now been observed for the first time (at several incident alpha energies corresponding to excitation energies in ^{6}Li between 3 and 10 MeV (see Fig. T7). At the energy of the parity-forbidden resonance (E_x=3.56 MeV), the observed continuum capture cross-section is smaller than originally expected. This enhances the sensitivity of the parity-violation measurement which is presently underway.

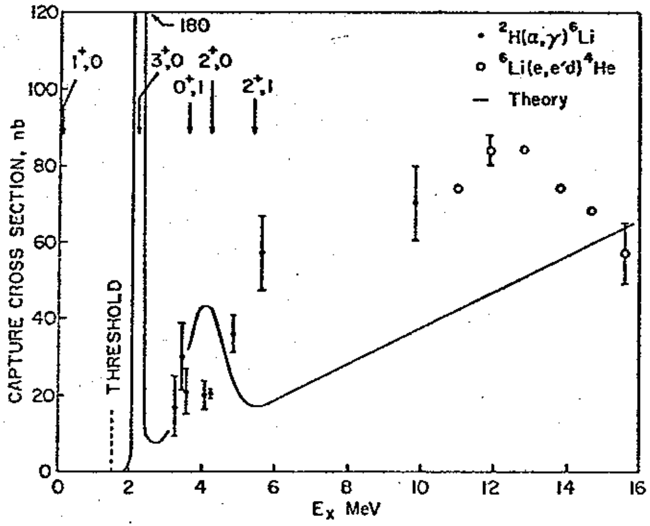


Fig. T7.--Radiative capture cross sections for ^{2}H(α,γ)^{6}Li.

II.6. Nuclear Astrophysics

The investigation of reactions with applications to astrophysics continues to be a substantial part of the program with the 50 MeV cyclotron. One extensive piece of work has involved the creation of the rare light elements (RLE) ^{2}H, Li, Be and B. Because they are so fragile the RLE cannot be formed in stars, as are most of the other elements, and some of them may be the ashes of primeval events in the universe. Experimental measurements of cross sections for production of the RLE by spallation of more common elements have been performed, with recent interest focussed on the $\alpha+\alpha$ reaction, which is an important source of ^{6,7}Li.[37] Together with work performed elsewhere at higher energies, these measurements allow the evaluation of the spallation contribution to the origin of the RLE. A simple result is apparently consistent with the observed abundances: namely that ^{6}Li, ^{9}Be and ^{10,11}B are made by the galactic cosmic rays, while ^{2}H, ^{3,4}He and ^{7}Li must be made elsewhere, probably in the primeval big bang. Assuming this is so, the abundance of ^{7}Li has been used to set an upper limit on the baryon density of the universe.[38] A value is found which is consistent with that obtained from the ^{2}H abundance, favoring an open, continually expanding universe. Future work involves additional experiments on the $\alpha+\alpha$ reactions. In a collaboration with V. Viola and his group at Maryland, the $\alpha+\alpha$ cross sections have been measured to 160 MeV, and these measurements will be extended to 320 MeV using the 500 MeV cyclotron.

Reaction rates in helium burning stars are also being studied. The rates of the two reactions $3\alpha\rightarrow{}^{12}$C and ^{12}C$(\alpha,\gamma)^{16}$O determine the relative amounts of ^{12}C and ^{16}O formed in helium burning stars and hence, eventually, in the material from which the solar system was formed. Properties of the 7.65 MeV 0^+ state in ^{12}C determine the $3\alpha \to {}^{12}C$ rate. Measurements of the more uncertain of these properties (excitation energy, radiative branching ratio Γ_{rad}/Γ and pair decay branching ratio $\Gamma_{\pi}/\Gamma)^{27,39}$ have been performed, and yield the rate with an uncertainty of only 18%, sufficient for astrophysical purposes. Unfortunately, the $^{12}C(\alpha,\gamma)^{16}O$ rate is substantially more uncertain, with values differing by a factor of at least four being consistent with the data. An attempt to reduce this uncertainty is being made through a novel approach in which the relevant parameters are obtained from the line shape for the 1^- doublet at 7.12 and 9.6 MeV, as observed in the $^{15}N(^3He,d)^{16}O$ reaction. Variation of the line shape with angle may permit a relatively unambiguous determination of the reduced α-width for the 7.12 MeV state.

II.7. Heavy Ion Studies

A number of experimental studies in the general energy range of the 500 MeV machine are presently in progress and are expected to continue for the next two years. Most of these involve the use of accelerators at Lawrence Berkeley Laboratory and collaborations with workers from Berkeley and other laboratories. A comparison of heavy ion peripheral reactions with Ar beams from energies close to the Coulomb barrier up to 200 MeV/A, is being carried out in order to investigate the rather striking similarities which have been observed between peripheral reactions induced by ^{16}O ions of energies 20 MeV/A and 2.1 Gev/A.[40] Another experiment involves the investigation of sequential fission following peripheral reactions induced by 20 MeV/A ^{16}O ions in Au and U targets. It is hoped that information about the momentum transferred to the target can be obtained by measuring the energy and angle of both fission fragments in coincidence with the projectile like reaction product.

Another collaborative experiment utilizes the Bevalac for study of subthreshold pion production in heavy ion collisions. The motivation for this experiment is given on pages 101(vi) and 101(vii) of the appended CSC proposal. The first run, using 400 and 250 MeV/A Ar beams on KCL and Pb targets, showed that the large H magnet, installed for this experiment works well as a 180° pion spectrograph. Three counter telescopes were used to detect 30, 60 and 90 MeV pions emitted near 0°. The threshold for free nucleon-nucleon pion production is 280 MeV. Hence, the 250 MeV/A data constitute the first subthreshold pion production measurement with heavy ions. The absolute values and the ratio of production at the two energies are in approximate agreement with Fermi motion calculations. During the next run, data will be taken as far below threshold as is practical, since collective effects in the process will be more important at these energies.

II.8. Proposed Research with the 500 MeV Cyclotron

Research use of the 500 MeV cyclotron is expected to begin early in 1980. Allocation of machine time will be based on a scientific merit review process in which all proposals are treated in an equivalent way, independent of whether the proposers are from MSU or elsewhere. The overall effectiveness of the research program will then key on selecting from among the large group of possible experiments those which will be most incisive in furthering our understanding of nuclei. The actual program will thus reflect the ideas of the broad national community and will undoubtedly differ significantly from plans visualized at this time.

We expect that some of the proposals from MSU physicists for use of the 500 MeV machine will include experiments which extend the present 50 MeV research programs to new regions. Examples include studies of exotic nuclei, high spin yrast line spectroscopy, giant multipole resonances and nuclear astrophysics.

In addition, we anticipate that many of the early experiments proposed for the 500 MeV machine will be based on the material described in Section III of the CSC proposal. The experiments described in Sec. III.1, "Structure of Discrete Nuclear States", for example, seem particularly well suited to the energies available from the 500 MeV machine. Resolution of individual states is an essential point in many of these studies, and the high quality beams from the 500 MeV cyclotron will be extremely useful in achieving the required resolution. (Since no stripping is involved in stand-alone use of the 500 MeV machine, beam quality should match the excellent quality presently obtained for heavy ion beams from the 50 MeV cyclotron--see pages 198-iii through 198-v of the appendix.) Studies of the nucleus-nucleus reaction process discussed in Sec. III.2 of the CSC proposal can go forward for beams with $A \leq 100$ and will be extremely valuable. Again the overall beam quality of the 500 MeV machine should make it possible to acquire more detailed information on these processes than has previously been available.

Finally, as discussed recently by Bertsch and Amsden,[41] the study of equal mass heavy ions of energies up to 50 MeV/A should reveal two new qualitative aspects of nuclear dynamics. First, the nuclei should be rather transparent to each other so that all collisions, even those with small impact parameters, should result in final states with most of the incoming energy carried as longitudinal energy of the forward-peaked fragments. Classically, there is a threshold for this central transparency which is predicted to be near 10 MeV/A. Second, the compressibility of nuclear matter when the two nuclei overlap can be related to the deflection of the fragments. At 50 MeV/A we are in a regime of fairly substantial compression ($\rho_{max}/\rho_o \approx 1.5$), and expect a reasonable sensitivity of the fragment deflection to the compressibility modulus.

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III. Accelerator Research and Development

Accelerator research and development is traditionally a major component of the research program at the MSU Cyclotron Laboratory. Originally, the major goal of this program was development of the isochronous cyclotron as a precision nuclear instrument. More recently, emphasis has shifted to development of the superconducting cyclotron with the goal of reducing construction and operating costs of large cyclotrons. A brief chronological review of the MSU superconducting cyclotron program, including a description of basic features of such a cyclotron, appears on pp. 104-106 of the appended CSC proposal. At present (June 1978), the accelerator program is largely directed to finalizing details of the 500 MeV cyclotron, with a smaller component (~15%) directed to design of an 800 MeV isochronous cyclotron, and a still smaller component directed to beam lines and experimental equipment.

Before commenting on the actual program, it is perhaps useful to restate the basis which we use for distinguishing research and development from construction. Activities which we classify as "research and development" (or "engineering", "design", etc.) range from conceptual studies of basic phenomena to detailed design of components and include preparation of construction drawings, construction of mock-ups or prototypes when these are not a part of a final device, and in general, all activities which would not have to be repeated to construct a second device using the same design. "Construction" on the other hand is all activity involved in buying, building and assembling the actual final hardware. Construction costs include internal man-hour costs for items fabricated internally, for installation of components, for supervision of these activities, etc. (and overhead and fringe benefits on all internal construction manhours), and in general all costs which would have to be repeated to construct additional copies of the same device using the same design. This basis for distinguishing between design and construction is reasonably logical, and also has the feature that "construction" costs are the directly relevant figure for anyone contemplating building a copy of the device at another laboratory.

At present, the research and development effort on the 500 MeV cyclotron is largely concerned with small details of the basic cyclotron design. The total volume of work in this category is large, reflecting the fact that a working cyclotron involves a very large number of small components not usually discussed in proposals and publications, but nevertheless essential. To handle the final wave of details on the 500 MeV cyclotron, we plan to expand our accelerator staff by a factor of about 1.5 relative to the present level. As design work on the 500 MeV cyclotron is completed, the effort of this group will shift; one segment of the group will become an operating staff for the 500, another will continue design work on the beam transport system and experimental facilities, and a third group will join the 800 MeV design team. (All of these steps are part of the overall plan presented to NUSAC and summarized in the Table on p. 212-iv of the Appendix.)

Figure T8 is a photograph of the 500 MeV magnet installed in its permanent location in the new west addition to the laboratory. The vacuum system and other components for source testing have been installed in the magnet, and the first cool-down in the new location is complete. The statements of progress prepared for the NUSAC review remain reasonably current, and we therefore refer to this material for a description of the program (appendix pp. 117-i through 117-xii, 121-i through 121-ix, 132-i through 132-ix, 139-i through 139-ii, and 145-i through 145-ix). In general, work on the 500 MeV cyclotron is going well, and we continue to feel that we can bring the accelerator into operation on the stated schedule and within the budget.

Design studies on the 800 MeV superconducting cyclotron are progressing rapidly with the full-time effort of a three-person group headed by Prof. F. Resmini. All major aspects of the design including magnet construction, trim coils, rf, extraction, and injection have now been checked in a preliminary way. A design report summarizing these results is in preparation, and several papers have been submitted to the Eighth International Conference on Isochronous Cyclotrons.

Final design work on the beam transport system for the 500 MeV cyclotron is now starting under Prof. E. Kashy. A significant conceptual change in beam transport planning is use of a beam line layout which permits beam splitting along the general lines of the system in use at GSI and that shown in the most recent Holifield Phase II plans. A well optimized beam splitter is, unfortunately, itself a rather complicated hardware system which

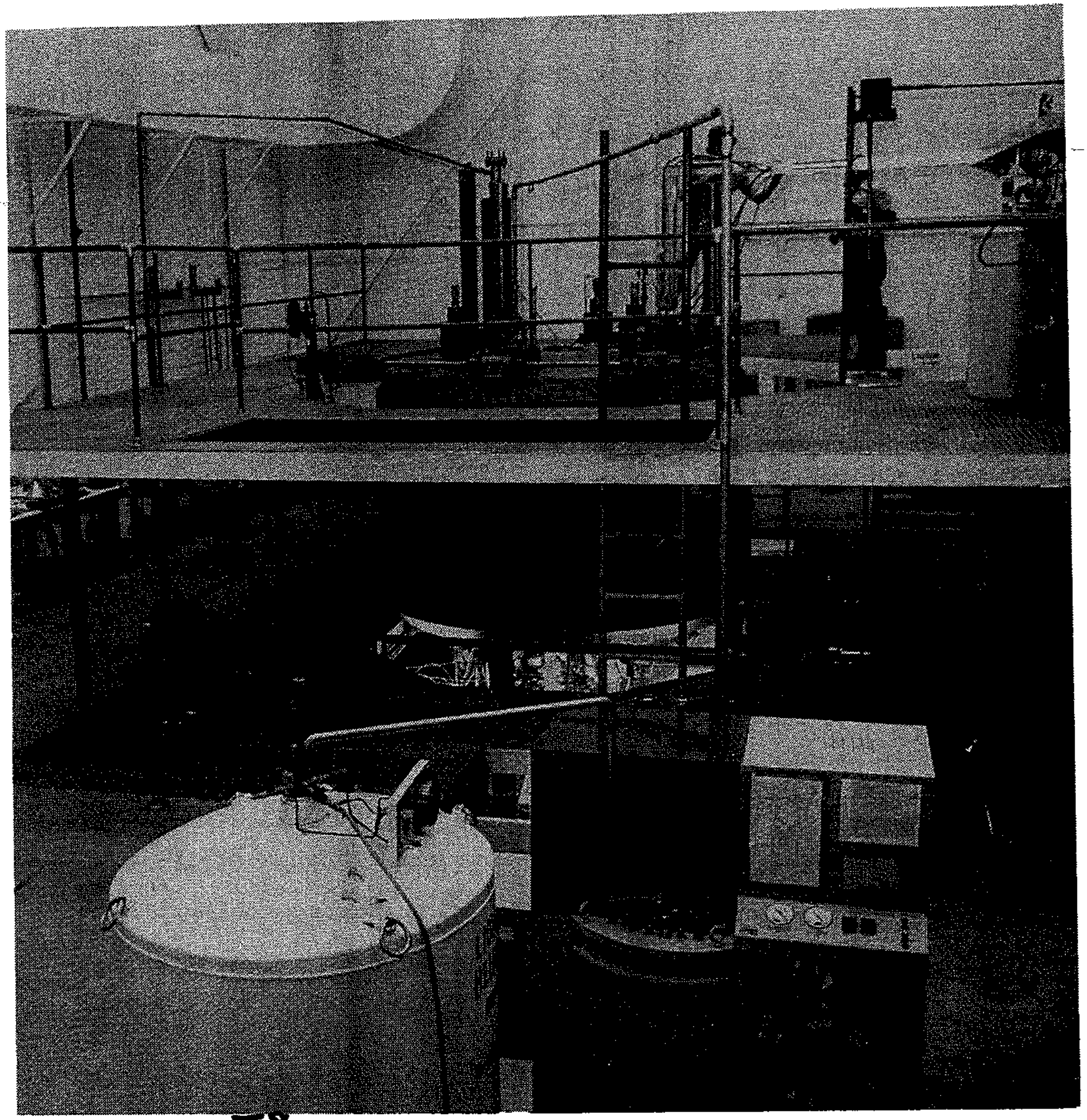


Fig. T8 ~~T1(III)~~. View of the 500 MeV magnet installed in its permanent location. Decking around the magnet terminates at the point where shielding walls will ultimately be located. The helium refrigerator is in the foreground.

will require a significant commitment of personnel, and its design involves presently unknown beam details such as the importance of beam halos. On an interim basis we have decided therefore to switch the beam, rather than split it, by using a small deflecting magnet at the splitter position. For most experiments switching is a reasonably effective substitute for splitting since the principal benefit of splitting is to allow a check-out of experimental equipment prior to run time, and shifting the beam from the "running" experiment to the "setting-up" experiment for a brief period can allow check out of equipment without seriously disrupting the running experiment. Installation of an actual splitter will proceed when personnel are available and as experience with beams in the new energy region solidifies design requirements.

The beam transport layout for the splitter/switcher system is shown in Fig. T9. Facilities are distributed on the primary branch lines according to an estimate of likely usage for each set-up, so as to make it as easy as possible to arrange a schedule in which successive runs are on different branches of the transport system tree. The arrangement shown is also compatible with the long range plan for expanded experimental facilities discussed in the CSC Proposal.

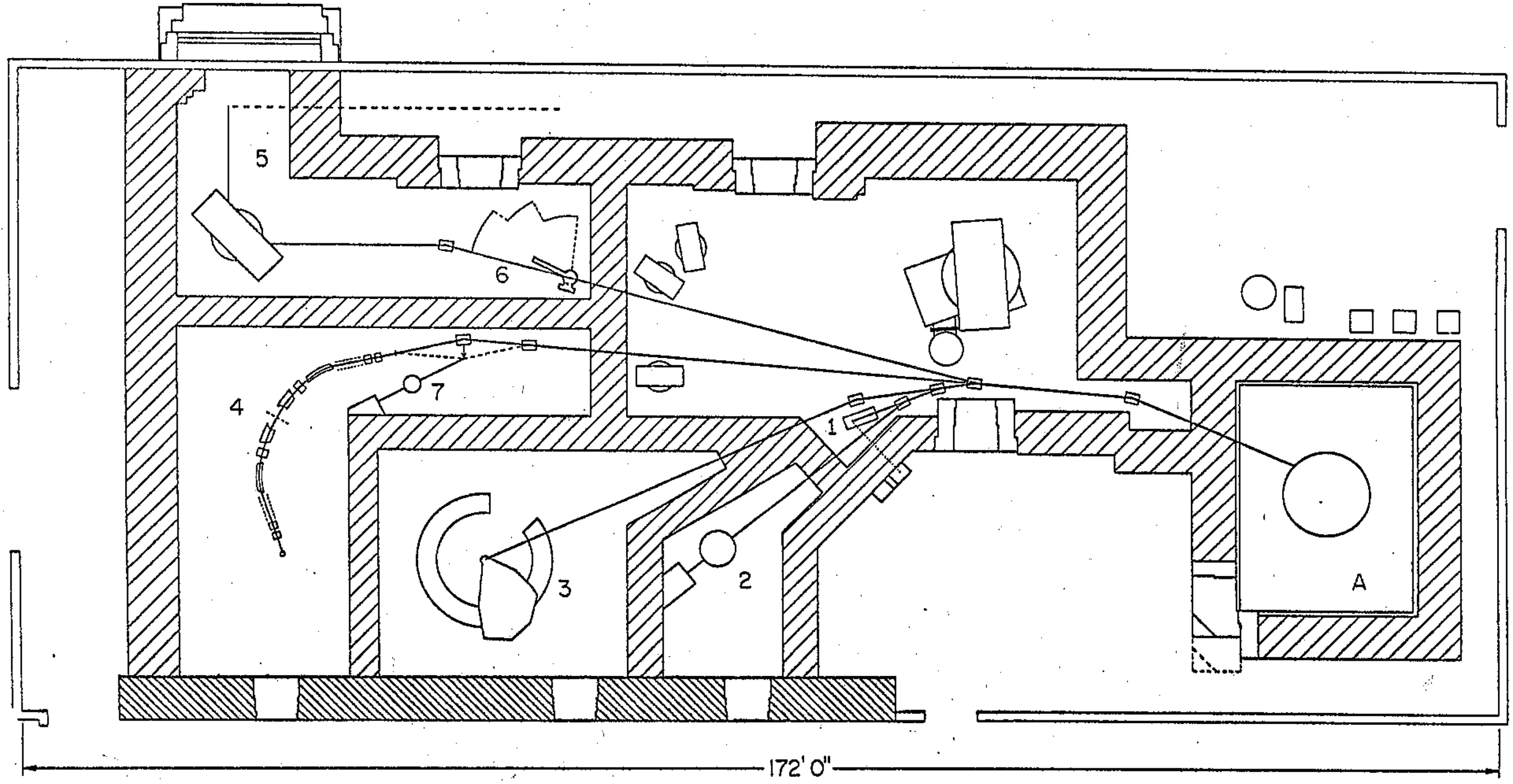


Fig. T9.--Beam lines for the K=500 cyclotron. Labeled Stations are 1) Cryogenic Helium jet, 2) 40" scattering chamber, 3) Split-pole spectrograph (K=105), 4) Reaction products mass filter, 5) Neutron time-of-flight swinger, 6) Coincidence time-of-flight chamber, 7) Gamma ray goniometer setup, including multiplicity filter. The K=500 cyclotron is labeled A and the K=50 cyclotron and the three 45° bending magnets are shown in their current position. Quadrupoles are not shown.

IV. Additional Experimental Facilities for the 500 MeV Cyclotron

The Phase I construction program approved in 1978 provides funds for completing the 500 MeV cyclotron and also for:

1) building a beam transport system with beam lines to connect the 500 MeV cyclotron to the two north experimental rooms (see Fig. T9) where our present split-pole spectrograph, 40" scattering chamber and gamma ray goniometer are located,

2) upgrading of the vacuum system in the three devices, listed above and

3) expanding the nuclear electronics pool of the laboratory.

Using these basic facilities and the existing data acquisition system of the laboratory, interesting and important experiments will be possible. The range of experiments and the number of users which can be effectively served will, nevertheless, be severely limited in comparison with what could be achieved with an expanded array of experimental equipment. Review of design characteristics of the 500 MeV cyclotron moreover leads to a judgment that it has a high probability of performing in good accord with design goals, producing unique, high quality, high energy, heavy ion beams. Beams with these characteristics will furthermore be of keen interest to a broad group of nuclear scientists. In view of this, we feel it prudent and appropriate to propose proceeding immediately with a significant increase in the experimental facilities relative to those included in the Phase I budget in order to broaden the range of experiments which can be performed with the facility and in order to allow its early use by a larger group of nuclear scientists.

The following subsections describe four major additional experimental facility items for which we therefore request funds, namely:

1) an expanded and much more powerful data-acquisition system with capability for handling the high-rate, high-complexity data expected from many experiments in the 10-80 MeV/A energy range,

2) a versatile time-of-flight coincidence chamber for performing basic exploratory studies of a broad range of heavy ion phenomena,

3) a combination gamma ray energy-sum multiplicity filter and Compton suppression spectrometer to provide a high-angular-momentum "tag" for complex events, and

4) a reaction product mass filter tailored to allow study of a broad range of heavy ion reaction products at very forward angles including zero degrees.

The budget also requests additional funds for the beam transport system and for beam lines to connect these units to the portions of the system already funded.

IV.1. Data Acquisition System

It is clear that the overall productivity of a complex nuclear science laboratory is strongly enhanced by the availability of a powerful, flexible computer facility. As a step toward such a system, we propose here to obtain an additional data acquisition computer and a "parallel processor" for use in conjunction with it and the present PDP-11/45.

The current computer configuration at the Heavy Ion Laboratory consists of an XDS Sigma-7 computer used for data analysis and general computation and a PDP-11/45 used for data acquisition. In a review of laboratory computation facilities conducted earlier this year, a sub-committee of our Sponsors Group noted that the present PDP-11/45 is utilized nearly full time for data taking, allowing little time for program development or experiment set-up and debugging, and providing no redundancy to insure against equipment failure. This committee assigned then highest priority to the addition of another data acquisition computer. The committee also pointed out that the requirements of a broad user group would best be satisfied by a data acquisition facility which was not highly specialized, but rather emphasized flexibility to meet a large variety of needs. As examples, the system should be able to process precision singles data at a high rate, process coincidence data from sophisticated detectors at a moderately high rate and handle coincidences among a very large number of relatively simple detectors.

The facility we propose is shown in Figs. T10 and T11 and consists of a control computer and a slave programmable parallel processor. Availability of third generation micro-processors with instruction times in the 2 μsec range permits the parallel processor to handle events assigned to it by the control computer with an effective speed of about 125 nsec per instruction. This approach appears more cost effective than attempting to achieve comparable processing speeds in a single computer, and allows one to greatly enhance the capability of the present PDP-11/45 by sharing of the parallel processor.

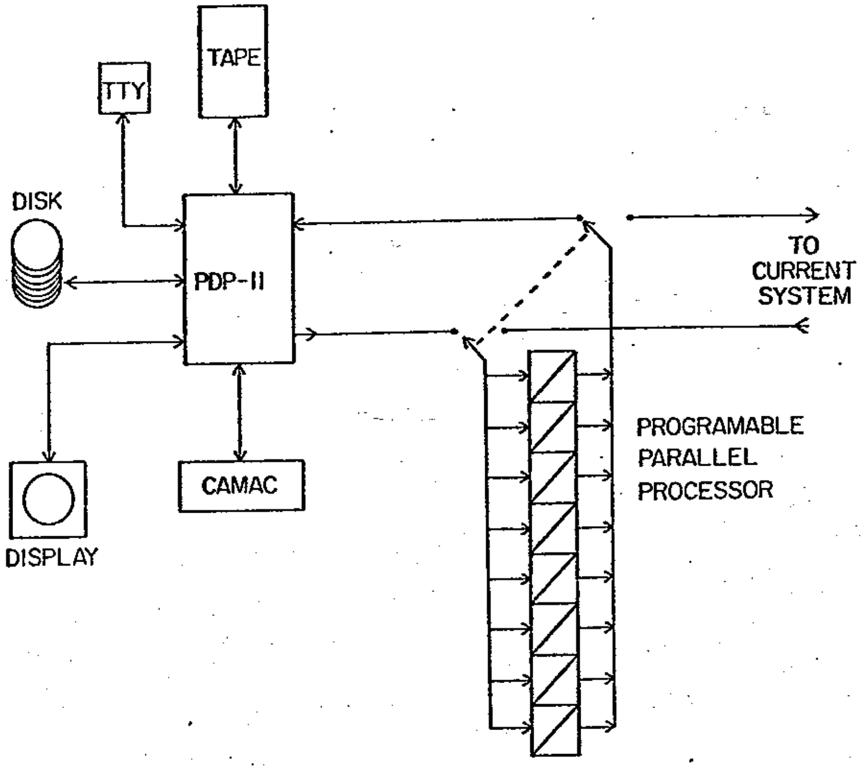
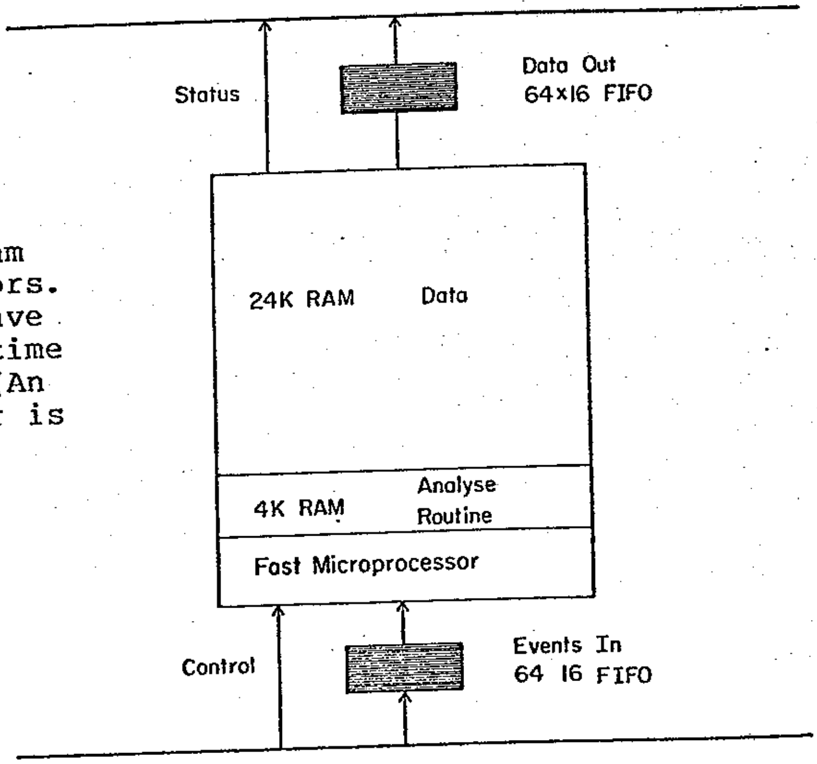


Fig. T10.--Schematic diagram of the proposed system. The programmable parallel processor can be switched to either the proposed PDP-11/70 or to the current PDP-11/45.

Fig. T11.--Schematic diagram of one of 16 array processors. The fast microprocessors have an instruction processing time of about 2 microseconds. (An example of such a processor is the upgraded PDP-11/2).



A PDP 11/70 computer has been chosen as the control computer for this system. It provides the short cycle time necessary to perform the high speed routing function and/or the substantial amounts of processing which will be required by some complex experiments and data analysis routines. The multiple high speed busses of the 11/70 serve to reduce interference between processing and I/O during high rate operation and permit the later addition of high speed data storage units such as fast disks or 6250 BPI tape drives. Advantages of the overall approach include:

a) Direct computer processing of data is normally much slower than hardware add-one-to memory systems. The proposed system recovers much of this speed loss and provides the flexibility of direct processing at a reasonable cost.

b) The system can be implemented from essentially off-the-shelf hardware, greatly reducing the load on a computer group which will also be strongly involved in design and construction of control systems for the 500 MeV cyclotron.

c) The main computing power is contained in a switchable unit, the parallel processor. Consequently only one of these is required. During debugging mode, when data are being taken by another computer using the parallel processor, its effects can be mimicked by software.

d) The addition of the parallel processor greatly improves the capability of the current PDP 11/45.

e) Large amounts of core storage (16x28K+128K) are available.

f) The parallel processor is easily expandable.

g) Currently operational software would not have to be rewritten--only the basic processing loop must be moved to the parallel processor.

Several modes of operation will be described to illustrate the capability of the proposed system.

a) Singles: Each input datum is acquired by the control computer and transferred to a particular slave CPU of the parallel processor, with the choice of CPU based on the type of event. The slave CPU processes this event fully and stores it in its spectrum area. Capabilities of clearing, modifying, starting and stopping the individual CPU are available. Should one data stream have very high rates, this flexible processor allows two or more parallel CPU's to be assigned to it, utilizing the speed advantage of the processor. Processing rates of over 200,000/sec, with gating functions, should be possible.

b) Coincidence: All data are acquired by the master CPU and transferred in parallel to the processor CPU's, each of which would process a part of the input data. For example, if the experiment involved 16 particle telescopes, a single telescope would be assigned to each processor CPU and its spectra would be stored in that CPU's data area. Up to five 64x64 arrays could be stored for each telescope. The spectra could be read out upon command from the master CPU for display or storage on disk or tape. Processing rates of over 100,000/sec with particle identification should be possible.

c) Mixed: In this mode of operation there is a mixture of (a) and (b) modes. To effectively deal with this an assignment of different parts of the processor to modes (a) and (b) is made.

d) Computational: In this mode each event requires substantial processing of all of its parameters as a group. In this case the control computer would pass all data for the first event to the first processor CPU, the second event to the second CPU, etc. Each CPU then processes its event and stores the spectrum in its data memory. The total spectrum is assembled by reading and summing the partial spectra from each CPU memory. An alternative is to store the data in a list in the slave CPU for later transfer to the control computer for processing.

The budget also includes funds for disk storage of programs and data, with disk size based on MSU and BNL experience; an 800/1600 BPI tape drive to provide relatively high speed event recording capability and to interface with drives available in most nuclear physics laboratories; a CAMAC system with crate branch driver; and finally a graphic display unit.

IV.2. Time-of-Flight Coincidence Chamber

There is significant interest in studies of the "macroscopic" features of heavy-ion reactions over a wide range of energies. Important information about the energy dependences of peripheral heavy ion collisions, deeply inelastic processes and fusion reactions can be obtained from single-particle inclusive experiments. Such experiments are particularly interesting in the transition region of a few tens of MeV/A, where the relative velocities of the colliding nuclei are comparable with the Fermi velocity of nucleons bound in nuclei. For these (and other experiments, such as elastic scattering and few nucleon transfer reactions), a complete (Z and A) identification of the reaction products is desirable. Furthermore, it is necessary to detect a wide range of particle types and energies to efficiently map out the energy and target dependences of isotopic cross sections and the overall spectral shapes. Often, measurements at small scattering angles are required as, for example, for the detection of evaporation residues surviving fusion reactions or for the investigation of peripheral reactions at the highest obtainable energies when the angular distributions are peaked at very forward scattering angles.

A valuable experimental technique for studying these processes involves a combination of time-of-flight and ΔE-E techniques.1) At the higher energies available with the 500 MeV cyclotron, flight times are of the order of 10 ns per meter of flight path. Long flight paths will therefore be needed to obtain mass resolutions of a few percent. We propose to construct a sliding seal scattering chamber2) for such measurements as sketched in Fig. T12. This design has the following characteristics:

1) Flight path variable (up to 5 m at forward angles.)

2) Scattering angle (for the time-of-flight telescope) continuously variable from -10° to $+100^{\circ}$ and $+35^{\circ}$ to 145°. The small negative angle capability is very useful for the determination of the 0° position with respect to the beam.

3) Good vacuum. ($\approx 4\times10^{-7}$ is obtained in a similar chamber at the Max-Planck-Institute in Heidelberg.)

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2) C.K. Gelbke, Nucl. Instr. and Meth. 128,175(1975).

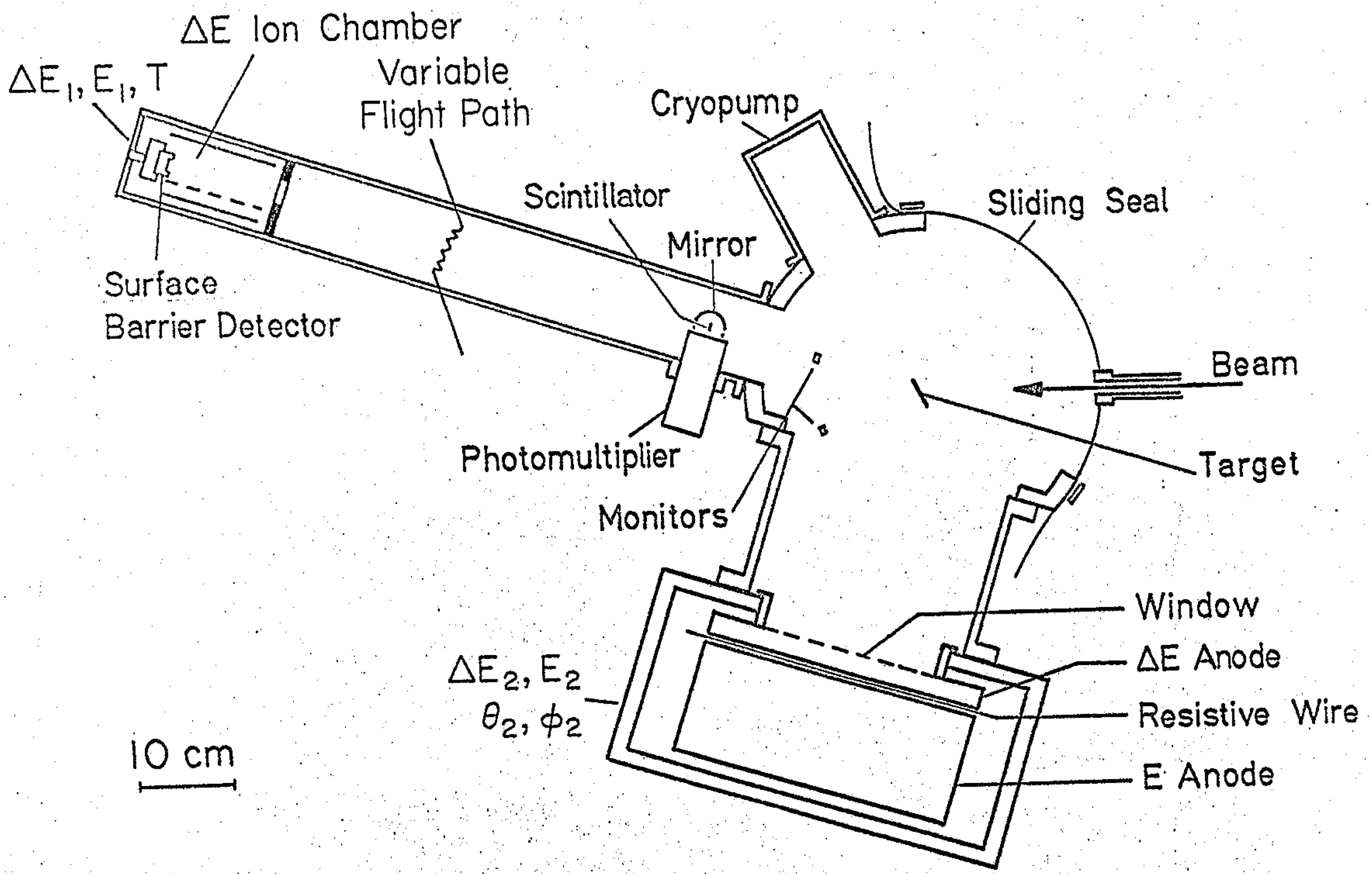

Fig. T12.--Schematic view, approximately to scale, for time-of-flight coincidence chamber.

4) Large window (30x30 cm^2) for the efficient installation of detectors to be operated in coincidence with the time-of-flight telescope. (Shown as an example in the figure is a large ΔE-E ion chamber[3] with two-dimensional position readout.)

5) Large windows (10x10 cm^2) for mounting the time-of-flight telescope. This leaves open the possibility of using large solid angle gas detectors for special experiments with low count rates.

The initial detector configuration for the chamber will include the following:

1) ΔE-E time-of-flight telescope consisting of a ΔE ion chamber and an E solid state detector, with an E ion chamber as an alternative for lower energies and/or for heavier reaction products, and

2) standard timing detectors, consisting of thin scintillator foils and avalance gas detectors, with a secondary electron channel plate detector as an alternative for experiments with very low energy threshold requirements. Coincidence detectors will, for the present, be deferred since these units generally involve special features tailored to meet specific research goals, and designs are best developed after actual beam experience.

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[3] C.K. Gelbke, et al., Nucl. Phys. A269,460(1976).

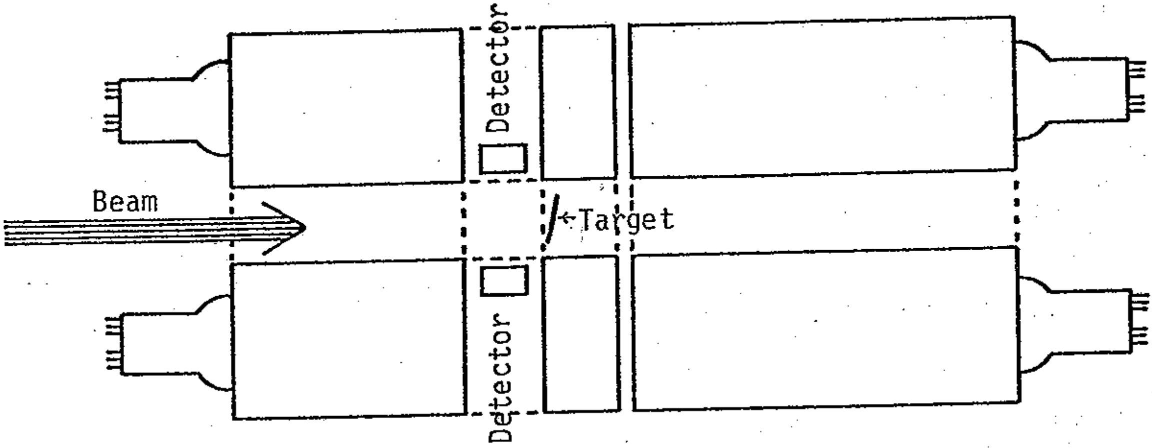
IV.3. Combination Multiplicity-Filter and Compton-Suppression Spectrometer

Heavy-ion induced processes are often accompanied by large angular momentum transfer, particularly in compound nuclear reactions. The amount of angular momentum in the residual system can be of interest either for an understanding of reaction mechanisms, as in deep inelastic scattering, or as a "tag" to select for study a particular deexcitation channel in spin-energy space.

For detailed investigations of such processes, multiple detector arrays have often been used to determine the multiplicity of γ rays emitted in the deexcitation of reaction products; the γ ray multiplicity is directly related to the angular momentum change. Recently however, Herskind and collaborators at the Niels Bohr Institute have demonstrated the utility of a simpler device of broad applicability for selecting deexcitation channels of a particular energy and angular momentum. In this device a large NaI(Tl) crystal surrounds the target (or reaction recoil products) and serves as a total-γ-ray-energy-sum spectrometer, a kind of γ ray energy "calorimeter". In general, high γ ray multiplicity (and high ℓ) events will also be accompanied by the greatest total γ ray energy release. By selecting the higher energy portion of the γ-ray-energy-sum spectrum in the NaI(Tl) detector, one has a simple, effective method for "filtering" out high angular-momentum events for study.

Although details of the final design will be influenced by research developments and experience in the next several months, a two-crystal approach allows numerous experimental possibilities and seems to provide the most flexible design concept. In the energy-sum mode, two large (e.g. 13"x13"), sectored NaI(Tl) crystals with axial bores two to three inches in diameter (for the beam line and target chamber) are operated in tandem (see Figure T13). A radial bore near the end of the first crystal permits coincident operation of one or two Ge(Li) detectors for spectroscopic studies. The second crystal is placed coaxially with, and downstream from the first to complete the energy sum configuration. Specifications for both crystals would be similar. Each of the two NaI(Tl) crystals would be split into four light tight sectors to allow for rough multiplicity

Fig. T13.--Cross sectional view of 2-crystal γ-ray-energy sum spectrometer in one possible operating configuration. In this mode two detectors (e.g. Ge(Li)) are shown in the radial bore.



selection in addition to the energy sum feature. Each crystal can also operate independently as a Compton-suppression spectrometer in a number of in-beam or off-beam configurations when used in conjunction with a Ge(Li) detector in either the axial or radial position. A 13"x13" NaI(Tl) crystal should achieve at least 95% suppression of Compton events produced by 1.33 MeV γrays.

In summary, the capabilities of a γ-ray-energy-sum multiplicity filter and a Compton suppression spectrometer can be incorporated into the general design concept of two large NaI(Tl) crystals. Such a device seems to provide great flexibility for anticipated experiments on the transfer and disposition of high angular momentum in heavy-ion induced reactions.

IV.4. Reaction Product Mass Filter

The main yield of reaction products from fusion and deep inelastic processes is in the forward direction for the beam energies and projectiles of the 500 MeV cyclotron. To study these processes and particularly their reaction products we are planning an electromagnetic filtering device with the following design goals:

a. Angular range of 0°-15°, achieved by deflection of the incident beam.

b. Solid angle =2 msr

c. m/q resolution =0.2% at an intermediate focal plane

d. Acceptance in momentum, velocity, and mass =5%

e. Maximum rigidity =2.4 Tesla-m (67 MeV/amu, N=Z=q).

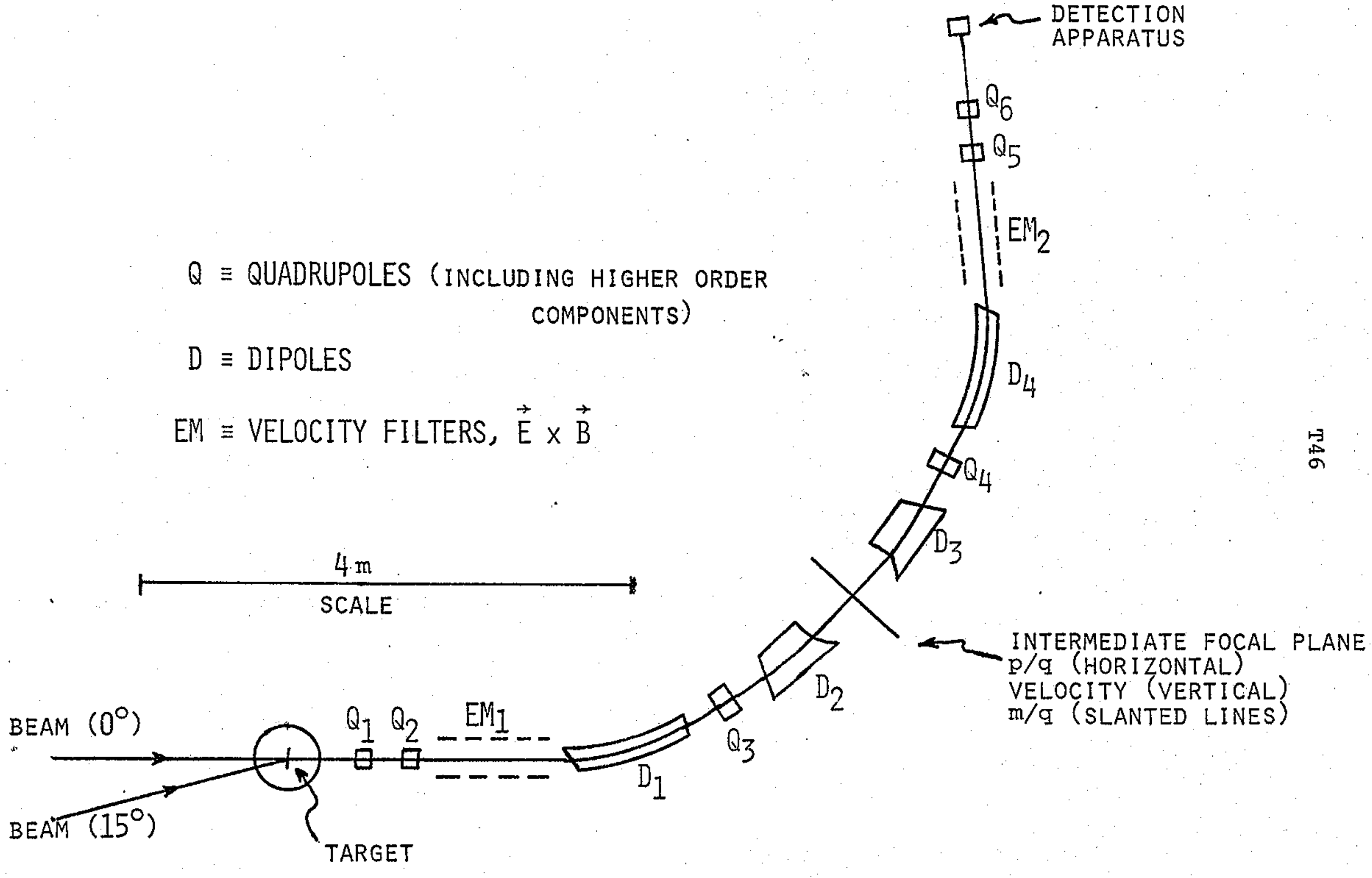
The present design is symmetrical about an intermediate focal plane, each half of the device consisting of three quadrupoles (of a special design which includes higher multipole terms) and two dipoles in addition to an electromagnetic velocity selector, as shown in Figure T14. The final design parameters are now being closely studied with the assistance of Prof. H. Enge as a consultant. The use of two existing dipoles will help to reduce the cost.

The main purpose of this device is to collect in a small spot separated products of nuclear reactions, particularly product nuclei far from stability. For example, compound nucleus reactions followed by evaporation result in a somewhat broad range of energies but a narrow range of angles. To study ^{36}Ca, for example, one could use the reaction

$$^{12}C+^{28}Si\rightarrow^{36}Ca+4n$$

The most favorable beam energy and projectile target combination would be chosen by means of evaporation codes like ALICE. Making the projectile heavier than the target will enhance the 0^{o} yield. A reasonable fraction of the ^{36}Ca's produced will be swept forward into the 2 msr solid angle. A slit placed in the intermediate focal plane will allow ^{36}Ca ions with a reasonable range of momenta to be refocussed onto a detection apparatus which provides information such as time-of-flight, dE/dX, and E.

REACTION PRODUCT MASS FILTER



Q ≡ QUADRUPOLES (INCLUDING HIGHER ORDER COMPONENTS)

D ≡ DIPOLES

EM ≡ VELOCITY FILTERS, $\vec{E} \times \vec{B}$

Fig. T14.--Schematic view of reaction product mass filter.

Other interesting possibilities involve more complex reactions. For example, with reactions such as ^{70}Ge on ^{40}Ca a very large number of new proton rich species in the vicinity of ^{100}Sn can be produced with good yields in fusion-evaporation[1)] reactions. Alternatively, experiments can be carried out with products of the deep inelastic processes using neutron rich projectiles and targets to produce neutron rich species. Recent work at other laboratories has shown such reactions to be good sources of nuclei far from stability, sometimes reaching as far as the neutron drip line for lighter nuclei.

Since product nuclei are focussed onto a small spot, one can plan various experiments to study these species--some examples that come to mind are beta-gamma coincidences and correlations, and delayed particle emission. One hopes then to measure the properties of chains of isotopes out to the limits of stability as has been done by the Orsay Group for Na. The first half of the device can also function as a spectrograph for many purposes, for example studies of back angle elastic scattering by means of inverse reactions and studies of forward angle transfer reactions.

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V. Budget

In the introduction (Sec. I) of this proposal a summary is given which shows a breakdown of expenditures by programmatic activity. In this section we give in addition a budget for each year which shows costs by type of expenditure. The budget for the first year of the two year period provides for approximately half of the total programmed staff growth, up to a level of 52 persons. A further addition in the second year to a total of 62 takes the staff to the level estimated in our presentation to NUSAC. Other budget items are for the most part moderately increased relative to present levels with the exception of electrical power, which we expect to remain fixed, reflecting the fact that the 500 MeV cyclotron should consume significantly less power than the 50 MeV cyclotron. A summary of costs for additional experimental facilities is also presented.

Proposed budget for additional experimental facilities

Data acquisition system:

PDP-11/70 with 88 Mb disk, 800/1600 BPI tape 75IPS, 128K words memory	$125,000
FP11/C floating point	6,000
CAMAC system with crate, branch driver control	10,000
Parallel processor, 28K words memory 11/2X CPU @9,500 each x 16	152,000
Processor interface, @1,250 each x 16	20,000
Graphic display	7,000
Total	$320,000

Time-of-flight coincidence chamber

Chamber construction	65,000
Detection system	20,000
Total	$85,000

Multiplicity filter and Compton supression

Spectrometer

Two NaI(Th) detectors	50,000
Associated electronics, mounting and shielding	10,000
Total	$60,000

Reaction product mass filter

Dipoles, quadrupoles and velocity filter	135,000
Mounting and vacuum hardware	85,000
Power supplies	25,000
Miscellaneous hardware	25,000
Total	$270,000

Beam transport and beam lines

Beam transport system	75,000
Beam lines, slits, beam plugs, viewers	35,000
Total	$110,000

Proposed Budget - MSU Nuclear Physics Program
January 1, 1979 through December 31, 1979

		NSF Man Months	BUDGET NSF	BUDGET MSU
OPERATING COSTS				
A.	Salaries			
	14 Co-Principal Investigators and Faculty Associates	33.6	103,000	206,000
	12 Research Associates	144	162,000	--
	36 Non-faculty Professionals	324	507,000	169,000
	16 Graduate Students		105,000	--
	20 Pre-Baccalaureate Students		50,000	--
	3 Secretarial/Clerical		32,000	--
	13 Technical, Shop & Other		145,000	--
	TOTAL SALARIES AND WAGES		1,104,000	375,000
B.	Fringe Benefits - 18% of non-student		170,820	67,500
C.	Indirect Costs - 69% of A		761,760	258,750
D.	Permanent Equipment: Replacement Components, Test Instruments, Special Experimental Requirements		65,000	
E.	Expendable Equipment & Supplies		156,000	
F.	Domestic Travel		32,000	
G.	Consultants		45,000	
H.	Publication Costs		21,000	
I.	Computer Costs		90,000	
J.	Cyclotron electricity		35,000	
	OPERATING SUBTOTAL		2,480,580	701,250
FACILITY ADDITIONS				
A.	Data Taking System		320,000	
B.	TOF Scattering Chamber		85,000	
C.	Gamma Ray Multiplicity Detector		60,000	
D.	Magnetic Reaction Product Filter		--	
E.	Additional Beam Transport System		110,000	
	FACILITY ADDITIONS SUBTOTAL		575,000	
GRAND TOTAL			$3,055,580	701,250

Proposed Budget - MSU Nuclear Physics Program
January 1, 1980 through December 31, 1980

		NSF Man Months	BUDGET NSF	BUDGET MSU
OPERATING COSTS				
A.	Salaries			
	15 Co-Principal Investigators and Faculty Associates	36	120,000	240,000
	14 Research Associates	168	204,000	--
	42 Non-faculty Professionals	378	639,000	213,000
	18 Graduate Students		128,000	--
	20 Pre-Baccalaureate Students		54,000	--
	4 Secretarial/Clerical		46,000	--
	16 Technical, Shop & Other		193,000	--
	TOTAL SALARIES AND WAGES		1,384,000	453,000
B.	Fringe Benefits - 18% of non-student		216,360	81,540
C.	Indirect Costs - 69% of A		954,960	312,570
D.	Permanent Equipment: Replacement Components, Test Instruments, Special Experimental Requirements		150,000	
E.	Expendable Equipment & Supplies		240,000	
F.	Domestic Travel		35,000	
G.	Consultants		55,000	
H.	Publication Costs		30,000	
I.	Computer Costs		160,000	
J.	Cyclotron electricity		35,000	
	OPERATING SUBTOTAL		3,260,320	847,110
FACILITY ADDITIONS				
A.	Magnetic Reaction Product Filter		270,000	
	FACILITY ADDITION SUBTOTAL		270,000	
GRAND TOTAL			$3,530,320	847,110

VI. Publication List

Listed here are research contributions to the open literature which have been authored or coauthored by scientists supported by the laboratory operating grant at the time the research was performed. The list is limited to papers which have appeared in print or have been submitted for publication since the compilation of the publication list for our previous operating proposal (July 1, 1975). The closing date for the present list is June 15, 1978.

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1. Spectroscopy of ^{52}Mn from the ^{54}Fe(p,^{3}He) Reaction at 40.2 MeV, A. Guichard, W. Benenson, and H. Nann, Phys. Rev. C11, 2027 (1975).

2. Masses of $T_z = -1/2$ Nuclei in the $1f_{7/2}$ Shell, D. Mueller, E. Kashy, W. Benenson, and H. Nann, Phys. Rev. C12, 51 (1975).

3. Unnatural Parity Transitions in ^{22}Ne(p,t), W.S. Chien, C.H. King, J.A. Nolen, Jr., and M.A.M. Shahabuddin, Phys. Rev. C12, 332 (1975).

4. ^{17}O(α,d)^{19}F to the $7/2^{+}$ and $11/2^{+}$ States, H.T. Fortune, L.R. Medsker, W.S. Chien, H. Nann, and B.H. Wildenthal, Phys. Rev. C12, 359 (1975).

5. Microscopic Description of Isobaric-Analog-State Transitions Induced by 25-, 35-, and 45-MeV Protons, R.R. Doering, D.M. Patterson, and Aaron Galonsky, Phys. Rev. C12, 378 (1975).

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11. Level Structure of ^{54}Mn from the ^{56}Fe(p,^{3}He) Reaction at 40.2 MeV, A. Guichard, W. Benenson, and H. Nann, Phys. Rev. C12, 1762 (1975).

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15. The $^{34}S(p,t)^{32}S$ Reaction, H. Nann and B.H. Wildenthal, Phys. Rev. C13, 1009 (1976).

16. Measurement of the Mass of ^{8}C by the $^{14}N(^{3}He,^{9}Li)$ Reaction, R.G.H. Robertson, W. Benenson, E. Kashy, and D. Mueller, Phys. Rev. C13, 1018 (1976).

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41. Inelastic Scattering of 40 MeV Protons from ^{24}Mg: (I) Natural Parity Transitions, B. Zwieglinski, G.M. Crawley, H. Nann and J.A. Nolen, Jr., Phys. Rev. C17, 872 (1978).

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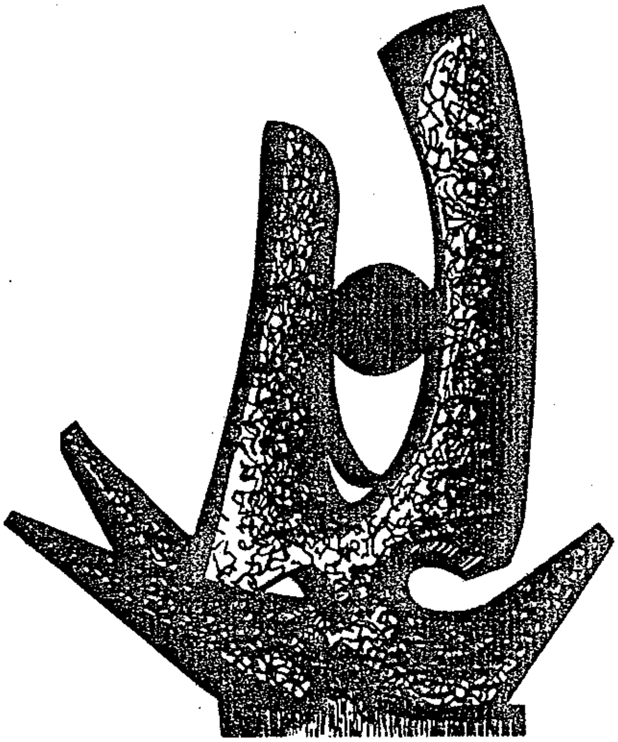
APPENDIX

CYCLOTRON LABORATORY

EAST LANSING, MICHIGAN

Proposal* for a
National Facility for
Research with Heavy Ions
using
Coupled Superconducting Cyclotrons



September 1976

MSUCL-222-A*

*Including Feb. 1978 Addendum

FEBRUARY 1978 UPDATE

of

PROPOSAL FOR A NATIONAL FACILITY

for

RESEARCH WITH HEAVY IONS

USING

COUPLED SUPERCONDUCTING CYCLOTRONS

prepared for the
FACILITIES SUBCOMMITTEE
of the
NUCLEAR SCIENCE ADVISORY COMMITTEE

East Lansing, Michigan

Introductory Comments--February 1978

This document responds to an urgent request from the National Science Foundation asking that we provide a description of plans for future nuclear facilities for review by the Facilities Subcommittee of the Nuclear Science Advisory Committee. In order to provide this material on the schedule requested, we primarily utilize the "Proposal for a National Facility for Research with Heavy Ions Using Coupled Superconducting Cyclotrons". This proposal, which we often refer to as the CSC proposal, was submitted to the National Science Foundation by Michigan State University in September 1976 on behalf of a sponsoring group of midwestern scientists. On the whole, the description of plans contained in this proposal is up-to-date. In those areas where significant developments have occurred in the 18 months since the proposal was submitted, addenda have been prepared--these are inserted in the proposal at the end of various sections or subsections (usually on yellow pages).

One of the major developments reviewed in the addenda is the successful operation of the 500 MeV superconducting magnet; results from a program of detailed studies of the magnet are in excellent accord with design requirements. The addenda also reflect the NSF decision of August 1977 to proceed with construction of a complete 500 MeV cyclotron including necessary beam lines to connect the cyclotron to present MSU experimental equipment. This action then changes the scope of the national facility proposal in that it now becomes a proposal for an 800 MeV post-accelerator to be added to the 500 MeV cyclotron, including expanded experimental areas and new experimental equipment appropriate for a research program matched to the capabilities of the coupled cyclotron system. The Section V addendum gives revised budgets reflecting the change in scope and updated to reflect 1978 cost factors. The schedule is changed to reflect what we understand to be the present earliest possibility for funding. We also briefly update the proposed research section of the proposal although the burgeoning status of heavy ion science makes it very difficult to do this comprehensively in a brief addendum.

PROPOSAL

to the

NATIONAL SCIENCE FOUNDATION

for a

NATIONAL FACILITY

for

RESEARCH WITH HEAVY IONS

using

COUPLED SUPERCONDUCTING CYCLOTRONS

submitted by

Michigan State University
East Lansing, Mich. 48824

H.G. Blosser
Director, Cyclotron Laboratory

R.E. Wilkinson
Vice President for Business
and Finance

Scientific Sponsors

This proposal is scientifically sponsored by the undersigned. Signatures convey individual intent to participate in the further planning of the facility, in the management of the facility, and in the use of the facility for furthering scientific knowledge.

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Addendum to Sponsor List:

Professor S.L. Blatt of Ohio State and Professor J.J. Kolata of Notre Dame are additions to the group of sponsors. Professor R.G. Arns, formerly of Ohio State (now Vice President at the University of Vermont) has resigned as a sponsor.

Heavy-Ion Facility Proposal

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Symbol on front cover: Silhouette of Metamorphosis,
Subrata Lahiri, 1965

Metamorphosis is a bronze sculpture which for many years has been the centerpiece of the front quadrangle of the MSU Cyclotron Laboratory. The sculpture was donated to the Laboratory by Mr. Subrata Lahiri, who worked as a student employee at the Laboratory while carrying out Ph.D. studies in the Art Department. Mr. Lahiri's small stature made him the ideal "caliber" for working between the pole pieces of the cyclotron during the construction period.

I. Introduction

This proposal requests a grant of $13,000,000 from the National Science Foundation for construction of a Coupled Superconducting Cyclotron (CSC) facility for nuclear science research using heavy ions. The proposed facility will be national in character and will provide a forefront capability in the 1980's for United States scientists working in nuclear physics and chemistry and associated fields. User access to the Laboratory will be based strictly on scientific merit without regard for institutional affiliation. Operational management of the laboratory will proceed under the guidance of a national user's group following the pattern now typical for major scientific facilities.

The proposed accelerator system will exploit a promising new accelerator, the superconducting cyclotron. Ion beams will have maximum energy ranging from 20 MeV per nucleon for uranium ions to 200 MeV per nucleon for nuclei lighter than calcium. The details of anticipated projectiles, energies, and currents are indicated in Fig. 1. This range of operating energies ensures that research with heavy ions can be expanded in scope and quality in the energy regions presently of interest and extended smoothly to higher energies above the constraints of Coulomb repulsion, surface interactions, and normal density. At these higher energies, qualitatively new aspects of nuclei--high-density phenomena, supersonic phenomena, coherent mesic phenomena--can be investigated.

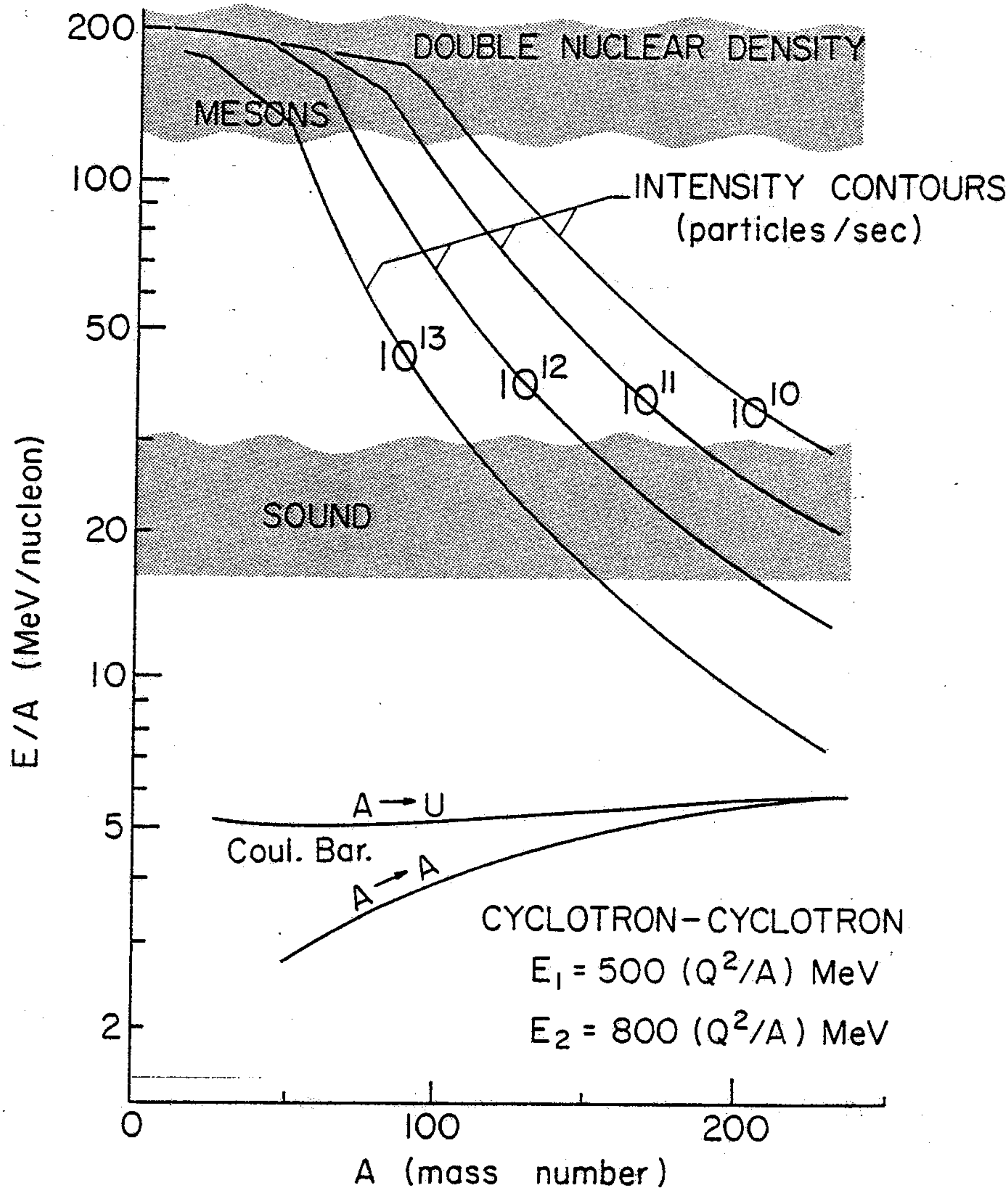

Fig. 1(I).--Intensity contours versus energy per nucleon and mass number for the proposed CSC accelerator system. The intensity contours assume an external beam from the first cyclotron approximately matching present performance of existing cyclotrons (as discussed in Sec. IV.1.3), and include all expected loss factors. The figure shows the overlap of the operating ranges with expected phenomenological thresholds, namely the onset of nuclear compressional waves in the vicinity of 20 MeV per nucleon and multiple meson production (involving possible coherent phenomena) at around 140 MeV per nucleon which also coincides with estimates of the energy at which the nuclear density is double.

Fundamental and exciting additions to scientific knowledge are expected from study of this novel nuclear realm, as has been discussed extensively during the last two to three years in reports of various study and review groups. These reports have recognized heavy-ion science as the major qualitative frontier in nuclear physics, involving new classes of phenomena as well as greatly expanding the range of conventional nuclear studies by allowing exploration of large numbers of new nuclei. Heavy-ion science was thus ranked as the highest priority nuclear physics endeavor in the Bromley Report. Scientific decision-makers in other countries clearly also share this view as is evidenced by the large investments in heavy-ion facilities taking place throughout the world.

Two major new U.S. heavy-ion facilities have already been proposed, referred to as Oak Ridge Phase II and SuperBevalac. Even if both of these major proposals are funded and expeditiously carried to completion, the U.S. will rank far behind other nations in heavy-ion facilities per active scientist or per total population. U.S. heavy-ion work will then continue to be <u>severely facility limited</u> even with both SuperBevalac and Oak Ridge Phase II. (A heavy-ion facility, in contrast with a high-energy facility, can generally sustain only a few concurrent experiments because (a) there is more difficulty in splitting the beam, and (b) major interest is usually in the primary beam rather than in secondary beams.) A major portion of the community of

U.S. nuclear scientists will thus not be able to participate in heavy-ion research in the future unless additional facilities are constructed. The heavy-ion laboratory proposed here will significantly add to the available national capability and will therefore give better balance to U.S. scientific effort and make it more competitive on a world scale.

The proposed East Lansing facility also has a special advantage in being qualitatively different from other U.S. facilities. The energy range is higher than Oak Ridge Phase II, and precision and intensity are much higher than SuperBevalac. The proposed facility is also based on a different accelerator technology, the superconducting cyclotron. On the national scale this has the advantage of broadening the technical basis of the heavy-ion accelerator program and therefore making the national program less vulnerable to possible unforeseen technical difficulties in any particular accelerator system.

The coupled superconducting cyclotron system offers multiple technical advantages, including substantial economies in power consumption and capital outlay, while retaining excellent quality, precision, convenience, and reliability. The first of the proposed pair of superconducting cyclotrons, the injector cyclotron, has a product of field and radius corresponding to $E=500\ Q^2/A$ MeV, and incorporates the prototype superconducting magnet now being constructed at MSU. The second cyclotron is a larger version ($E=800\ Q^2/A$) of the same basic design. Since the magnet for the injector cyclotron is already well along in construction it will come into operation significantly before the remainder of the facility; the building and experimental equipment are arranged so that experiments with this cyclotron can begin immediately with the dual goal of pursuing interesting topics of science accessible in the injector energy range and developing and testing experimental equipment for the full laboratory. Fig. 2 shows the performance expected from the first stage cyclotron.

The proposal involves utilization of the research areas and equipment of the present MSU Cyclotron Laboratory with expansion of the existing building to both east and west as shown in Fig. 3. The small west extension of the building is designed to be built quickly without disturbing existing experimental areas and would house the injector cyclotron. Beams from the injector can then feed to existing experimental rooms as soon as the injector comes into operation. The second cyclotron would be installed in the place now occupied by the present cyclotron, a location which allows effective use of all existing experimental areas in addition to the new experimental areas to the east (the present cyclotron will be offered for transfer to a facility approved by NSF). The expansion of building and experimental areas would approximately double the total laboratory size. Total floor space (old plus new) would be 70,000 square feet, 35% of which would be the high-bay experimental areas. Major new ancillary facilities include a recoil-mass spectrometer, a superconducting reaction-product separator, and a large new spectrograph with mass-energy product 800. The facility will also utilize the existing MSU spectrograph with

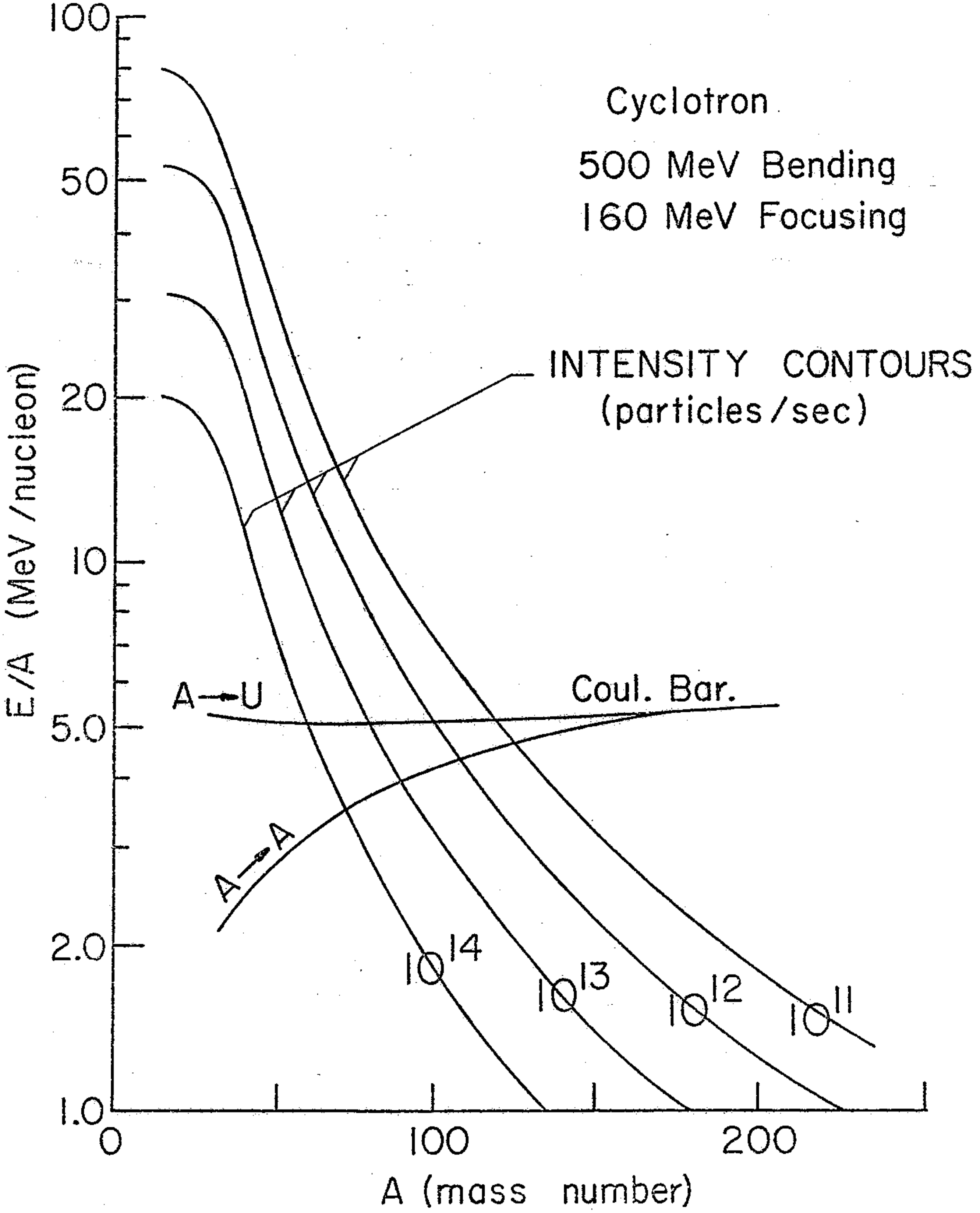

Fig. 2(I).--Intensity contours versus energy per nucleon and mass number for the 500 MeV cyclotron with a central ion source. The intensity contours are a smoothed approximate fit to heavy ion intensity data from existing cyclotrons (as discussed in Sec.IV.1.3).

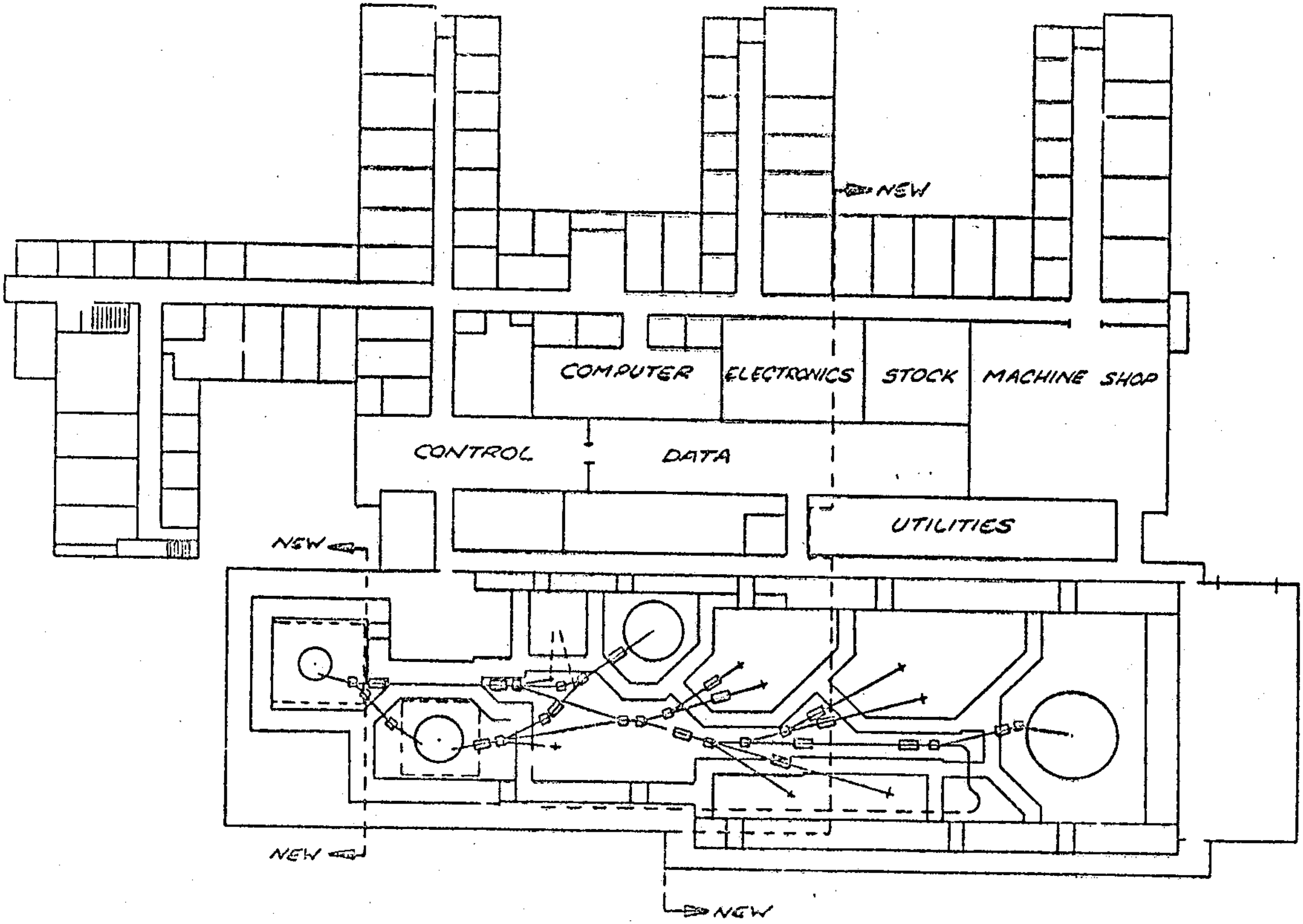

Fig. 3(I).--Plan view of the MSU Cyclotron Laboratory and proposed additions. The 500 MeV first stage cyclotron would be housed in the small west addition at the lower left of the figure. The much larger east addition would double the available experimental area and would also provide large added areas for offices, laboratories, and shops.

mass-energy product 90, the existing neutron time-of-flight facility, and numerous other items of present equipment.

From interactions with colleagues here and elsewhere, we sense broad agreement on the high intrinsic interest of the fields of research opened by a facility with the chacteristics proposed. It also seems generally accepted that the successful testing of the MSU prototype magnet will establish the superconducting cyclotron as an unusually attractive device for reaching the desired accelerator performance goals. The main question from fellow scientists regarding this proposal is whether East Lansing, Michigan is an effective and appropriate site for such a facility. In view of the central importance of this question we review here our own weighing of the advantages and disadvantages of this site before proceeding with descriptions of the facility and its research use.

Generally the record of universities in constructing and operating major scientific facilities is a mixture of pluses and minuses. But the issue for <u>this</u> proposal is, of course, not whether universities tend in general to be either good or bad on technical projects; rather the issue is whether the <u>specific site and technical group proposed here</u> is good--good in the sense of offering a high probability that the project will proceed smoothly and efficiently through its construction phase and end up as an effective facility for reaching the desired research goals. We feel our proposal is an excellent choice when measured against this criterion. The following subsections review major points relevant to this conclusion.

I.1. Qualifications of the accelerator group

The MSU Cyclotron Laboratory has the balanced team of engineers and scientists needed for construction of optimized major scientific facilities; the laboratory is in fact widely noted for its technical expertise. Major previous projects include the present MSU cyclotron, the high-resolution spectrograph system and the timesharing computer system. The accelerator system proposed here does not constitute a qualitatively larger design, construction or operating effort than the present MSU cyclotron and associated facilities. (Specifically, the present proposal is about twice as large a project--the qualitative difference in the new laboratory lies in its much greater importance to the total U.S. community of nuclear scientists.)

The present accelerator group is basically the same team which conceived, constructed and operates the exceptionally reliable and precise MSU cyclotron system. (It is perhaps also relevant to note that construction of present facilities was accomplished in close accord with original schedule estimates and budget.) It is this group, strengthened by the experience gained on the earlier cyclotron project, which proposes to build the new accelerator.

Over and above the past record of the accelerator group is the fact that they, and the group at Chalk River, have pioneered in the design of superconducting cyclotrons. East Lansing is thus at present the U.S. center of superconducting cyclotron expertise. This proposal is predicated upon the successful testing of the prototype superconducting magnet and the consequent validation of the superconducting cyclotron as an exceptionally desirable device for heavy-ion acceleration. This important technological innovation can be most efficiently exploited by continuing and augmenting the efforts of the existing MSU accelerator team.

In addition, if the operation of the cyclotron is put in the hands of the East Lansing group as proposed here, one can envisage a continuing evolution and improvement in the capabilities of the instrument which would be less likely if the instrument were transferred elsewhere and operated by a group lacking familiarity with the intricacies of the design. Interaction between those who design and build an accelerator and those who use it in their experimental research is a key element in the evolution of any accelerator; users then are able to obtain thorough information on the intrinsic capabilities and best modes of performance of the accelerator. In turn, the users provide the accelerator's builders with a continually expanding body of data on both existing and ideal performance characteristics; from this feedback, the day-to-day reliability and convenience of operation continually improve. The present pattern of operation of the MSU Cyclotron Laboratory is an excellent example of the effectiveness of this continued interchange between builder and user. In this process the ultimate performance characteristics of the cyclotron and related systems have been extended far beyond the originally anticipated goals. The laboratory plan which we propose here should ensure the same evolution for the superconducting cyclotron facility.

I.2. Strengths in nuclear science

The local group of scientists is an element of key importance in the overall effectiveness of any facility; this group must carry most of the burden of designing and debugging innovative experimental equipment so that outside users find facilities which are both technically advanced and ready to use. The MSU nuclear science group is an ideal match to what one desires from a local group, namely large, vigorous, and productive, and with an unusually strong tradition in development of forefront nuclear facilities. The nuclear science strength of this proposal is further enhanced by the skill and experience of scientific sponsors from outside MSU. Taken together, the total group of sponsors (local and regional) has broad relevant experience with a variety of accelerators, projectiles and detection systems. (Many of the sponsors are not presently working on experiments using heavy ion beams, reflecting experimental involvements which exploit the unique capability of existing light-ion accelerators at Michigan State and other Midwestern laboratories; we do not view this as a disadvantage; a good nuclear scientist is, above all else, broadly versatile and accustomed to changing experimental techniques as new beams become available for more effectively probing nuclear phenomena.)

It is important to note that the research program on the CSC accelerator will be totally novel in many aspects and involve experimental problems without close analogs in the programs of existing laboratories, either those emphasizing studies with light ions or those concentrating on studies with heavy ions at lower energies. Solution of these problems will demand creative innovation based on knowledge of the widest possible range of experimental techniques. Selection of staff for such a facility most importantly keys on whether a group is imaginative and effective in the type of experiment they are doing, rather than on whether the group is presently working with the same or different projectiles. We feel the local and regional sponsors of this proposal have clearly demonstrated the experimental skill and imagination which one desires from the staff of such a facility.

An additional important point regarding the local staff is that Michigan State University has programmed a new full professor position in nuclear science to be filled during construction of the proposed facility. This position would be at the highest MSU salary level and would be tailored to attract a highly productive senior heavy-ion scientist. The individual would then be available to participate in final detailed planning of experimental facilities. With all these factors we feel our proposal reflects outstanding staff capability in nuclear science.

I.3. MSU as sponsoring institution

The sponsoring institution, Michigan State University, has for many years given strong support to nuclear science, and as a part of this proposal affirms its commitment to continue this support and to make increases such as indicated above. Michigan State University in addition has the advantage of being a large public institution with relatively secure sources of support for its continuing programs. MSU also has extensive relevant experience in administering projects of magnitude and complexity comparable to that envisioned here. These include both major regional and international programs and a number of large on-campus laboratories with annual operating budgets in the million dollar range. MSU is also known for its unusually flexible and innovative administrative procedures. Traditional academic administrative patterns are frequently bypassed when this can reasonably be expected to increase the effectiveness of some unit in pursuing its basic goals. (The present MSU Cyclotron Laboratory has benefited greatly from special administrative arrangements aimed at maximizing its effectiveness.)

I.4. East Lansing as a geographical location

The midwest region has a concentration of large universities with outstanding academic traditions and large numbers of faculty and graduate students. The large group of scientific sponsors of this proposal reflect the broad interest in this facility in the midwest region and assures the availability of a large nearby pool of active interested scientists and scientists-in-training. The midwest in addition is geographically centered in the country: Chicago and Detroit are easy points of access by direct flight from all points in the world, and Lansing, the capitol of Michigan, is well connected to Chicago and Detroit and to all parts of the midwest via interstate highway and air connections. Flights to

Lansing occupy two pages of Airline Guide listings; flights to Detroit 13 pages. The Lansing airport is a 15-minute drive from the Laboratory; the Detroit airport 90 minutes.

I.5. Advantages of a university site

The proposed facility would be the only one of the world's major heavy-ion facilities to be sited in a traditional university situation (as distinct from National Laboratories sited at universities). We feel that the educational and intellectual environment of a university is certain to have a major positive impact on the ultimate scientific return from the laboratory.

Another advantage of a university site is reduced cost. Several factors contribute in this area. First of all, the absence of a large management hierarchy and other factors leads to low overhead rates; the gross costs of standard units of effort such as cost/hour for machine shop time, etc., are then sizeably reduced. Secondly the pool of low-cost student labor can be an invaluable supplement if a full-time staff provides continuity; student assistants are intelligent and the pool can be quickly expanded or contracted according to the needs of the project at any given time.

Finally, the proposed on-campus location offers significant advantages in the important area of user facilities, including housing, food, transportation and social amenities. Both long-term and short-term visiting researchers (and spouses) can be housed economically in existing facilities immediately adjacent to the laboratory site. The conveniences and attractions of the physical and social environment of the campus and its immediate surroundings will be attractive to all of the laboratory's visitor-users, with consequent positive effects on morale and efficiency. In summary, location of the heavy-ion laboratory on a large vigorous university campus offers a combination of intellectual benefits and practical efficiencies, and constitutes a stimulating and satisfying place to live and work.

Summarizing our overall view as to the effectiveness and desirability of East Lansing, Michigan as a site for the proposed facility, we feel:

(1) The most effective procedures by which the proposed accelerator can be built and brought into use as a research instrument involve entrusting it to the MSU accelerator and nuclear science group, a group which has an excellent record of performance in accelerator design and construction and in the use of cyclotrons in nuclear science, and a group which leads in the study of the type of accelerator proposed herein.

(2) Michigan State University in particular has demonstrated an organizational efficiency and interest in nuclear science which makes it an appropriate host institution.

(3) A large university campus can in principle be a very advantageous site for a scientific laboratory with a national clientele. The academic strength and resources of the Midwest region and its central location make it a particularly well chosen location for a national facility.

(4) The location of the laboratory in E. Lansing centers the facility amidst the large and strong group of midwest nuclear physicists. Groups at Illinois, Minnesota, Michigan, Notre Dame, Ohio State, and Wisconsin, among others, have had excellent records of productivity and leadership in nuclear science from the very beginnings of accelerator based work. The strong interest of these groups in a heavy-ion facility has been expressed by their representatives at the series of meetings held to lay the ground work for this proposal. There is hence a substantial and talented pool of nuclear scientists with an active direct interest in using this facility.

We are thus confident that location of the CSC accelerator in East Lansing will significantly enhance the efficiency of its construction and operation and add to the productivity of its research program.

II. Organization of the laboratory

The proposed CSC heavy-ion facility will have a uniquely powerful capability in a broad range of fundamental studies; there is then an imperative responsibility to ensure that this facility will be freely available to the full scientific community. The facility should, moreover, be attractive and convenient for users. Further, and perhaps most important, the facility _must_ operate in a manner which the scientific community will consider _efficient_ and _fair_. Our organizational planning has been directed to searching for optimum organizational arrangements for reaching these goals.

This section describes a plan which we believe will accomplish operation of the laboratory in the desired fashion. These ideas are not presented with a sense of rigidity; both the sponsoring institution and the sponsoring scientists convey their continuing commitment to operate the laboratory in accord with advice from the scientific community and the sponsoring agencies. The sponsoring institution and sponsoring scientists _specifically affirm_ their willingness to negotiate _changes in organizational format_ or in _operating procedures_ whenever broadly based advice from scientists and sponsoring organizations suggests that the overall effectiveness of laboratory operation would thereby be improved. In this spirit we believe we have a high probability of reaching our goal of making the proposed CSC laboratory the most open and accessible facility in nuclear science.

The organizational format which we propose is a product of a lengthy series of discussions among a multi-university group of midwestern scientists. These meetings (which were initiated at the suggestion of scientists from the University of Wisconsin) have been going on for some eighteen months and have considered the multifaceted problem of 1) scientific rationale for a heavy ion facility, 2) optimum choice of accelerator, and 3) optimum organizational format. At the most basic levels the concepts in this proposal reflect the influence of this broad group. (The initial suggestion of two cyclotrons as the optimum accelerator system was put forward by scientists from the University of Michigan; the original suggestions as to the optimum organizational format were contained in contributions from Ohio State.)

The organizational format which we propose distinguishes between scientific management and business management. The goal of the scientific management structure is to ensure that the facility is operated on an open-to-all, scientific-merit basis and at the same time to preserve efficiency by having clear, well-defined decision-making processes. A format which we feel likely to accomplish both of these objectives is to have a broadly based panel of sponsoring scientists to fix general laboratory policies and to participate in the selection of the laboratory director; the director in turn would be given broad freedom to proceed with detailed implementation of general policies. This plan includes provisions which would make it possible for a person from any institution to be selected as laboratory director (the director in this arrangement is envisaged as being on leave from a home institution for the period of his service in a fashion similar to procedures which have worked successfully at CERN and elsewhere). There would also be a Scientific Advisory Committee and an Experiment

Selection Committee paralleling formats now in use at most major science facilities in the country. Details of all these arrangements would be formalized in bylaws to be adopted with the consent of the funding agency. Initiation of this process would be in the hands of the scientific sponsors of this proposal, with the intent to shift the composition of the group from its present regional character to a broadly national one as appropriate interest evolves.

Business management of the proposed laboratory is a support function to assist in reaching the goals of the scientific aspect of the project. Primarily then, a business management procedure should be efficient and responsive. For reasons reviewed below the sponsors have concluded that it is best to have a one-university business management arrangement; Michigan State University is proposed as the official sponsor of this project and the MSU business office would handle detailed contractual matters. (In accepting this role, MSU makes an unqualified commitment not to use its special status to favor Michigan State scientists relative to scientists from other universities. A covering letter contains detailed stipulations in this regard. The items described in the covering letter include commitments to make available the present MSU Cyclotron Laboratory and its equipment, to make available the site for the proposed laboratory, to continue present university supported Cyclotron Laboratory staff, and other items. Further, MSU is receptive to the negotiation of additional agreements consistent with the goals stated here.)

The main alternate business management arrangement, namely, some form of multi-university legal sponsorship for this proposal, seems to the sponsors to be much more cumbersome and, in fact, basically untenable at the present time. Such an arrangement in particular would require inter-university contractual agreements or an inter-university corporation, etc.; appropriate agreements would have to be negotiated by respective business officers; the present tentative character of the funding for the project makes this group generally reluctant to invest required time and money to reach such an agreement. This situation will change if funding becomes clearly probable; if a multi-university corporation is at that time viewed by the funding agency as advisable, Michigan State is ready to participate in appropriate negotiations.

Some guidance as to the comparative effectiveness of multi-university or single university contractual sponsorship can be obtained by reviewing present major scientific facilities operated under one or the other of these arrangements. We are not expert in this area but have discussed the matter on several occasions with informed persons. From these discussions it seems that there is no clear correlation between details of the management format and generally held opinion as to the effectiveness of the organization. Single institution management seems always to be viewed as efficient; the common difficulty is when the managing institution is perceived as manipulative or biased in its control; many examples show that this difficulty can be avoided when the intent to do so exists. The sponsors of this proposal believe a strong intent to avoid biased management does exist at Michigan State, and we have therefore decided to put this proposal forward based on one-university management, which has then the concomitant advantage of being an expeditious procedure. We feel it extremely likely that this arrangement will accomplish efficient and effective management of the laboratory for the indefinite future. In addition, if the management arrangement should fall short of these expectations, the funding agency has the continuing option of reviewing or changing the management format and a continuing MSU commitment to negotiate reasonable arrangements for making its cyclotron facilities available to the program.

In summary we feel that the organizational arrangements proposed here have a high probability of reaching the desired goals of operating the laboratory in a manner which the broad community of scientists will consider efficient and fair and, beyond that, of making the laboratory accessible and hospitable to all interested scientists.

III. Scientific justification

We discuss in this section some of the areas in which significant, even unique, advances in our knowledge of the physical world will be forthcoming from experimental research on the CSC heavy-ion accelerator. The versatility of the proposed accelerator system, both in terms of the availability of a complete variety of ion beams and the broad range of attainable energies, makes essentially every present and projected area of heavy-ion research (except the full relativistic realm) available as a research option. However we do not envisage that every facet of heavy-ion science will be constantly represented in the CSC research program. Instead, it is highly probable that at any future date the facility will be substantially oriented toward a much smaller group of problems, with the objective of revealing and clarifying those phenomena for which the accelerator's characteristics make it the unique research instrument. In order to foresee which areas of heavy-ion science will yield optimal response to concentrated research programs utilizing the CSC accelerator, consideration must be taken of its exceptional levels of beam intensity and beam quality as well as its energy capability. Thus it may happen that the frontiers to be opened using the high resolution capability will be as important as those involving new energies. And the crucial evidence for a new discovery may involve extremely rare events, in which case the high beam currents available from the CSC system would be essential.

In this part of the proposal we survey currently active areas of heavy-ion science as well as new fields which we judge will become important in the future. Our basic guideline for the discussion is to consider what research would be done with the CSC facility if it were available today, with the understanding that what research actually will be done when the facility is operational will undoubtedly in many cases be very different. In particular, the research topics about which most is now understood, and about which the most precise present proposals can be formulated, are just the ones most likely to lose some of their attractiveness in the intervening time. On the other hand, the research topics which are likely to be fresh three and four years hence are in general now suggested on rather vague theoretical grounds or are utterly unsuspected. In view of this situation, we will try to maintain some sensitivity to the actually contemplated construction schedule in our discussion. This schedule is reviewed in Section IV, and indicates that the first cyclotron should become available for experimental use in the middle of 1978, roughly two years from now, with full coupled cyclotron operation for experimental purposes projected to follow in an additional two years.

Since the research capabilities of the injector cyclotron standing alone occupy an intermediate position between present heavy-ion facilities and the full capabilities of the CSC system, the single cyclotron will be used in the 1978-80 period predominantly for research which involves upward extrapolations in energy from work with present cyclotron and tandem acclerators.

Work with the single cyclotron during this time will serve as a bridge to the new realms of research which will open up when coupled operation commences. After the full CSC system is operational, a fraction of the beam from the injector cyclotron can be used to maintain particularly interesting research programs at the intermediate bombarding energies.

Research ideas have been grouped in four major categories in the following discussion. The artificiality of the divisions which such classifications entail seems inescapable in such a survey. To mitigate this difficulty we will attempt to note the cross-correlations which permeate much of the integrated body of heavy-ion science as often as seems practical. The most appropriate classification scheme has seemed to us to be one oriented to the attitudes and goals of the scientists engaged in the research. Major groupings are thus entitled, "Structure of discrete nuclear states" (III.1), "Nucleus-nucleus reaction processes" (III.2) "New and unusual nuclei" (III.3) and "Nuclear and atomic phenomena under extreme conditions" (III.4). We have essentially omitted discussion of the use of heavy-ions as research probes in other areas of science. This is in keeping with our view of the proposed facility as a laboratory primarily dedicated to a concentrated study of the fundamental aspects of nuclear matter. Of course, if compelling items of interdisciplinary research for which the CSC facilities are particularly well suited arise, they will certainly be fitted into the research program.

The source material upon which the discussion is based includes the proceedings of several recent international conferences on heavy-ion science, for which we adopt the following shorthand notation.

Proceedings of the International Conference on Nuclear Physics, ed. by J. de Boer and H.J. Mang, pub. by North-Holland/American Elsevier, 1973, = "Munich, 1973".

Reactions Between Complex Nuclei, ed. by R.C. Robinson, R.K. McGowan, J.B. Ball, and J.H. Hamilton, pub. by North-Holland/ American Elsevier, 1974, - "Nashville, 1974".

The Second High-Energy Heavy-Ion Summer Study at the Lawrence Berkeley Laboratory, July 15-26, 1974 (LBL-3075) = "Berkeley, 1974".

Proceedings of the International Conference on Nuclear Structure and Spectroscopy, ed. by H.P. Blok and A.E.L. Dieperink, pub. by Scholar's Press, 1974 ="Amsterdam, 1974".

Macroscopic Features of Heavy-Ion Collisions Symposium at Argonne National Laboratory, April 1-3, 1976 = "Argonne, 1976".

The Third Summer Study in High-Energy Heavy-Ion Physics at the Lawrence Berkeley Laboratory, July 12-16, 1976, = "Berkeley 1976".

III.1 Structure of discrete nuclear states

The research projects discussed in this section are typically closely related to present heavy-ion (and light-ion) nuclear research. The characteristics of the beams from the injector cyclotron are ideally suited for many of these experiments and they are thus likely to form a major portion of the 1978-1980 research program. Such studies have as their general goal the understanding of nuclear phenomena in the realm of low excitation energies. The dominant underlying features of these phenomena are either 1) single-particle orbits and an associated Hamiltonian governing the interactions of nucleons in these orbits, or 2) a system of surface vibrations and rotations which are systematized into a formalism uniting a description of these collective motions with certain aspects of single-particle motion. Experiments are designed to yield information about individual nuclear levels and their relationships to one another. The comparison of the predicted level structures from a theoretical model with the experimental data then constitutes a critique of the underlying theoretical construct and provides a guide to correcting or refining it.

Most measurements in this field of research are ultimately reduced to the values of matrix elements of either electromagnetic or nucleon-transfer operators. Experiments in the first category include those utilizing various techniques for measuring the static electric and magnetic moments of (excited) nuclear states, and for measuring the mean lives and other features of their radiative decays, and the probabilities of their excitation by changing Coulomb fields. Experiments in the second category include the conceptually simpler and more thoroughly explored process of the stripping into or the picking up from the target of a single nucleon, and the more complex processes of transferring into or out of the target two or three coupled nucleons. These topics have, of course, been extensively studied with H and He beams as well as with heavy-ion beams. The transfer of four coupled nucleons, generally in the context of alpha-particle transfer, is conventionally allocated to the domain of heavy-ion experimentation.

The major advantages of heavy-ion beams for measurements of electromagnetic phenomena are well known; further improvements in experimental capabilities will accrue from utilizing such beams at higher bombarding velocities. In contrast, the early hope that a better understanding of nucleon-transfer phenomena would quickly follow from experiments with heavy-ion beams was found to be over-optimistic. A host of unexpected complexities in heavy-ion-induced transfer processes diverted attention from the original aims to those of understanding the complexities themselves. However, intensive theoretical and experimental efforts are now successfully delineating the essential features of these processes. In particular, the effort which has been expended in attempting to understand nucleon-transfer phenomena with lower-energy heavy-ions has produced signal advances in the understanding of multi-step processes. The full understanding of the combinations of these electromagnetic-like and nucleon-transfer processes will vastly expand the body of available information on nuclear states in the low-energy domain. Ultimately, it is also possible that experiments at higher bombarding energies will exhibit some of the originally anticipated simplicities.

III.1.1 Precision measurements of nuclear lifetimes and moments

The developments of Doppler-shift-attenuation (DSA) techniques and then recoil-distance-measurements (RDM) during the last decade have made possible profound advances in our knowledge of the characteristics of nuclear levels.[1,2] However, the accuracy of experiments in which the nuclear reactions are induced by H and He ions is severely limited ($\sim\pm 50\%$) by intrinsic difficulties in the analysis of the slowing down in matter of ions recoiling with small ($v/c \lesssim 0.01$) velocities.[3] Recent works[4,5,6] indicate that much more precise information on nuclear lifetimes can be obtained in experiments in which heavy ions impinge upon light-ion targets. Such "inverse" reactions, e.g., $^{2}H(^{35}Cl,p)^{36}Cl$, produce decaying recoils with velocities in the range $v/c \sim 0.1$. At these velocities slowing-down times are much better understood and the total uncertainty in such measurements can be brought to below 10%.

Information on nuclear lifetimes at this higher level of accuracy can deepen our comprehension of nuclear behavior as significantly as did the original DSA lifetime measurements themselves. With these precision data it will be possible to go beyond classifying transition matrix elements as "strong" or "weak". Such qualitative results have confirmed our general pictures of nuclear structure but often fail to discriminate between the different plausible explanations of nuclear behavior in a given region. With absolute measurements to the level of 10% accuracy, clear choices can be made between different formulations (e.g., rotational vs. vibrational vs. mixed-configuration shell-model) of nuclear structure. The validity of a model as a function of mass can be tested and the degree of mass and state independence of electromagnetic operators can be determined. For example, the electromagnetic matrix elements at the closed-shell-plus-or-minus-one-nucleon systems are sensitive to the coupling between the single-particle and high-lying collective vibrational degrees of freedom. These latter features in turn depend on fundamental parameters such as the effective mass and the compressibility of nuclear matter. However, the excited-state lifetimes of, for example, the A=39 and A=41 nuclei are so short that they have yet to be measured accurately enough to distinguish between existing theories. The experimental problems should yield readily to attack through such reactions as $^{3}He(^{40}Ca,^{4}He)^{39}Ca$. Such distinctions will lead to a better understanding of the fundamental parameters mentioned above.

Research in nuclear lifetime measurements will certainly be vigorously pursued at currently active heavy-ion accelerators in the next years, but the field is so broad and deep that important topics will continue to emerge. The increased beam energies for heavy projectiles which become available at the first and second stages in the CSC laboratory's development will yield important benefits in several aspects of lifetime measurements. For example, in the DSA experiments, increments in ion velocity translate into better known stopping powers, larger energy shifts, and, in general, the ability to measure longer lifetimes. There are also simple, straightforward advantages in RDM experiments which can be obtained from increments in ion velocities beyond those available from present accelerators. Uncertainties which arise from inaccuracies in the smoothness and alignment of the target foil and catcher surface can be reduced, and again shorter lifetime transitions are brought within the scope of the technique. In addition to lifetime measurements themselves, measurements of magnetic moments of nuclear states which have lifetimes on the order of picoseconds can be made with the large magnetic fields (100 megagauss) produced at the nucleus by atomic electrons. These fields are especially large and easy to calculate in one-electron atoms which are produced by stripping electrons from fast recoiling atoms produced in heavy-ion collisions. Since the charge state depends on the velocity, with higher velocities it should be possible to extend this technique beyond the present day limit of about Z=20. Light and medium mass projectiles from the injector cyclotron and the heaviest beams from the coupled system will both offer exceptional capabilities for such measurements.

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III.1.2 Coulomb-excitation measurements

Because the Coulomb interaction is precisely known and the transition processes stimulated by a changing electric field strength can thus be calculated exactly,[1] the study of transition and moment matrix elements of nuclear levels via Coulomb excitation is an important topic in nuclear science. The higher-charge probes which became available with the advent of heavy-ion beams effected a renaissance in this field. The key to further exploitation of the technique lies in access to a multiplicity of bombarding energies and ion masses. With this capability higher energies and charges can be utilized to excite states previously out of reach, and the differing charge and velocity dependence of various terms in the excitation process can be used to discriminate between the various paths (direct vs multiple step, etc.) by which a given state can be populated. Interference between the Coulomb and nuclear interactions can be studied at energies close to the Coulomb barrier[2] in order to extract information about shape parameters of nuclei[3] and to resolve ambiguities[4,5] in the signs of matrix elements.

The CSC system will provide a complete array of ion masses and velocities for Coulomb excitation, and beam resolution will match the maximum utilizable for such studies. With coupled-cyclotron operation, for example, the observation of Coulomb excitation from the bombardment of actinide nuclei by ^{208}Pb or ^{238}U will become possible. Assuming 20 fm separation between the centers of the two nuclei to be large enough to avoid any Coulomb-nuclear interference, such experiments could be carried out at ~5 MeV/amu. Calculations performed using the sudden approximation show that the most strongly excited state would be the $I = 26^+$, with an excitation probability of ~15%. The $I = 36^+$ state would be excited with a probability of ~1% and should be observable. At present,[6] the 24^+ state is the highest excited state observed in U^{238}.

Identification of such high-spin states is traditionally accomplished by means of γ-ray spectroscopy, but difficulties with this technique arise because the γ-ray lines from the highest transitions are Doppler broadened and are thus difficult to detect. (The higher-lying states may also be particle- and fission-unstable). The high duty cycle available with the CSC system, however, makes particle-coincidence measurements feasible, so that Doppler broadening could be minimized. Another option would be to use the high resolution capability of the accelerator and a magnetic spectrograph to separate elastically and inelastically scattered ions. A FWHM resolution of 200 keV, for example, seems attainable, which is to be compared to the separation between the 22^+ and 24^+ states in U^{238} of 480 keV, and a separation (in the absence of backbending) between the 34^+ and 36^+ state of ~740 keV. An experiment involving the separation of inelastically scattered particles is much easier to interpret in terms of a level scheme than is an experiment in which only gamma rays are observed.

With the injector cyclotron alone, studies similar to those outlined for actinide nuclei can be carried out in the rare earth region.[7] This could be accomplished, for example, either by using ^{136}Xe-beams at about 3.7 MeV/amu or by bombarding a lead target with the rare-earth projectile in question. Typical beam energies in this case would be about 4 MeV/amu, near the optimal energy for reaching the highest rotational states which can be Coulomb-excited. Preliminary estimates indicate that this limit would be at $I \sim 24-26$. Projectile-excitation experiments with lead targets will also be valuable for Coulomb excitation studies below the deformed region ($A<150$). Many states in light-and medium-mass nuclei can be Coulomb excited in this way, and their electromagnetic properties can be investigated for the first time since the larger projectile-target charge products will now compensate for the weaker coupling potentials. Studies of the angular distributions of Coulomb-scattered ions (if necessary in coincidence with γ-rays) and relative excitation probabilities from different targets, will allow determination of electric quadrupole moments not only of the first but also of higher excited states of many nuclei. With present techniques, the precision of quadrupole-moment determinations is limited to typically ~.05 to ~.1 e-barns. Projectile excitation techniques should result in reorientation effects which are 4 to 5 times larger than are presently achieved, and measurements with a precision of ~0.01 to ~0.02 e-barns should be possible.

The information which can be obtained in Coulomb-excitation studies has vital bearing on many open questions in nuclear structure. In both the rare-earth and actinide regions the accuracy of the rotational model for high-spin states can be probed, going beyond energy determinations to measure if the B(E2) ratios along the intra-band cascades are correctly predicted and to measure the strength of the couplings between bands at various J values. Detailed features of the backbending phenomena known to occur in the rare earth region can be elucidated[7] and the possible occurrence of backbending in the actinides determined.

Immediately below the rotational region, for A= 100-140, the predictions of the Iachello-Arima interacting-boson model[8] for transition rates can be tested. Throughout the periodic table, more quantitatively accurate information on E2 strengths is needed to elucidate the origins and behavior of the "effective charge" renormalization needed in shell-model analyses of nuclear structure. Quadrupole moment measurements, even of first excited 2^+ states, still present many challenges to theoretical understanding,[9,10] and measurements of values for higher excited states would provide extremely discriminating tests of different model formulations.[11] In summary, a vast amount of illuminating information on nuclear structure can be obtained by experiments which can utilize the premium beam quality and the higher ion energies and masses which the CSC system will provide.

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III.1.3 Transfer and inelastic-scattering reactions

Heavy-ion initiated reactions in which one to several nucleons are transferred between target and projectile or in which low-lying excited states in either or both systems are populated by inelastic scattering can be studied in several contexts. Detailed properties of known states can be probed by the special features inherent in a selected projectile mass and energy. Alternatively, the physics of the reaction process itself can be the principal focus of investigation. Finally, new individual levels and classes of levels can be populated, identified and studied by virtue of some of the unique features of heavy-ion reaction processes without recourse to complex reaction calculations.

Detailed study of previously known levels and of reaction mechanisms have naturally progressed apace. Extensive experimental work near the Coulomb barrier established that the gross behavior of heavy-ion transfer reactions in that regime was dominated by semi-classical effects.[1-4] Angular distributions were not characteristic of transfer quantum numbers but, rather, were uniformly peaked at angles fixed by the "grazing" condition, and cross sections were dominated by the "Q-value window". Investigations are now being pursued at higher energies[5-7] (twice the Coulomb barrier and up); oscillatory structure at forward angles with some ℓ and j dependence begins to supersede the bell-shaped, grazing-angle-peaked curves and the Q-value dominance fades away as bombarding energy climbs.

The interpretation of these heavy-ion reactions involves fixing the proper theoretical formalism and determining the proper values for the parameters of the formalism. Quantitative analysis began with zero-range DWBA calculations. It seems clear now that, in general, heavy-ion reactions demand careful consideration of the exact, finite-range corrections to this theory.[8] Moreover, coupling of the simple direct-transfer channel to various inelastic scattering channels also appears essential.[9] As these complications have been surmounted by the further development of reaction theory codes, it has developed that many of the most informative aspects of the data actually lie in what were originally considered liabilities of complexity.

The extra degrees of freedom allowed by the breaking of the zero-range constraint mean that study of the same final set of nuclear levels is possible by a sequence of different heavy-ion transfer reactions. Moreover, the importance of coupled-channels effects is proving to yield unique insight into many basic features of nuclear structure.[9] The signs and magnitudes of quadrupole and hexadecapole deformations of several different low lying states can be inferred from detailed coupled-channels fits to angular distributions, and properly chosen comparative populations of the same family of states can yield identification of the basic natures (particle-hole, two particle-two-hole, two proton, two neutron, etc.) of their wave functions.[10-12]

Selected experiments (optimum choice of projectile, target, and bombarding energy) carried out with the injector cyclotron with good resolution should significantly assist in reaching the goal[13] in which a self-consistent (simultaneously treating elastic and inelastic scattering, and one- and two-nucleon transfer) analysis can quantitatively account for observed strength and angular distributions. With such an analytical command of the data, an unambiguous microscopic view of many new aspects of nuclear wave functions will be at hand.

A more qualitative, semiclassical approach to transfer reactions often reveals much of the basic physics behind the observed phenomena and this kind of analysis is particularly suited to the less thoroughly explored cases of transfer of more than two-nucleons.

Three-nucleon transfer with high-energy heavy ions can be seen on such grounds to selectively populate high-spin states. Such studies have so far been carried out for light nuclei.[6,14] Not only have the experiments revealed a new richness of simple high-excitation level structure, but there is the promise that detailed analysis of the data will yield considerable insight into the fundamental constitution of these excitations. The dependence upon projectile mass and energy and angular momentum transfer of the enhancement factors for heavy-ion transfer can be exploited by measuring spectra at a sequence of bombarding energies. For example, the $^{12}C(^{20}Ne,^{16}O)^{16}O$ reaction can be employed in the range 10-30 MeV/amu to attempt via excitation functions to identify the high-spin, high excitation states of ^{16}O.[15] Such experiments, with their requirements on extended energy variability and good energy resolution, are extremely well suited to the capabilities of the CSC system.

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III.1.4 High-spin phenomena

Nuclear states which have high values of total angular momentum are of particular interest wherever they are found. (It is a happy coincidence of nuclear spectroscopy that these states tend to have unusual characteristics both in formation and decay because of their high J-values and are hence relatively easy to identify among the more numerous levels of lower spin. In particular, heavy-ion bombardments offer a variety of techniques by which such states can be preferentially populated and studied.) In the shell-model view, high-spin states must be formed with a restricted set of configurations of high-j orbitals. For deformed nuclei, high-spin states correspond to increased rotational frequency or to intrinsic states of several high-spin quasiparticles in a sense similar to the shell-model picture.

In light and medium nuclei, and around shell closures, the energies of high-spin states provide information about the persistence of shell effects. For example, there is a maximum angular momentum which can be generated with N particles in a given shell-model space, e.g., J=8 for 4 particles in the sd-shell (^{20}Ne). The discovery of the J=10 state in ^{20}Ne and its energy will indicate whether the "ground-state-band" of ^{20}Ne (J=0-2-4-6-8), which can be explained nicely within the sd-shell model context[1], extrapolates smoothly in the rotational scheme to J=10 or whether there is a clear break in energy. Similar investigations in the f-p shell can likewise establish bounds on the validity of model space assumptions in that region.

Since the wave functions of high-spin, few-particle systems must be quite simple compared to the extensively mixed wave functions of lower J, decay rates between high-spin states and their individual electromagnetic moments can be interpreted in terms of fundamental nucleonic characteristics with a minimum of ambiguity. Such data will continue to yield the best possible information on effective charges and g-factors. This feature is being exploited to great advantages in both the fp-shell[2] and Pb regions[3] and in deformed nuclei[4] with techniques such as those discussed in Secs. III.1.1 and III.1.2. This same wave-function simplicity also permits comparison of high-spin spectra in, for example,[5] ^{206}Pb and ^{205}Pb, to be utilized to test for three-body effects in the effective nuclear Hamiltonian.

There is presently extensive activity in exploring the behavior of high-spin states in deformed nuclei with a special emphasis on the phenomenon known as "backbending", which is a variation from the strict rotational relationship between energy and J-value. Combined experimental and theoretical efforts have led to an understanding of this striking behavior and of the dominant role that the Coriolis force plays in deformed rotating nuclei. This understanding has led to the interpretation of a large body of data in diverse regions of the periodic table, e.g., the occurrence of decoupled bands[6] and also to the use of the spectra of high-j particles as probes for nuclear shapes.[7,8] The bulk of this experimental information has come from (HI, xn) and (α,xn) studies.

Other present efforts are concentrated on detailed understanding of the reaction mechanism in (HI, xn) reactions[9-11] with emphasis on cross sections and γ-ray multiplicities. From studies[9] of the 'continuum' γ-radiation, information on the moment of inertia at ultra-high spin values (~ 60 ħ) can be inferred. As the spin increases, it begins to play a larger role in nuclear behavior. Nuclear structure study has hitherto been dominated by N, Z, and E. However, at ultra-high spins, the rotational energy becomes comparable to the Coulomb and shell-effect energies, opening a new dimension in nuclear structure. Recent calculations[12] have indicated that dramatic shape changes may occur with increasing spin. For instance, a nucleus which is prolate in its ground state may be driven oblate at high spins, passing through intermediate triaxial shapes.

If the nucleus does become oblate, then the angular momenta of yrast states is expected[13] to be generated not by collective rotation but by alignment of particle orbits about the symmetry axis. Under such circumstances "yrast traps"[14] may occur and may indeed be a signature of the occurrence of oblate shapes. These phenomena may also be viewed as the interplay between collective and few-nucleon degrees of freedom.[15]

The method of choice to probe the many possible exciting phenomena at high spin is by (HI, xn) spectroscopy. For example, 600 MeV Sn ions, may be utilized to bring in large values (~80 ħ) of angular momentum, a requisite for such investigations. Rather sophisticated experiments would be required; for example, a multiple NaI system could be used as a multiplicity filter to accentuate high-spin events. The search for yrast traps would entail a study of delayed activity, either α-or γ-emission.

It is estimated that for sufficiently long-lived traps (≈a few nsec), α-emission would be the favored mode of decay. The decay of a high-spin (say 60 ℏ) isomer via an $\ell=20$ α-particle would lead to a high-spin state of the daughter, which should then decay via γ-emission with high multiplicity. The use of the γ-ray multiplicity-filter in conjunction with α-detectors is immediately suggested. The lifetimes of yrast traps could vary over a wide range (from a few psec to min) so that beam pulsing, mass separation (using the recoil spectrometer proposed in Sec. IV), rabbit or He-jet transport, and chemical techniques may be invoked.

For lifetimes of the order ~50 nsec the natural pulsed beam of the cyclotron is an advantage. For lifetimes of the order of tens of psec, one can utilize the high recoil velocity available from the collision of an energetic heavy ion on a lighter target in two ways. First, the relatively large recoil velocity (23 μm/psec for, say, 600 MeV Sn on ^{44}Ca) makes it feasible to shield γ-detectors from the target so that only delayed activity free from prompt contamination may be observed. Second, a recoil electron spectrometer can be constructed to observe only delayed electrons from recoiling products.[16] A suitable arrangement consists of a solenoid with one section blocked off and another free for a Si(Li) detector to observe atoms which have recoiled from the target located in the blocked section. The observation of psec-delayed electrons or γ radiation may make it feasible to observe discrete ultra-high spin states, since one or more decay paths along the yrast region may be slightly retarded. Certainly the occurrence of yrast traps will also make this possible. It should be noted that discrete states have so far been observed to only about spin 24 $\hbar$.

The recoil electron spectrometer proposed above may also be used for lifetime measurements in the psec range. For (HI,xn) reactions it offers an advantage over the usual Doppler-shift plunger or Doppler-shift-attenuation methods (see Sec. III.1.1) in that the delayed spectra are free from the large prompt continuum radiation. In addition, it is also suitable for Coulomb excitation measurements (see Sec. III.1.2). Lifetime information on discrete high spin states (6-22 $\hbar$), which, as was noted, is important for testing nuclear models, is presently very limited. The availability of energetic heavy ions (from either the one- or two-stage cyclotron) coupled with the recoil electron spectrometer, appears to be a promising combination for providing vital lifetime information. The multiplicity filter proposed above can be used to great advantage in locating γ-rays among the various high spin levels populated in Coulomb excitation.

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Addendum to III.1

Progress in the application of heavy ion beams to nuclear structure problems has been evident in several areas since section III.1 of the CSC proposal was written. Not surprisingly, the two laboratories presently capable of accelerating very heavy ions (A>50), Berkeley and GSI, have led the way. A number of techniques outlined in these sections have now received trials, in some cases with impressive results.

Generally speaking, the features peculiar to nuclei at very high spins have dominated structural investigations with heavy ion beams. Coulomb excitation to very high spins, large angular momentum of residual nuclei following HI reactions, and very high recoil energies are characteristic phenomena that have been used to great advantage in recent experiments at GSI and Berkeley. The group at GSI[1] has used ^{238}U beams to Coulomb excite ^{238}U as high as spin 28. Problems with Doppler-broadened line shapes which were anticipated earlier can apparently be minimized by 0° counting. Although higher-order Coulomb excitation processes complicate the analysis of such data, in principle it should prove possible to extract B(E2) values for states with angular momenta greater than $30\hbar$ by such techniques. Complementary model-independent lifetime data can be obtained by the Doppler-shift attenuation method, and in this case the GSI group has obtained lifetimes for states from I=10-24 in ^{238}U by line-shape analysis. Data of this type, heretofore unobtainable by conventional compound-nuclear processes, should now be within reach for a number of actinide nuclei.

In lighter nuclei, both the GSI and Berkeley groups have proved the utility of Coulomb excitation techniques in several pioneering experiments, and the very high recoil velocities ($v \simeq 0.1c$) obtainable in "inverse" reactions allow direct lifetime measurements by the recoil-distance technique. In ^{158}Dy for example, the GSI group has obtained data to spin=24 and lifetime of the order of 0.5 ps in the ^{26}Mg(^{136}Xe,4n) reaction. The importance of this technique for high-precision measurement of electromagnetic transition matrix elements, which was outlined earlier in the CSC proposal, now has been demonstrated and of course applies equally well to much lighter nuclei.

Significant progress has also occurred in the area of yrast-line spectroscopy of very high-spin isomers. Again, the large recoil energies of residual nuclei, this time following (HI,xn) reactions, has been utilized to isolate product nuclei in a search for so-called "yrast trap" isomers (cf. III.1.4) at GSI.[2] The combination of physical isolation of the isomeric species and a γ-ray multiplicity filter allowed isomer sensitivities to 50 μb or less to be achieved in a time range down to a few nanoseconds. Discovery of a region of high-spin isomers near the N=82 closed shell offers the first indications of the possible territory to be explored in such experiments. Subsequent work at Chalk River, Rochester, Oak Ridge and GSI confirms the validity of the earlier GSI results.

The multiplicity filter technique alone, of course, does not answer the question of whether high-spin isomers exist in a given nucleus. Many nuclei, for which γ-ray multiplicity experiments at GSI, Chalk River, and elsewhere gave negative results, may yet be found to decay by several low multiplicity cascades through a series of isomers. Experiments to test for such a possibility over a large region of the nuclear chart will necessarily be difficult and protracted but are within the scope of current techniques. To date, no evidence has been reported for α-particle emission associated with decay of very high spin isomers, but on-going experiments at GSI and elsewhere, which are designed to test for subnanosecond isomers, may change this picture.

While it is true that traditional studies of discrete line spectra are much to be desired as a source of definitive information on nuclear structure, in the regime of high excitation energy and large angular momentum where the level density is very high, such studies become difficult or impossible. Nevertheless, it is clear that much can be learned by careful analysis of the energy and multiplicity of particles and/or photons emitted following heavy-ion induced compound-and direct-reaction processes. For example, although direct observation of transitions along the "cold" yrast line may be difficult, the Risø group has shown that mapping the "entry line", (the point at which deexcitation by γ-radiation begins following particle evaporation) may yield information on nuclear moments of inertia at very high spins.[3] Generally lying some 5 MeV above the yrast line, the entry line reflects the level density, which in turn is related to the moment of inertia, as is the slope of the yrast line itself. Beside their promise for exploring bulk nuclear properties, such studies also provide useful tests of statistical model calculations of nuclear level densities of high spin and excitation energy.

A somewhat different and more direct approach pioneered by the Berkeley group has made use of γ-ray multiplicity measurements as a function of energy to deduce information on nuclear moments of inertia and shapes at very high spins.[4]

Though experiments of this type are in their early stages, it is clear that the γ-ray multiplicity filter, either as an array of discrete detectors, or as a single large energy-sum detector, has emerged as the primary tool for labeling high angular momentum processes in heavy-ion induced reactions of all kinds. Recent multiplicity measurements indicate that 20-30$\hbar$ units of angular momentum are commonly associated with deep inelastic scattering reactions. This suggests the possible utility of such reactions for spectroscopic studies of residual nuclei at moderately high spins in regions not easily accessible by other means.

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III.2 Nucleus-nucleus reaction processes

Our discussion of nucleus-nucleus collision processes is oriented toward the conventional[1] picture which allocates cross section strength according to impact parameter or partial wave number (see Fig. 1). An alternate qualitative interpretation of the various paths that heavy-ion reactions may follow can be phrased in terms of the reaction times involved. Grazing or peripheral collisions, which encompass elastic scattering and the few-nucleon-transfer and inelastic-scattering transitions to residual states at low excitation energy, are lumped into the category of "quasi-elastic processes". These reactions involve only a narrow band of partial waves near ℓ_{max}, and the corresponding interaction times are of the order of one nuclear period. The remainder of the reaction cross section, which involves lower partial waves, is apportioned between compound-nucleus formation ("fusion") and what we will call "characteristic heavy-ion process" ("CHIP") events.[2] The latter are discussed in the literature under the names "deep-inelastic", "strongly damped", "quasi-fission", and "relaxed" processes. The CHIP reactions have features intermediate between quasi-elastic and fusion reactions and they are unique to the domain of collisions between complex nuclei. Their importance, even dominance in some circumstances, has been one of the most exciting revelations to emerge from the first few years of heavy-ion research at higher energies. While intuition might indicate that fusion events should correspond to the low range of partial waves and interaction times of many nuclear periods and the

CHIP events to intermediate ℓ-values and interaction times, the quantitative interpretation of the complete reaction process is still uncertain.

The total picture of what happens when two energetic nuclei collide is so vast and variegated that extremely powerful and ingenious experimental techniques will be required to gain a reliable and comprehensive view. Present attempts to gain global views of the reaction process have dealt with relatively light nuclei[3,4] and utilized highly developed detector systems. Alternatively, radio-chemical techniques[5,6] have been employed to gain a rather specialized view of the products of collisions between heavy nuclei (see Fig. 2).

There is a multitude of frontiers in this area which need to be explored during the next few years. The role of the CSC injector cyclotron in this field during its two years of stand-alone operation will involve extending the present type of experimental measurements with light- and medium-mass beams (~C to ~Ni) significantly upwards in energy (to 30-70 MeV/amu). Coupled-cyclotron operation will yield light-mass beam energies up to or beyond the limits of the reaction models currently in use and will yield a factor of ~2 increase (~8 MeV/amu to $\geq$20 MeV/amu) in the beam energies for heavier ions compared to the energies available from present linear accelerators. In all of these experiments, the good beam characteristics of the superconducting cyclotrons combined with high-resolution spectrometers and detectors may reveal new features of the physical processes not observable with linear accelerators.

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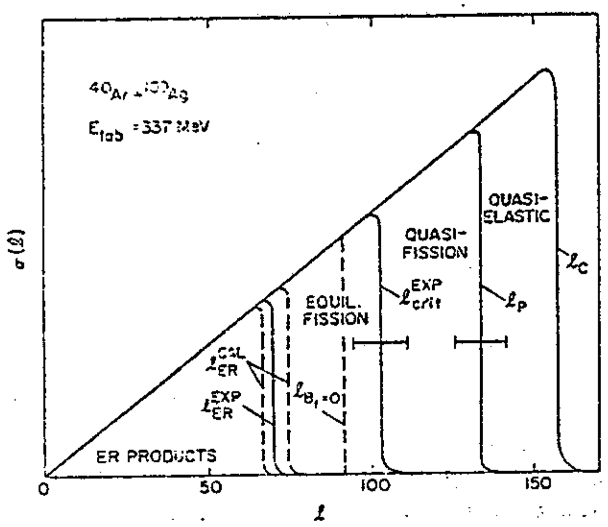

Fig.1(III.2)--(from Ref. III.2-1) Schematic allocation of reaction cross section on the basis of impact parameter.

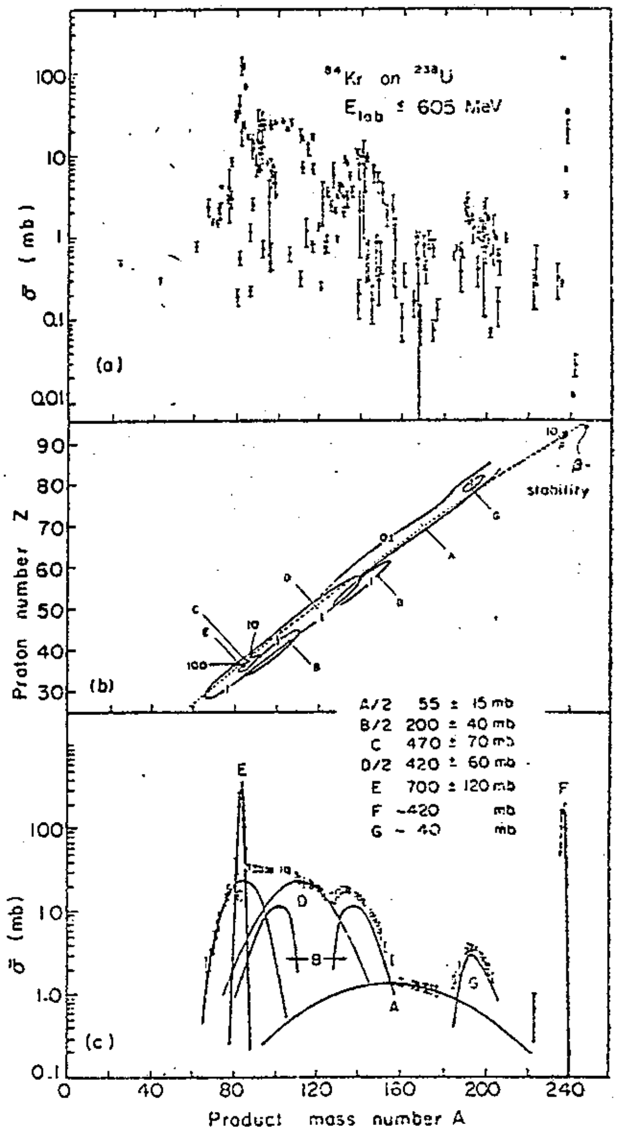

Fig. 2(III.2)--(from Ref. III.2-4). Radiochemical profile of reaction products from ^{84}K+^{238}U. a) Independent and cumulative yields of individual isotopes, calculated with the assumption of a general interaction barrier of 450 MeV (see Ref. 8), corresponding to an effective target thickness of 11.6 mg U/cm^2. b) Contour lines for equal independent yields in millibarns. c) Total integrated mass yields (upper and lower limits are indicated at those mass numbers for which experimental data were obtained) and their decomposition into individual components: (A) complete fusion-fission, (B) transfer-induced fission, (C) quasi-Kr, (D) cascade fission of the quasi-U, (E) and (F) transfer reactions ("rabbit ears"), and (G) yields of unknown origin.

III.2.1 Peripheral collisions

Peripheral collision processes subdivide into elastic and quasi-elastic categories. Various individual quasi-elastic reactions were discussed in Section III.1.3 in the context of what could be learned from these processes about the nature of discrete nuclear states. It is quite possible, however, that research in the future, particularly at higher energies, will also find new insights into nuclear properties and reaction mechanisms from a study of the gross features of the quasi-elastic process. The same sort of exciting and unexpected phenomena that were revealed at lower energies in the discovery of the CHIP cross sections may emerge from systematic study of the quasi-elastic process in the 5-100 MeV/amu energy region, since it can be expected that these "fast-reaction-time" events become relatively more important at higher collision velocities. The energy ranges of the CSC acclerator will be ideally suited to exploration of the macroscopic features of the quasi-elastic process as it evolves as a function of collision masses and energies. For example, present data on the energy dependence of single-nucleon transfer appear to be most complete for the (^{16}O,^{15}N) reaction on ^{208}Pb, where Berkeley data[1] extend up to ~20 MeV/amu. Experiments on the injector cyclotron with C, O, Si and Ca beams can extend the energy range up to 50-80 MeV/amu for such studies. Correspondingly higher energies and heavier beams will of course become available with completion of the CSC system. At the same time that the extended energy capability of the CSC system allows a thorough delineation of the energy dependence of the envelope of cross section strength of single-nucleon transfer, to pick an example, the good energy resolution of the CSC beams will also permit the observation of any inherent micro- and intermediate-structure which may exist in the differential population of the various single-particle states.

In studies of elastic scattering there are differing points of view in ongoing studies. There is a traditional line of research which pursues the trends established in the pioneering studies[2,3] at Yale of the ^{12}C and ^{16}O optical potentials. Current experimental research in this line is directed towards extending the energy and mass ranges with the hope of eliminating some of the multiple ambiguities in the optical-model parameter space. Attention is still concentrated on light-mass systems. The constraints imposed by requiring simultaneous fits to data at a wide range of energies seem to eliminate some of the ambiguities,[4] but it appears difficult to surmount completely the limits to knowledge imposed by the strong-absorption feature of colliding heavy ions.[5] It has also been observed that the requirement of simultaneous reproduction, via channel-coupling, of elastic scattering, inelastic scattering and one- and two-nucleon transfer, serves to remove many,[6] but far from all,[7] of the ambiguities in an optical-model formulation.

An alternate but somewhat parallel interest in elastic scattering phenomena stems from attempts to account for nucleus-nucleus scattering in terms of nucleon-nucleon and matter-distribution parameters. These "folding model" formulations appear quite successful at present.[8-10] Their use provides the opportunity to link fundamental microscopic aspects of nuclear structure to the macroscopic aspects of heavy-ion scattering.

Experimental data from the Coulomb region all the way to full relativistic velocities are necessary for a full working out of the implications of this approach, and scattering in the range 10- 100 MeV/amu is vital.[11] Elastic scattering experiments with C, O, Si, Ca, and Ni projectiles will be completely straightforward with the CSC system. Work can begin with the injector cyclotron, in fact, and continue smoothly into coupled operation. The relative simplicity of these measurements means that they will be early items in the research program, and data sufficient to delineate fully the experimental situation should rapidly become available.

Measurements of the elastic scattering of heavier nuclei presently concentrate on the two characteristics which are universal (see Fig. 1) for strongly absorbed particles following semi-classical orbits. These features are 1) differential cross sections which remain close to the Rutherford values out to some angle θ_G and 2) exponentially decreasing ratio-to-Rutherford cross sections for further increases in angle beyond θ_G. Various semiclassical, sharp cut-off models allow such data to be analyzed to extract effective interaction radii and total reaction cross sections. While this approach is applied throughout the entire mass range of complex nuclei, most interest currently centers on heavy systems.[12-14] Present experiments in this region fail to resolve the elastic from the inelastic and transfer components, and better resolution beams will immediately improve quantitative understanding of the various aspects of this process and its implications. Hence, the CSC system accelerating heavy nuclei (e.g., Xe, Au, Pb, and U) with good energy resolution in the

10-20 MeV/amu range will yield data which should substantially expand knowledge in this area.

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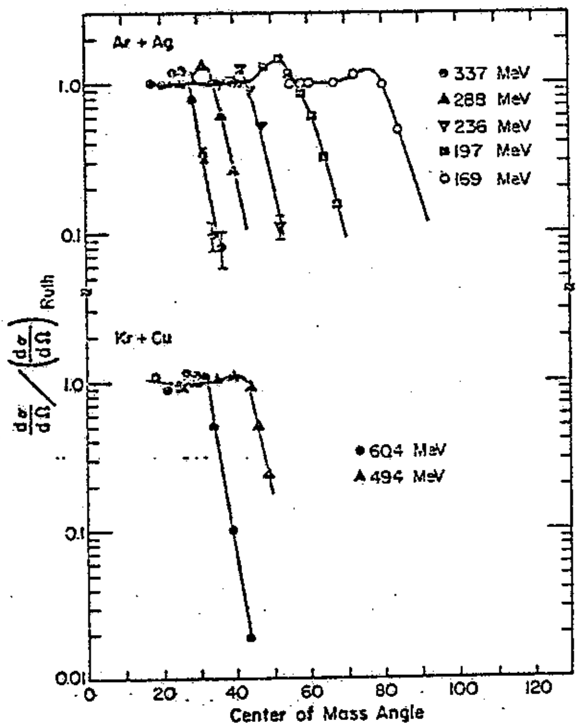

Fig. 3(III.2)--(see ref. III.2.1-12). Elastic scattering angular distributions. Smooth curves have been arbitrarily drawn through the experimental points. Curves are normalized at 1.0 in the region where count rate to Rutherford cross section ratios were constant.

III.2.2 Fusion

The concept of compound-nucleus formation between particle and nucleus, which played so important a part in nuclear physics in its first decades, can be extended to encompass phenomena resulting from the interaction of two complex nuclei. In heavy-ion physics the formation of the compound nucleus or, in alternate words, the fusion process, plays a central role. Study of fusion is undertaken to learn about the interaction potentials between nuclei, about macroscopic nuclear parameters such as viscosity and friction, and about the limits of stability to nuclear matter under the stress of high angular momentum.

The interaction of two light complex nuclei at energies comparable to the Coulomb barrier leads to fusion with a high probability. Measurements of the cross sections for the process in this region are made by detecting[1-4] the "evaporation residues", i.e., the compound nucleus minus whatever nucleons and alphas have boiled off before it recoils into the detector. The recoils are concentrated at angles close to 0°, and as energies and masses are raised, this creates increasingly severe problems which ultimately must be solved by separating the beam from the recoils. (Equipment designed to cope with this type of experiment is discussed in Sect. IV.) As the mass of the fusion product passes ~ 80 the probability that fusion of the system is followed by spontaneous fission becomes dominant. Measurement of the fusion cross section for heavier systems thus involves measurement of the ensuing fission fragments.[5,6] and requires extrapolation back from these data to the formation of the presumed parent compound nuclei. It is not always easy to distinguish the fragments of complete fusion from those of partially completed processes, and hence some ambiguity attaches to such results. Precision coincidence measurements with good time and energy resolution are necessary for more advanced experiments.

For a given combination of projectile and target, the fusion cross section first rises rapidly with increasing center-of-mass energy and then, past a certain point, decreases slowly up to the present upper limits on investigated energies. The typical profile for light systems is shown in Fig. 1. Mechanisms which limit the fusion cross section have been sought both in the internal dynamics of the compound system and in the external dynamics of the entrance channel.

Calculations with the liquid-drop model[7] show that the angular momentum which a system of given mass can sustain is limited by vanishing fission barriers to some limiting ℓ_{critical}. Partial waves corresponding to larger ℓ-values should thus not contribute to fusion, which then places an upper bound on the cross section, as expressed by the formula $\sigma_f=(\pi\lambda\!\!\!^{-}{}^2)(\ell_c+1)^2$. There is some experimental evidence that these limits are exceeded, but so far the violations are within the margins of uncertainty in the model assumptions. Ultimately, experiments must be able to test the finer corrections to the simple liquid drop formulation. Shell corrections in particular are vital in the context of predicting properties of super-heavy elements. Presently, existing data such as those of Fig. 2 seem better explained by entrance-channel effects in which a limiting $\ell_{critical}$[8,9] or corresponding $R_{critical}$[10,11] controls the fusion cross section. The formulation of Glas and Mosel[11] successfully accounts for data such as shown in Fig. 1. Underlying these theories are assumptions about the nuclear potential in the surface region,[12,13] hence a thorough understanding of fusion should facilitate a general understanding of fission.

Further experimental work on the fusion of light nuclei must first test the limits of the present theoretical explanation. Cross sections between 15 and 50 MeV/amu for nuclei in the C-Ca range will obviously be a significant expansion of the presently sampled energy range (see Fig. 1) and should clearly show if and where the $R_{critical}$ formulation fails. Presumably at high enough energy the liquid-drop limit may become the dominant factor in the cross section. There is also growing evidence that fusion cross sections contain exciting and surprising detailed features quite beyond the compass of the simple models used so far to explain the gross energy dependence. The discoveries at Argonne of oscillations in some fusion excitation functions[14] (see Fig. 2) and of "step functions" in cross sections seemingly attributable to major-shell radii[15] strongly suggest that only the rudiments of this field have as yet been glimpsed. Precision experiments with a wider variety of nuclei and bombarding emergies are urgently needed.

Consideration of the latest data[16,17] with heavy-mass projectiles and targets at energies approaching 10 MeV/amu indicates, in contrast to the light-nucleus data, that a simple, unified formulation of the process in terms of an $R_{critical}$ is not apparently universally valid[15,16]. Recent experimental evidence[17] points towards a vanishing σ_F at energies up to 10 MeV/amu as the composite projectile-plus-target mass is increased. It is vital to ascertain whether increased center-of-mass energy, and hence smaller distances of closest approach, will yield measurable fusion rates for heavy systems. Along with study of light-nucleus fusion on the injector cyclotron, medium mass nuclei should also be studied in the 10 MeV/amu range. Heavier masses will be studied in the >10 MeV/amu region when coupled operation is available.

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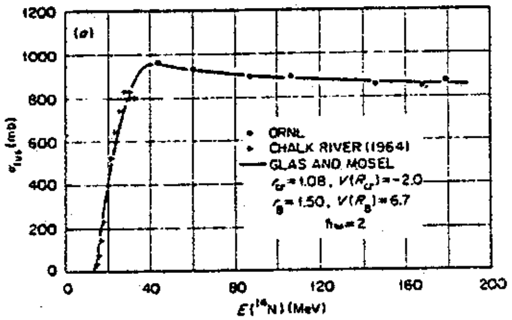

Fig. 1.(III.2.2)--(See Ref. 4). Measured fusion cross sections as a function of bombarding energy. The solid line is a theoretical fit to the data (see text).

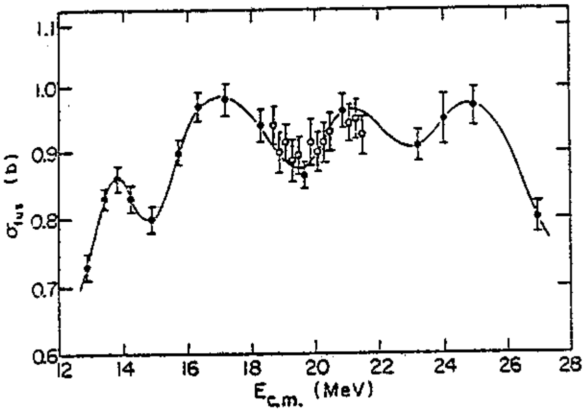

Fig. 2.(III.2.2)--(See Ref. 14). Total fusion cross section as a function of the c.m. energy. The closed circles represent measurements of the complete angular distribution. The open circles represent measurements at $\theta_{lab}=6°$ only, where the total fusion cross section was estimated from the ratio $\sigma_{fus}/[d\sigma_{fus}/d\Omega(6°)]$ at neighboring energy points. The solid line is only to guide the eye. Note the suppressed zero on the cross-section scale.

III.2.3 Characteristic Heavy-Ion Processes

The dawning recognition that a major portion of the total reaction cross section for high energy heavy ion collisions is manifested in a process intermediate between complete fusion and the peripheral, quasi-elastic processes is the source of much of the present excitement in heavy ion physics. This new and unexpected process was first clearly recognized in pioneering work at Dubna, with the ^{22}Ne + Th (ref. 1) and ^{40}Ar + Th (ref. 2) reactions, and in complementary work at Orsay[3,4] and Berkeley[5]. This earlier work and much recent work[6-8] have concentrated on systems of large composite mass. Current research[9-12] is, however, showing that the CHIP phenomenon is already clearly present for $A_p + A_t \sim 40$. The key signatures of this process are (Fig. 1) the emergence after collision of two fragments, roughly comparable to the projectile and target nuclei in masses and with center-of-mass kinetic energy approximately equal to the Coulomb potential energy of two adjacent charged (Z_t and Z_p) spheres, and (Fig. 2) a concentration of reaction cross section in the vicinity of the grazing angle. Hence, the process appears to be one in which kinetic energy is fully equilibrated, but mass, charge, and momentum are only partially equilibrated. A graphic explanation for the general nature of this kind of event, is pictured in Fig. 3: two nuclear spheres collide, stick together for a partial rotation, with equilibration of energy and some exchange of mass occurring as they stretch apart and separate.

Beyond establishing the ubiquity and central importance of the CHIP reactions, present experiments, with their increasing detailed view of the distribution of the reaction products in terms of atomic number, mass, energy and angle, do not yield a particularly coherent picture. For example, the scattering of ^{84}Kr on ^{208}Pb-^{209}Bi has been studied at laboratory energies between 500 and 700 MeV with the conclusion that the total reaction cross section is dominantly comprised of "quasi elastic" and "deep inelastic" quasi-Kr reaction products which have angular distributions strongly peaked near the grazing angle.[4,5,13] Unexpected aspects of these results are an incipient failure of full equilibration at the highest energy, and a fusion-fission cross section[13,14] lower than that expected from the constant R_c hypothesis (discussed in Sec. III.2.2). Nor is there evidence for the nuclear "orbiting" postulated[15] to explain the forward-angle cross section strength observed for Ar and Cu scattering.[2,16] In general, bombardments with lighter-mass ($A \tilde{<} 120$) projectiles show more forward peaking, larger fusion cross sections and/or more dispersion in the range of mass products. As mentioned in Sec. III.2.2, a fundamental conceptual problem involves a distinction between a) the fission products of complete fusion, with their $(\sin\theta)^{-1}$ angular distributions and tendency toward mass symmetry and b) the fringes of the mass dispersion of the deep inelastic process which have characteristics similar to those of fusion-fission events.

Overall, it appears that even the major boundaries of the deep-inelastic process remain to be determined. The extension of present studies to all masses through ^{238}U at energies up to ~8 MeV/amu should take place in the next two years. It seems obvious, however, that a range of significantly higher energies is needed to clarify the situation. Surveys on this topic with the higher energies from the CSC complex seem certain to be high on the list of initial research projects of the new laboratory. The factor of 2 increase over the GSI and Super-hilac uranium energies, the factor of 4 and 8 increases in Xe and Kr energies, respectively, and the factor of 20 increase in Ar energies over the present linac and cyclotron values, will permit experiments which should aid greatly in distinguishing between the various models for this phenomenon. In addition to this expansion in the range of bombarding energies studied, accompanied by a more detailed inspection of the dependence of the effect upon projectile and target mass, efforts must be continued in the direction of gaining a higher resolution of the features of the emission spectrum. Prime questions to be answered concern the fate of the initial angular momentum corresponding to a surface contact of two heavy ions and the detailed disposition of the lost kinetic energy. The study of the characteristics of the decay fragments as inferred from gamma-ray multiplicities typify these more complex experimental investigations.[17]

A full understanding of the CHIP phenomenon will probably be coincident with a comprehensive and unified picture of all aspects of heavy-ion reactions in the subsonic regime. It will entail a qualitative expansion in the understanding of nuclei in macroscopic, semi-classical terms and the uniting of this representation with a more fundamental microscopic picture. The first efforts[15,18-21] in these directions are promising both in the insight they yield into current observations and in the new aspects of nuclear phenomena which involve concepts such as mass diffusion and radial and tangential friction. However, beginning efforts to understand deep inelastic phenomena in terms of underlying fundamental processes have invoked couplings either to giant resonances[22] or to successive nucleon transfers[23] but not to both. Still another such theoretical approach involves direct calculation from general principles via time-dependent Hartree-Fock techniques.[24,25] The present diversity and lack of cohesion in both theoretical and experimental work are symptomatic of the explosion of interest in this field. The capability of performing precise measurements for a rationally gridded set of nuclei and bombarding energies which will be provided by the CSC system should allow clarification of the experimental picture and a sharper focusing of the theoretical efforts to understand the phenomenon.

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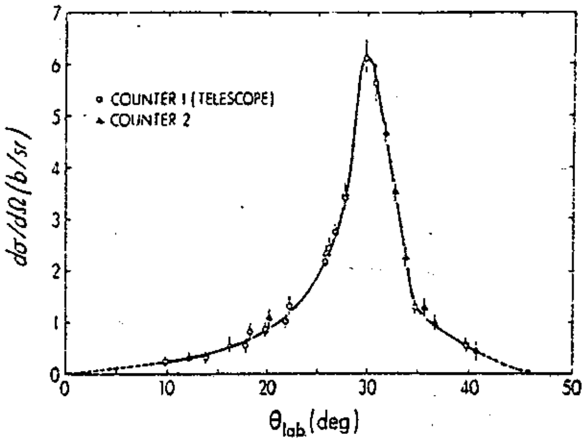


Fig. 1.(III.2.3).--(See Ref. 6). The differential reaction cross section in b/sr as a function of laboratory angle for the reaction $^{209}Bi+^{136}Xe$ at 1130 MeV (laboratory energy).

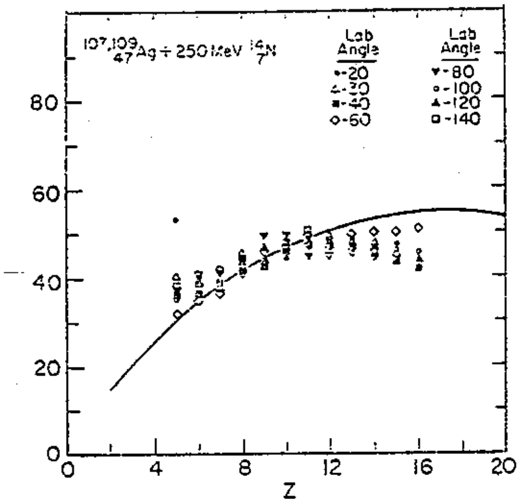
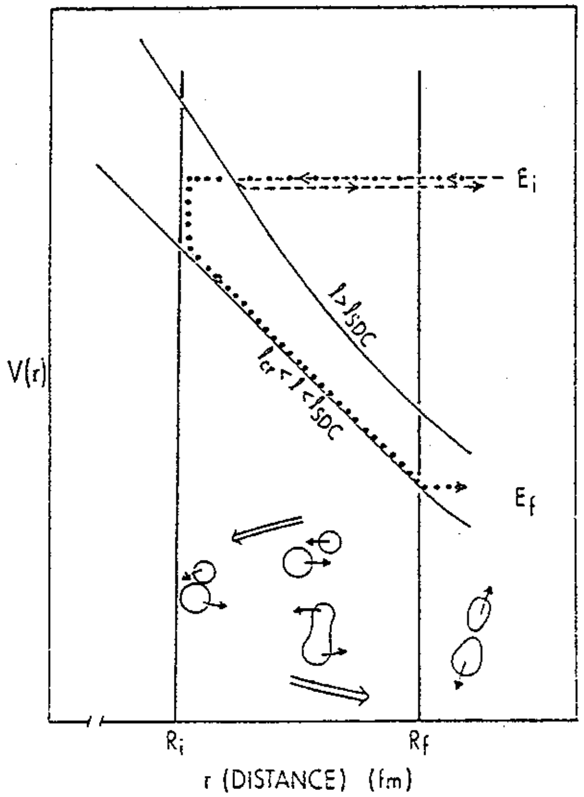


Fig. 2.(III.2.3).--(See Ref. 10). Most probable kinetic energies of the relaxed peaks versus Z in the c.m. system. The solid curve is the expected kinetic energy arising from the Coulomb repulsion of two spherical fragments in contact. Except for forward angles and for Z near the projectile, the observed kinetic energies follow the solid curve at all three bombarding energies

Fig. 3.(III.2.3).--(See Ref. 21). Schematic representation of the energy for the strongly damped collision process. For $\ell>\ell_{SDC}$, the projectile and target fail to reach a distance R_i at which they interact strongly and, therefore, elastic scattering or few-nucleon transfer occurs. For angular momenta $\ell_{cr}<\ell<\ell_{SDC}$, projectile and target reach R_i where the radial and rotational kinetic energies are suddenly dissipated. At this point the system sticks and a neck develops during rotation and stretching under the influence of a repulsive conservative force and a retarding radial friction. The sketches in the lower part of the figure indicate the shape of the system as the strongly damped collision develops in time.



Addendum to III.2

In the two years since the CSC proposal was written, a considerable amount of information on the nucleus-nucleus collision process has emerged. This information and the resulting improvements in the models have reinforced the importance of a high quality accelerator to bridge the gap between the present lower limit of the Bevalac and the upper limit of lower energy heavy ion accelerators.

Elastic scattering, for example, will continue to be of high interest, but these experiments are all but impossible without good energy resolution. As the mass of the target and projectile increase, so do the energy resolution requirements of the accelerator. Likewise, probing more deeply than do existing measurements into the nucleus-nucleus potential with elastic scattering also requires higher and higher energies.[1] The recent discovery[2] of a rapid transition from moderately absorbing and refracting potentials to very strongly absorbing and diffracting ones as the projectile mass goes from 6 to 12 is an indication of the kind of information which will be obtained when the CSC beams permit measurements of elastic scattering at energies at which Coulomb domination has disappeared even for heavy targets and projectiles. The recently discovered[3] back-angle rise and the intermediate and gross structure in the elastic scattering of ^{12}C and ^{16}O on ^{28}Si immediately calls for an extension of experiments into the region of higher masses and energies which the CSC could provide.

In the field of transfer reactions new results[4] on the energy dependence of transfer reactions induced by ^{16}O ions on ^{208}Pb have revealed an unexpected failure of DWBA. At present it is completely unclear whether this failure is inherent in the model or whether it is peculiar to the particular choice of the system studied. The extension of these experiments to higher energies and projectile mass will be important in clarifying these problems with DWBA which must be solved before studies of the type outlined in Section III.1 of the proposal can give reliable nuclear structure information.

Studies of deeply inelastic collisions (or CHIP as they were called in Section III.2.3) are still limited to the low energy domain $[(E-V_c)/A \leq 5$ MeV/A]. After the initial simplicities, more questions are now being raised than answered. Recent experiments which resolve individual isotopes[5,6] have shown that the charge-to-mass ratio of the products is rapidly equilibrated. Higher energies and hence shorter interaction times will permit a view of the non-equilibrated products which may reveal much more about the interaction process. There are also some recent interesting preliminary data[7] which relate to the very successful transport theories.[8,9] These data question the idea that energy independent transport equations can be used.

A topic was largely passed over covered in the original proposal, but which is now of increasing interest, is heavy-ion induced fission. Measurement of coincident fission fragments yields information on the momentum transfer to the fissioning nucleus prior to scission. It has thus been established that nuclear fission becomes increasingly important for reactions in which only part of the projectile momentum is transfered to the target nucleus.[10,11] by combining detection of the fission fragments with other coincident products such as high energy light particles, one can hope to obtain information on the momentum transferred in various kinds of collisions-for example fireball events. The first experiments[12] of this type are underway at Berkeley with 20 MeV/A ^{16}O beams.

Recently a remarkable similarity has been observed[13] for peripheral reactions induced by ^{16}O at 20 MeV/A and 2 GeV/A incident energy. Whereas the relative cross sections for the production of elements Li, Be, B, C and N change rapidly below 20 MeV/A, these do not change appreciably in going up to 2 GeV/A. However isotope production cross sections are very different at 20 MeV/A and 80 MeV/A but seem to remain constant above 80 MeV/A.[14] No measurements presently exist between 20 and 80 MeV/A. These findings indicate that a transition region for peripheral collisions is present well within the energy range of the CSC.

In peripheral collisions with high energy ^{16}O ions, it has also been recently shown that the widths of the energy spectra change little above 20 MeV/A.[15] Interpreting these spectra in terms of nuclear temperature, one finds a limiting value of about 8 MeV. It is intriguing that this corresponds to the temperature limit of bound nucleons in a fermi gas model at equilibrium. However at present, this phenomenon is not completely understood, and studies with heavier projectiles, which should produce higher temperatures,[16] are required.

Another idea in heavy ion collision studies is the formation of "hot spots" in deeply inelastic collisions.[17] The detection of hot spots and the measurement of the spatial extent of the interaction region will be studied in the future via particle-particle correlation experiments. Some features of proton spectra[18] observed in ^{16}O induced reactions at 20 MeV/A might perhaps be related to nuclear fireball observations at the Bevalac. The CSC facility can be used to study the entire energy range from low energy evaporation, through hot spot formation and into the fireball regime. The fireball[19] and firestreak[20] models have had considerable success in explaining high energy central collisions. In this simple geometric description, the projectile gouges out a chunk of matter to produce a thermally equilibrated highly excited object. The agreement of the predictions with the observed energy and mass dependence of the various particles emitted is astonishing particularly when baryonic degrees of freedom and density gradients in the collision zone (the firestreak model) are included. The energy spectra of light fragments from the bombardment of Al and U targets by ^{4}He and ^{20}Ne between 250 and 2100-GeV/A have been examined.[20] Using a multiplicity filter to accentuate central collisions, it was shown that the temperature of the fireball produced at the interaction region reaches values up to 100 MeV.

Many objections to the fireball picture have been made, the most frequent being that there does not seem to be time enough to reach equilibrium. Other models have been suggested, including inter-nuclear cascades or knock-out processes,[21] which avoid that question and predicts different correlations for the outgoing fragments (still to be checked experimentally). Nevertheless the success of the fireball and firestreak models are impressive.

It seems clear that the fireball model cannot continue to work at lower energies because eventually the projectile can no longer pass through the target nucleus. The transition region between 50 and 200 MeV/A, which is well matched to the CSC energy range, will provide a key testing ground for models of central collisions. If a thermal equilibrium picture is really appropriate, the apparent size of the fireball should increase and the temperature fall as total absorption is approached. On the other hand, if direct or knock-out schemes are appropriate, no such behaviour is to be expected. Of course, experimentally this will be a difficult energy range to deal with because of the intrusion of peripheral reactions into the kinematic region of the fireball. Multiplicity filters and the high intensity beams of medium-weight nuclei available from the CSC will be essential in clarifying these problems.

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III.3 New and unusual nuclei

Present knowledge of nuclear systematics encompasses a narrow band of nuclei which extend from the neutron and proton up to the transuranic elements. It is along this line that intensive experimental study has taken place, and it is principally with these data that nuclear theories have been tested. A major extension of knowledge further along the valley of stability is a most exciting possibility. Various theories dealing with nuclear binding energies and decay barriers predict "islands of stability" to exist near Z=114,126... These regions are separated from the known valley of stability by a sizeable region thought to be dominated by rapid spontaneous fission.

Normal nuclear formation processes appear incapable of bridging the gap from the end of the valley of stability to the "super heavy" islands. Despite this, very recent evidence[1] indicates that "super-heavy" nuclei near Z=126, N=228 may have been formed in primeval processes and have survived in quite some numbers and variety. The further testing of these seemingly contradictory conclusions will be of great importance to many aspects of heavy-ion science. A number of mechanisms which use high-energy heavy-ion beams can in principle create super-heavy nuclei in the laboratory; preliminary investigations of several of these have, however, not yet given a positive result. Nonetheless, the great interest such systems hold for atomic and nuclear physics and chemistry demands serious further efforts to produce and isolate such nuclei. The CSC accelerator will be an extremely effective facility for pursuing such a search.

A more diverse and equally fundamental area of study can be pursued in the directions perpendicular to the valley of stability. Reliable estimates suggest that 80% of the nuclei stable to nucleon emission are yet to be discovered. The interest in creating and determining the properties of these new nuclei is, moreover, not merely a multiplication of present knowledge commensurate with the added specimens. Rather, since many of these new nuclei lie quite far from the line of stability, information about nuclear structure and processes will emerge that is qualitatively different and potentially more critical than that obtained along the valley. The large Q-values associated with the ever steeper walls of the valley of stability and the quite different properties of the T=0 and the T=1 nucleon-nucleon interaction are two of the reasons for expecting that moving nuclear studies away from normal N-Z ratios will be vastly informative.

It is clear that the practical barrier to extending our understanding of nuclei by studying nuclei with abnormal N-Z ratios lies in the difficulty with which they are produced. Thus at present the production of nuclei far from beta stability is limited by the type of projectiles and beam characteristics available with existing accelerators. The ISOLDE project for example, studies those nuclei produced by 600 MeV proton bombardment, and the work of Volkov's group at Dubna is hindered in accuracy by the energy resolution of their beams. The MSU group's high-precision mass measurements could be extended to nuclei much farther from stability if higher-mass high-energy beams were available.

The CSC accelerator, with its wide range of projectiles and energies and its good beam quality and intensity, will have the capability of utilizing near optimum reactions for producing any desired nuclide. The best techniques for forming the nuclei of interest will be an important first study for projects in this area. The general class of nuclear reaction required is dictated usually by the goal of the experiment, but the particular choice of target, projectile and energy is usually the key to the success of the experiment. The following subsections consider the principal alternatives for producing and observing unusual nuclei and some of the things which their study will allow us to learn.

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III.3.1 Production of nuclides far from stability

a) Transfer reactions

Because of their very low cross sections, transfer reactions are primarily utilized to establish the particle-stability of a nuclide and to measure its mass, rather than to produce it in quantities sufficient for off-line measurements of other properties. The additional demand of a two-body final state with both outgoing particles in the ground state reduces the cross section even further, but it permits the determination of the mass from the Q-value of the reaction. If this requirement is relaxed, one must then measure the mass of the particle itself, which is much more difficult to do with high precision. Of course, if one only wants to demonstrate particle stability it is sufficient to detect the nucleus and there are then no requirements on the reaction.

Even for the case in which the physics information demands measurement of a two-body final state with both nuclei in the ground state, a wide choice of reactions leading to the same goal can be available. Consider the determination of the mass of ^{22}O: the nucleus itself can be detected, as for example[1] in the reaction $^{232}Th(^{22}Ne,^{22}O)^{232}U$ or an associated particle as, in the examples of the $^{18}O(^{18}O,^{14}O)^{22}O$ (ref. 2) or $^{26}Mg(^{22}Ne,^{26}Si)^{22}O$ reactions. In addition to these three paths there are many other conceivable ways to reach ^{22}O. In general it has been found that rearrangement is much more prolific than transfer of multiple identical particles, and one would therefore expect reactions like the first listed above to be the most efficient provided good energy resolution can be maintained.

The bombarding-energy dependence of the cross sections of multiparticle transfer with heavy-ions is practically unknown since studies with rare transfer reactions have almost always been run at the highest energy available from the accelerator being used. Increased bombarding energy gives several apparent production increases from such known effects as thicker targets and the ability of the targets to withstand higher currents. However, these factors could be offset by sharply dropping cross sections. Absolute energy resolution is extremely important in studies using transfer reactions, and increased beam energy can therefore adversely affect the results. The optimum precision is obtained when the figure of merit $\sqrt{Y}/\Delta E$ is maximized, where Y is the yield per second (assumed feasible) and ΔE is the energy resolution in the final state (assumed sufficient to resolve excited states). Target thickness enters both Y and ΔE, as does the beam energy. Rough calculations show that an energy of 20-50 MeV/nucleon is the optimum range for the lighter heavy ions but this has not been experimentally verified. Establishing the empirical rules for production efficiency would therefore be an important first item of study. It is also not known whether transfer reactions still remain useful for production of rare, very heavy nuclei. To know the useful limit requires experiments establishing cross section dependence on A and E as well as on Q-value, transferred isospin and transferred number of nucleons.

b) Compound nucleus formation

As in the case of transfer reactions, there will often be a large number of feasible compound-nucleus reactions which can produce a given nuclide. Unlike transfer reactions, however, the main effects which determine cross sections are relatively well known and production efficiencies can be calculated, e.g., with such codes as ALICE.[3] These reactions typically produce neutron-deficient nuclides with the highest probabilities. Hence, similar target and projectile masses are the best combinations to produce nuclides as far as possible from the line of stability. As in the case of transfer reactions, the optimum bombarding energy is strongly dependent on the goal of the experiment.

Another question is whether the reaction codes satisfactorily predict the relative yields of different reactions and different energies which lead to the same nuclide. For example, the cross sections predicted by ALICE for production of ^{172}Pt with a ^{144}Sm target (at the energy at which each cross section is maximum) are:

Reaction	Energy (MeV)	Cross Section (mb)
^{144}Sm + ^{40}Ca	280	2.2
^{144}Sm + ^{36}A	200	1.1
^{144}Sm + ^{32}S	160	0.5

Similarly calculated maximum cross sections for production of various Er isotopes using the ^{120}Sn(^{40}Ca,2pxn) reaction are:

A of final Nucleus	x	Cross Section (mb)
157	1	0.049
156	2	4.15
155	3	11.9
154	4	18.6
153	5	33.8
152	6	75.3
151	7	46.2
150	8	25.4
149	9	0.77

According to the calculations, the energies at which each of these cross sections reaches its maximum vary between 80 and 240 MeV. These predictions are, however, largely unverified even for light projectiles, and experimental checks are needed.

c) Other Processes

Transfer and compound-nuclear reactions are somewhat specialized with respect to which nuclei are produced with appreciable cross section. There are also much less specific production methods. For example, heavy-ion-induced fission should produce a wide range of mass numbers, and the range should grow with increasing mass and energy of the projectile. This must be compared to spallation by H and He bombardment as a means of producing neutron-rich nuclei. No data are presently available on the products of bombardment of heavy nuclei with such light projectiles as 800 MeV alphas or ^{3}He's. It is known that protons in this energy range produce light ions all the way to the neutron drip line.[4] Heavy-ion spallation will certainly extend this region, but the cross section for producing a particular nucleus may be unworkably small. Exploratory experiments will be an important guide.

One can also speculate that the "CHIP" reactions at angles far from the grazing angle may result in the emission of some species near the projectile mass but quite different in T_z. The CHIP events have such a large probability that even if a small fraction produces nuclides far from stability, the fact that they have a small range of energies may make them interesting candidates for study.

In summary, the CSC facility will open a wide variety of possible processes for producing new nuclei. Experimental programs in this area will involve a major element of systematization of knowledge about alternate production processes. At the same time as this is done, measurements of properties of the new nuclear species produced can be moving vigorously forward.

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III.3.2 Detection and measurement of nuclei far from stability

Key elements in experimental work with "exotic" nuclei are collection time, detection efficiency, and background suppression. Technical aspects of possible electric- and magnetic-field devices for charged-particle analysis are discussed in Section IV, as are features of various detector systems, but we will look ahead with a few qualitative remarks. Experience with transfer reaction measurements of exotic light nuclei indicates that a concentrated, all-fronts attack on the problems of small cross sections coupled with high backgrounds can be surprisingly successful.[1] This experience underscores the value of large (~100 msr) solid angles for detection. The optimum approach may involve sophisticated multiparameter detector arrays combined with electromagnetic collection and analysis. Of course, in all this, an energy resolution capability comparable to that inherent in the reaction products must be maintained.

Off-line experimentation with exotic nuclei necessitates fast transfer of the activity coupled with high transmission efficiency. A variety of techniques are currently used in such work and are being considered for integration into the CSC facility. Of course, basic He-jet devices will play a central role. Recent developments, such as the use of aerosol dispersions[2] and of cryogenic techniques,[3] suggest the exciting untapped potential in He-jet technology.

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III.3.3 Physics of nuclei far from stability

Interest to date in nuclides which have N-Z ratios far removed from the valley of stability has concentrated first on simply establishing their existence, that is their stability against fast hadronic decay. Subsequently, or simultaneously, attempts are made to measure the masses of their ground states. These data are then parameterized in terms of one or another of the mass formulas.[1-4] The mass systematics of nuclear ground states are intrinsically interesting in themselves. In one context they yield information on the general macroscopic parameterization of nuclear energy in terms of volume and surface effects, etc. In another context, very general symmetry features of the nuclear interaction are tested. In either context, study of masses far from the line of stability offers the opportunity to test theoretical concepts founded on close-to-stability data.

At a deeper level, the mass formulas can be viewed as ways to systematize binding energy data. In this view, agreement of mass data from new exotic nuclei with an existing mass formula illustrates an increasingly universal symmetry which then demands explanation at a more microscopic level. Likewise, the failure of experimental measurements to follow schematic predictions at increasing distance from stability indicates either a breaking of a symmetry or the failure to consider terms which, while unimportant near stability, become significant at different N-Z ratios.

Mass measurements are approaching completeness only for the lightest nuclei. The singular example of the work by Klapisch and collaborators[5] on the Na isotopes illustrates the excitement and richness which await a wider exploitation of this field. Their measured masses of ^{31}Na and ^{32}Na are violently at variance with ordinary theoretical formulations and suggest that dramatic disturbances of shell closures can occur at very large N-Z ratios. It should be noted that the "relative masses" (i.e., excitation energies) of states in the same N-Z system may ultimately reveal more about fundamental nuclear constitution than does the ground state mass alone. Excitation energies of the first excited states of even such "simple" exotic nuclei as ^{21}O and ^{22}O will reveal much more about the relative single-particle and two-particle aspects of the effective nuclear interaction and about its isospin dependence than do much more copious data on more normal nuclei. Hence techniques for mass measurements, such as transfer reactions, which allow determination of excited state masses as well as ground state masses, have a special appeal. The first results[6] of such experiments show promise of what can be accomplished with concentrated efforts founded on optimum accelerators such as the CSC system.

While theoretical work has tended to concentrate on lighter nuclei, experiments on heavy systems, such as the work[7] on the Hg isotopes with the ISOLDE system, indicate that equally exciting discoveries await thorough exploitation of mass measurements in the heaviest possible systems.

Equally exciting and challenging is the opportunity to go beyond measuring the masses of exotic nuclei and attempt to determine experimentally some of their decay properties. The recent work of Hardy[8] and collaborators suggests some of the new types of information on nuclear properties which can be obtained via study of such phenomena. The large Q-values associated with beta decay far from stability contribute to making a variety of beta-associated effects amenable to new types of experimental studies, and such features as Gamow-Teller strength functions from beta-delayed proton decay and the Fermi decay of heavy N=Z systems can be investigated.

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Addendum to III.3

As was discussed in Section III.3, the CSC is an ideal accelerator for studies of nuclei far from stability, and recent developments have made the prospects even more exciting. Using the spallation of Uranium by high energy protons and very clever experimental techniques, Klapisch and coworkers[1] have pushed mass and lifetime measurements and gamma ray decay studies in the sodium isotopes out to ^{35}Na, which has an excess of 12 neutrons over the stable isotope, ^{23}Na. Similar techniques can be used to study many nuclei far from stability, which were shown to be produced prolifically in the bombardment of ^{232}U by ^{40}Ar, at Dubna.[2] Such large yields of exotic nuclei have now been shown to be a general property of deep inelastic[3] or CHIP collisions as was suggested in section III.3.1.

The first precise mass measurements with heavy ion beams have also been carried out in recent years. The best work has been done at Chalk River,[4] Canberra,[5] Orsay[6] and Heidelberg.[7] For example, the Heidelberg group achieved an accuracy of 30 keV for the mass of ^{17}C and feel that a considerable improvement would be obtained at higher energies. Precise high energy ^{48}Ca beams on neutron-rich targets are a particularly exciting upcoming development in this field.

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III.4 Nuclear and atomic phenomena under extreme conditions

In this section we consider novel nuclear phenomena which may be generated at three different threshold energies[1] accessible with the CSC accelerator. The lowest of these thresholds, the "sonic boundary", occurs when the velocity of the projectile nucleus equals the speed of "sound" in nuclear matter. The required energy is estimated to be about 22 MeV/amu for a system such at Kr+Pb. Another threshold, that leading to the "strong compression" regime, is associated with the energy necessary to overlap two similar large nuclei completely, thus doubling the normal nuclear density. Estimates for the energy of this threshold lie near 160 MeV/amu. Lastly, the threshold for meson production in nucleus-nucleus collisions will be crossed well below 140 MeV/amu by virtue of the Fermi momenta of the nucleons in the projectile and target nuclei.

We are considering here the creation of mass and energy densities unavailable to conventional nuclear science. Some aspects of these different environments have not yet been dealt with theoretically at any sustained level. Some phenomena which may possibly result are predicated on exciting but frankly speculative theories such as the Lee-Wick conjectures[2] about abnormal nuclear states which have an order of magnitude more binding energy than normal nuclei. Even the best developed theories for phenomena in these regimes incorporate large uncertainties which arise from formal and conceptual difficulties and from lack of knowledge about relevant nucleon and nuclear parameters. Such theories are concerned with the conditions