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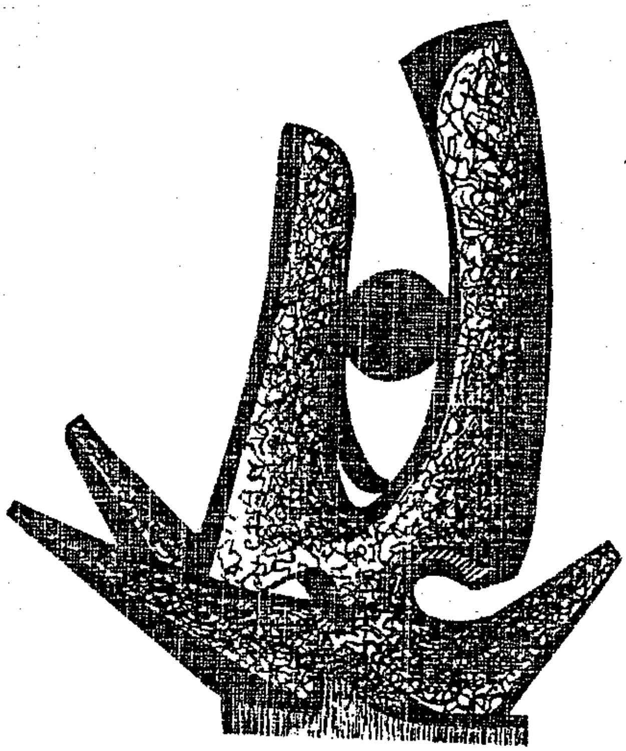
MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

Operating Proposal

NSCL Research Facility
and
MSU Nuclear Science Program



MARCH 1983

MSUCL-404

PROPOSAL

to the

NATIONAL SCIENCE FOUNDATION

for

OPERATING SUPPORT

of the

NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY
RESEARCH FACILITY

and the

MICHIGAN STATE UNIVERSITY
NUCLEAR SCIENCE PROGRAM

Period: November 1, 1983 - October 31, 1986

Submitted by

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ENDORSEMENT

This proposal has the approval and support of Michigan State University.

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INTRODUCTION AND STATUS

INTRODUCTION and STATUS

This proposal requests funds to support the operation of a national user facility based on the "K500" superconducting cyclotron and for support of the research activities of the MSU experimental nuclear science group. At the time of writing the first running period on the K500 cyclotron is in progress; newly acquired samples of raw data are frequently seen on the laboratory bulletin board and the excitement of possible novel implications is apparent in the vibrant tone of corridor discussions. Completion of the first experimental running period is expected in a few months and the second running period is scheduled to begin in the summer.

The three year period covered by this proposal (Nov. 1, 1983 through Oct. 31, 1986) is expected to be both a time of prime scientific exploration with the "Phase I" facility and a period of high productivity for the MSU nuclear science group. Unfortunately these years are also expected to be a period of continued stringent funding for nuclear science as a whole, and the operation of the NSCL facility and the support of the large MSU research group combine to give a funding request which is a significant fraction of the total funding of the NSF nuclear physics program. Noting this, the items which we have included in this request have been subjected to extensive internal review and discussion, addressing the appropriate level of compromise between the national need for frugal, tightly budgeted programs and the compelling scientific desire to exploit a novel new facility and to support the research of an experienced and productive in-house staff. In this internal review the funding level proposed for each activity has been carefully screened in order to arrive at the facility operation plan and the research plans which are described in the several sections of this proposal. The cost tables attached to each section, in conjunction with the accompanying text, are intended to describe each program at a level of detail on both

I. Facilities Operations and Development

II. User Services and Support

III. Major Special Items

IV. Staff Research

V. Accelerator Research and Development

Section AP-I of the separately bound Appendix gives the NSF guidelines for determining assignment of expenditures to the above categories.

Each of the above defined major sections of this proposal has its accompanying budget; a summary budget section at the end of the proposal combines the budgets contained in the five programmatic sections into an overall budget for the requested grant. A convention which has been adopted in formulating budget tables is to first present all budgets in terms of present (1983) salaries and prices. A correction for decreased purchasing power due to estimated inflation is then inserted in Section VI to give the final "Summary Proposal Budget". This procedure hopefully makes the budgets in each of the programatic sections of the proposal directly interpretable in terms of current known costs. The less predictable correction for effects of future inflation is separately addressed in Section VI. Finally, Section AP-2 of the Appendix gives Curricula Vitae and publication records for the principal investigators and for other staff participating in the nuclear research program and Section AP-3 of the Appendix gives an alphabetical list of the staff of the Laboratory with a brief statement describing the principal duties of each person.

It seems useful to describe the guidelines which distinguish the operating program from the construction program. In terms of goals, the two programs are markedly different and this difference is used to determine assignments of various activities. The goals of the operating program are:

In contrast to the broadly defined objectives of the operating program, the objectives of the Phase II construction program are quite specific, namely, realization of the array of nuclear research equipment and building structures described in the Phase II proposal, actual items ranging from the K800 cyclotron and experimental apparatus to data processing and analysis equipment. Supporting documents furnished to Congress as a part of the line item budget process describe the items to be constructed, the performance goals and the research objectives. These statements then became the basis for the appropriation. The construction project thus has a sharply defined goal--the realization of working hardware with properties as described in the line item legislation.

Budgets for the construction project provide for all costs properly allocable to the project including both external procurement costs and relevant internal costs such as wages, salaries, fringe benefits, etc. for personnel working on the project. (Costs for many internally stocked items are too small to justify detailed record keeping; such costs are distributed between operations and construction on a prorated basis.) Budgets for the Phase II construction project also provide support for Research and Development costs related to the construction project for the years 1980 through 1984, this being an item not usually included in federally funded construction projects, but which was nevertheless specifically included for Phase II in the course of the unusual series of budget actions which evolved for the project. This aspect of the Accelerator Research and Development component of the Laboratory's program will shift from the construction budget to the operating budget in the second year of the three year period covered by this operating proposal. This work is then described in section V while noting that, for the first year, most of the effort will be funded from the construction budget.

academic year would be devoted to teaching, non laboratory committee work, etc., and since half of the academic year is 40% of the 12 month year, 40% would be entered in the "NON-NSCL" column of Table II for this individual. The remaining 60% of the individual's 12-month effort would be Laboratory related and divided amoung various activities as shown in the Table. Budget descriptions which appear in the later programmatic sections of this proposal first show the FTE's and salary costs allocable to the particular category in direct correspondance with the effort distribution from Table II; after this, the portion of the salaries paid by the University is deducted to give a final budget entry which is the grant supported portion of the salaries for each budget category.

Table II does not include personnel of the separately funded nuclear theory program although that program is clearly a critical central element of the total Laboratory program. Faculty supported under the theory grant are Professor Bertsch and Assistant Professors Scholten, Stoecker, and Toki. (Theory personnel are included in the writeups in Section AP-3 of the separately bound Appendix.)

Table II includes four positions for which candidate searches are presently in progress, 3.1 of these (on an FTE basis) being associated with the operating program and 0.9 being associated with the construction project. Details of the need for these additional persons are described in the proposal sections where the additions are planned. A visual image of the Laboratory staff is given in Fig. 1 which is a photograph of many of the staff grouped around the K500 cyclotron.

Turning to a review of program status, an overall comment at the time of writing of this proposal (March 1983) might well describe the state of the laboratory as one of high hope and expectation. Over a period of years a large investment of construction funds has flowed into the laboratory, the object of this investment being construction of a

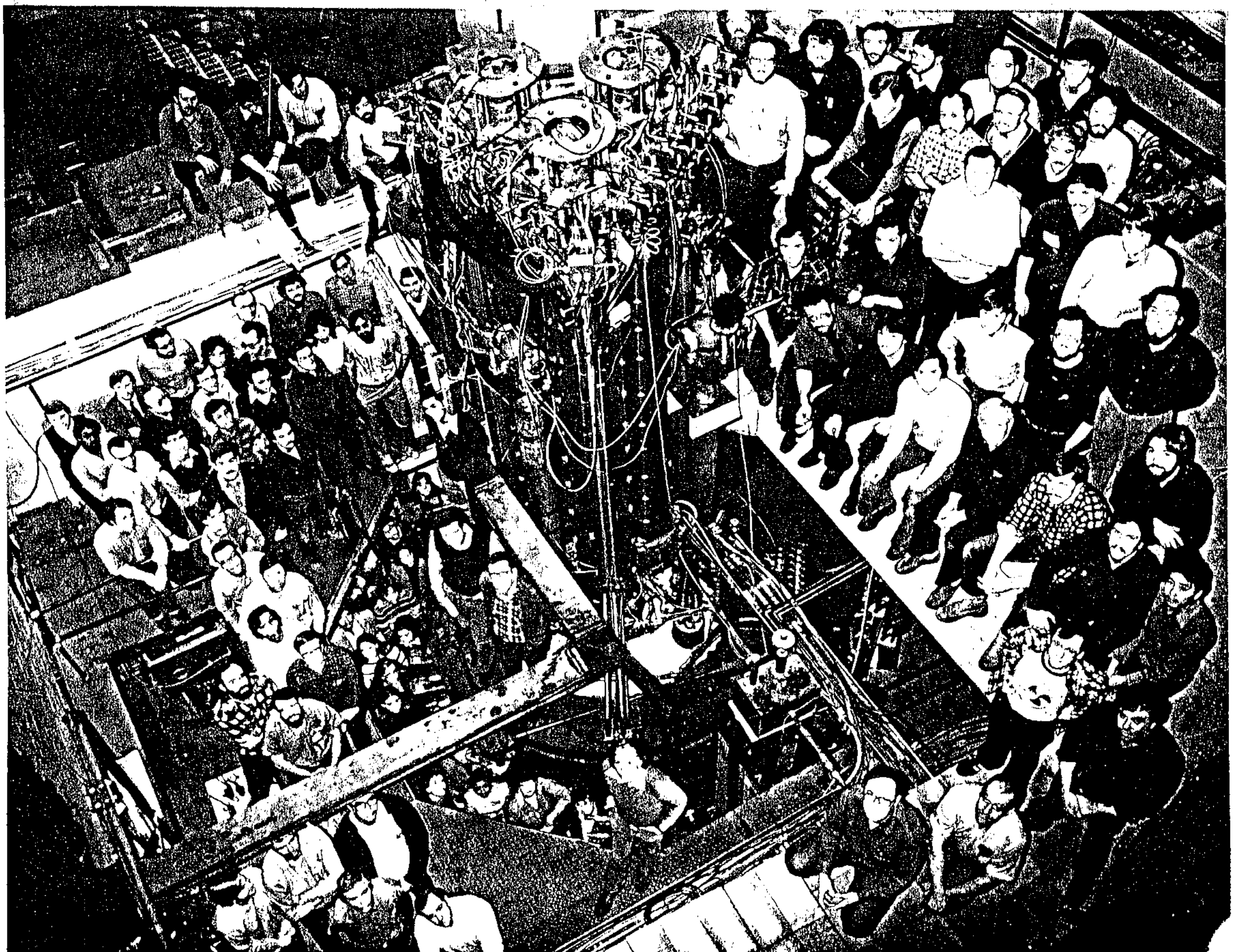

Fig. 1 - A top view of the K5ØØ cyclotron and most of the NSCL staff. (June 1982)

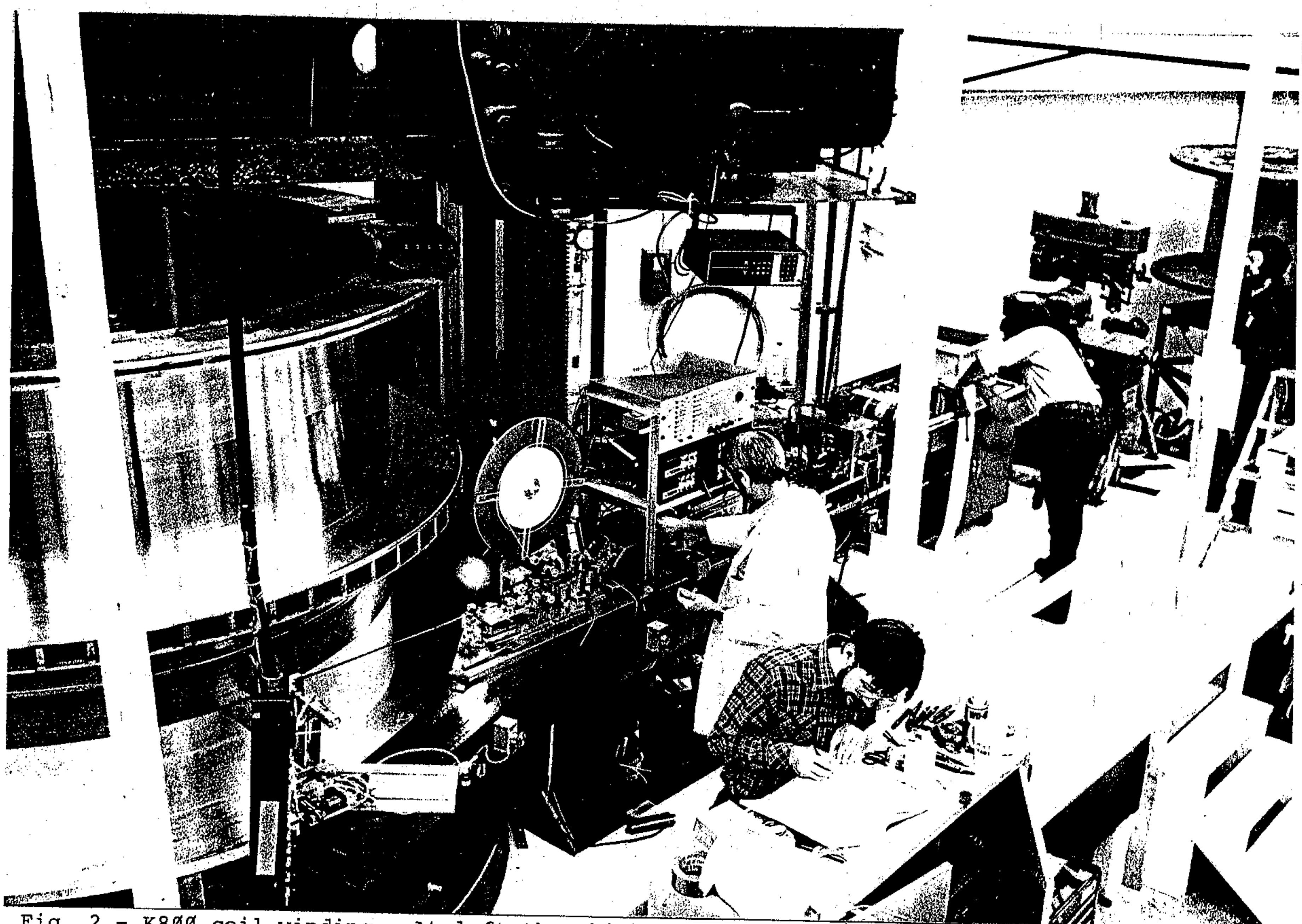

Fig. 2 - K8ØØ coil winding. At left-the shiny stainless steel bobbin mounted on a vertical lathe. Wire feeds from spool(far right) through inspection and insulating equipment (center).

the system used for the K500 coil, but significantly upgraded to be much less dependent on continuous intensive operator attention. Winding of the coil is expected to be completed in July and the first full field test of the magnet should occur in December. A photograph of the grid circuit of the rf amplifier is shown in Fig. 3. The next major rf system milestone, scheduled for June is operation of the first rf amplifier at full power into a dummy load. High power operating tests on a full dee and dee stem assembly should begin in January 1984 with the expectation of achieving full design voltage several months later.

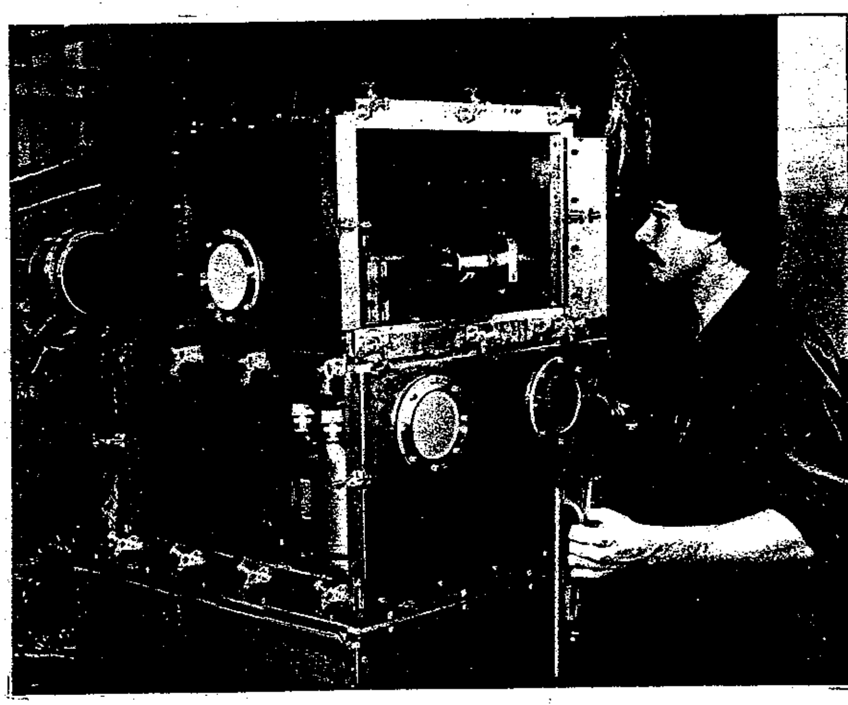

Fig. 3. View of the first K800 rf amplifier. The 200 kilowatt power tube is visible at the lower left where an access panel is removed and driver tubes are visible at the upper center.

Another major Phase II system, the central helium refrigerator liquifier, has been in operation in the building for some months but has not yet been turned over by the manufacturer since system performance at this time is

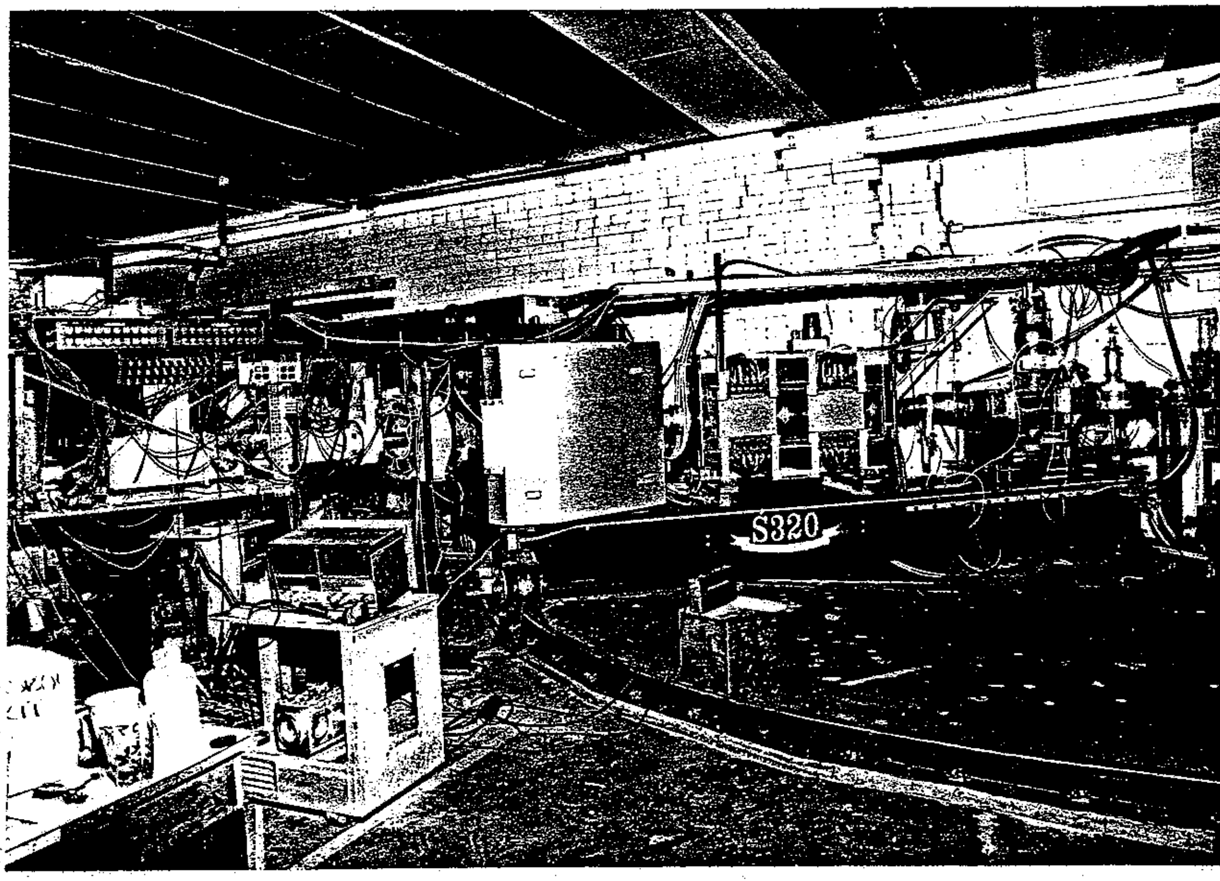

Fig. 4. View of the S32Ø spectrograph. Phased out components from other laboratories (Penn. dipole magnet, SREL quadrupoles, Minn. scattering chamber) allowed this spectrograph to be constructed at a very low cost; it has the important function of providing magnetic analysis up to the maximum rigidity available from the K5ØØ cyclotron.

Scheduling of facility use will involve a series of shutdowns beginning in the third year of the 84-86 period to allow installation of sections of the Phase II beam transport system and relocation of some Phase I experimental devices. As soon as the central magnet corridor is complete it will be possible to resume experiments on a staggered basis--running in the vaults on the north side of the central corridor while experiments are running in the south and vice versa. Total interruption of main components of the

TABLE I

OBLIGATION PLAN

3/28/83

Ident. No.	Reporting Category	80 (DOE)	81	82	83	84 (NSF)	85	Total
	Fiscal year	80	81	82	83	84	85	Total
	BUILDING							
1110	Building Addtns & Altns							
1120	Site Improvements	0	5,050	100	140	0	0	5,290
1130	Utilities							
1140	Standard Equipment	0	40	200	60	0	0	300
1150	A/E Services	705	20	0	0	0	0	725
1100	Total	705	5,110	300	200			6,315
	K800 CYCLOTRON							
1210	Major Procurements	1,705	265	55	0	0	0	2,025
1220	Fabrication	350	230	926	1,500	1,409	0	4,415
1200	Total	2,055	495	981	1,500	1,409	0	6,440
	BEAM TRANSPORT, SHIELDING, REFRIGERATION							
1310	Major Procurements	590	0	200	0	745	0	1,535
1320	Fabrication	160	0	2	1,245	793	0	2,200
1300	Total	750	0	202	1,245	1,538	0	3,735
	EXPERIMENTAL FACILITIES							
1410	Experimental Equipment	0	100	470	1,705	1,070	0	3,345
1420	Data Processing	45	470	580	250	0	0	1,345
1400	Total	45	570	1050	1,955	1,070	0	4,690
	DESIGN							
1510	R&D Related to Construction	713	892	980	1,050	1,100	0	4,735
1520	Eng. & startup	7	558	987	850	883	300	3,585
1500	Total	720	1,450	1,967	1,900	1,983	300	8,320
CONTINGENCY		0	0	0	0	0	3,800	3,800
Expend.& Obligations-Annual Tot.		4,275	7,625	4,500	6,800	6,000	4,100	33,300
Total Project Expend.&Obligations		4,275	11,900	16,400	23,200	29,200	33,300	

Detail Number by WBS to Third Level

I. FACILITY OPERATION AND DEVELOPMENT

I. FACILITY OPERATION AND DEVELOPMENT

The status of the Phase I facility was reviewed in the Introduction; the statement of principal significance is that the first experimental running period is now in process and available beams and energies are as previously listed. This running period is expected to terminate in June and a two month cyclotron upgrading shutdown will then begin. During this time the Program Advisory Committee will hold its second meeting and when operation resumes after the shutdown, beam time will be allocated based on approvals from the PAC-II meeting. Beams for the second running period will be limited to ions and energies which have been operationally tested at the time the call for proposals is issued and will probably include the beams now available plus Ne^{6+} and Ar^{6+}.

During the second running period machine improvements from the shutdown will be tested and additional beams and energies will be developed as allowed by the improvements; these new beams then will be made available to experimenters in the third running period. The restriction of including only those beams which are already operational in the second call for proposals will help to avoid a difficulty experienced in the first running period, namely that since the first call for proposals was issued before any external beams had been tested (the extraction system was not yet installed at the time), an unexpected difficulty with holding deflector voltage limited operations such that a number of approved experiments (about one-fourth of the total) will not be able to run. This situation then brings one of the scheduling guidelines adopted in setting up the PAC process into unexpected early effect, namely a provision stating that PAC approvals would lapse after a period of one year. The group of PAC-I experiments which are now prevented from running will need to be resubmitted to a future PAC when the required beams are again operational; if the scientific relevance of the proposed studies remains, there is of select an outstanding PAC consisting entirely of members who had been recommended by both groups, namely; H. Britt (Los Alamos), D. Cline (Rochester), S. Koonin (Cal Tech), P. Paul (Stony Brook) and D.K. Scott (MSU). The effectiveness of the PAC-I process is certainly primarily due to the diligent efforts of this group.

The experimental hardware which is available for Phase I is shown in Fig. 1, which is a drawing of the experimental floor layout. Two spectrographs, a large precision scattering chamber, a helium jet facility, a smaller special scattering chamber for neutron studies, a reaction product mass spectrometer, and a general purpose location for user devices are available on five beamlines, which feed into two independent experimental rooms. One of the spectrographs, the S320, has a bending capability matched to the maximum K500 beam rigidity (taking account of electron stripping in the target); the other is a split pole spectrograph which can handle rigidities corresponding to 23 MeV/nucleon and with a broad range capability which makes it particularly well suited for pion production experiments and for studies of exotic nuclei.

The 60" Scattering Chamber is the primary apparatus for counter experiments; detector telescope packages can be mounted both in-plane and out-of-plane in a clean, cryopumped environment. The Helium Jet facility is of the cryogenic type, with a transport time in the range of milliseconds from target to detector. The RPMS (Reaction Product Mass Spectrometer) as now setup is a prototype of a future higher resolution Phase II device; the present configuration should resolve individual masses up to mass 100 with a flight time from target to detector in the microsecond range so that very short lived systems can be observed; the RPMS will also act as a beam preparation system for high yield reaction products thus opening the possibility of doing reaction experiments with unstable nuclei as the projectile. The location labeled "User Location" in simple experiment, a third dedicated to data analysis of a highly complicated multi-parameter experiment, and the fourth, which has reduced peripherals, in use for program development and testing. After initial screening of the data, interpretative analysis typically shifts to the 78Ø where calculations can be handled comparing experiment and theory .

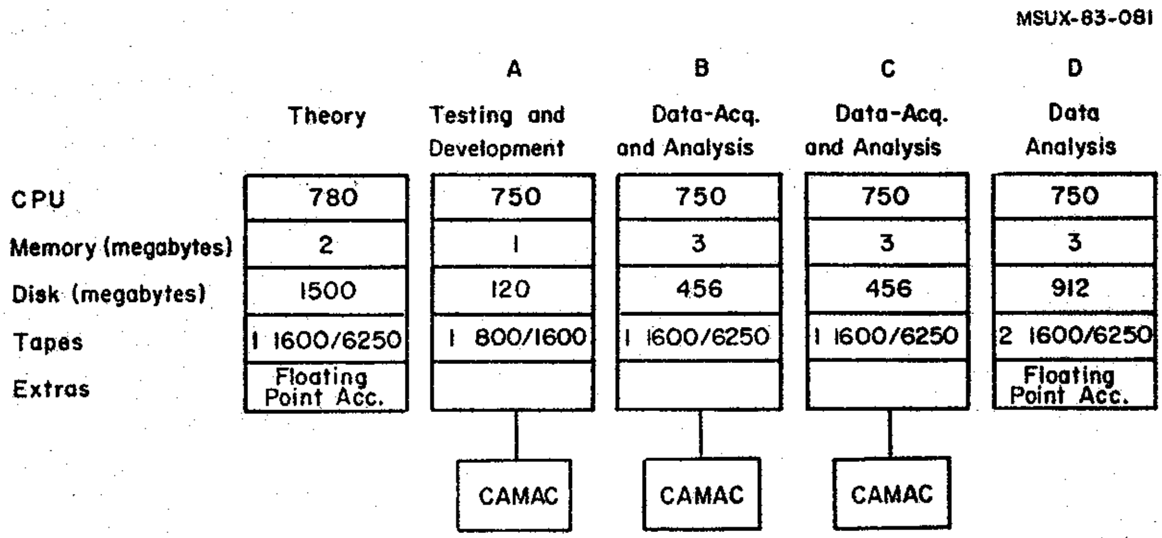

Fig. 2.

As indicated above, most of the Phase I systems are now constructed and others are sufficiently close that they will probably be on line as this proposal is being read. Results from experiments which are now complete are in the process of analysis and should soon begin to appear as publications. Fig. 3 shows a sample of the type of data which is obtained, II of the Introduction and at this time reflect considerable experience as to the level of effort required to operate the cyclotron and other experimental facilities in a reliable way. This experience has unfortunately established that the level of manpower required to keep beam reliably on target is considerably higher than had been originally planned--these plans assumed that the Phase I facility could be handled by one operator--based on the operating experience with the K50 in its later years where the operator could leave the console for long periods of time (returning when summoned by alarms set to detect a fall-off in beam current). In his time away from the console the operator was able to recondition the alternate ion source and frequently handle miscellaneous maintenance operations as well. The K50 in its early years of course required much more attention, most of this associated with repair and upgrading of marginal components until finally most of the elements with failure rates of more than once in ~25 months were eliminated from the system. The hope that the K500 would come on with all such weak links eliminated in the design was clearly over optimistic--hard experience with actually running the machine has brought home the clear message that at least two people must be present to keep the facility in a state of reasonably smooth operation and in difficult situations 3 or 4 may be required. To cope with this, we are presently backing up the 4 man operator group (one operator per shift + one shift of overtime in order to span a continuous 168 hour week) with a rotating shift assignment involving 2 principal investigators and a group of senior scientists. The burden placed on this group by this arrangement is great--a combination of trying to keep normal assignments in reasonable motion plus handling accelerator shifts--and clearly beyond the level which can be sustained in a long term way. (A significant loss of efficiency also results due to the diversion of this group from normal assignments.) In order to improve this situation we plan in the latter months considered typical and expenditures are estimated on the basis of ten hour life. (A recent hafnium cathode achieved a 16.6 hour lifetime running with $^{12}C^{+4}$ ions.) The next most expensive item is the chimney which suffers from erosion due to ion back bombardment.

An important need in operating the Phase I experimental program is the addition of spare ion source assemblies. In our 1982 budget we provided funds for one spare assembly for the upper source and one for the lower. With our present operating experience, we now realize that two spares for each source are essential in order to be able to achieve continuous round-the-clock operation. This additional requirement stems in large part from an unanticipated radioactivity of the ion sources following their use in the K500 cyclotron. (This is caused by the very high K-value of the cyclotron). The phenomenon is due to bombardment of the central region of the cyclotron by ions which have undergone charge state change in the acceleration process. The activity levels observed have ranged from a few mr/hr to several R/hr. The additional sources will permit a slower rotation of sources so as to allow time for decay of the radioactivity thus reducing personnel exposure incurred during the ion source rebuilding operation. The additional sources will also provide essential backup in situations of abnormal source failure. The cost of these two sources is shown in Table I.2.

The yearly cost of our cryogenics operation is shown in Table I.3. The liquid nitrogen is used in the operation of the helium liquifier, in the K500 LN_2 thermal shield as well as in the three cryopumps of the cyclotron beam chamber. A small amount is also used in the experimental program. As mentioned earlier, we hope to be able to reduce the LN_2 costs by $\simeq$ 25% via improved cryopump design. Modifications of the present cryopump are currently under study.

Table I.4 shows the procurement cost of planned RF-system upgrading the goal of which is to increase

Control system expenditures are listed in Table I.6. The control module upgrade will greatly improve our ability to tune high-charge-state, very low current beams by providing improved capability for measuring very small currents with reasonable frequency response (>15Hz). (The cyclotron differential beam probe is an example where both sensitivity and frequency-response are needed.) The magnet main coil current is not now in the control system and funds for interfacing that supply are provided.

Table I.7 shows expected yearly costs of maintaining and adapting the low conductivity water (LCW)system, the building electrical and the hydraulic system. The electrical costs include day to day modifications such as adding outlets, replacing or repairing switches and contactors, rerouting DC power to supply additional magnets, etc. .

The service contracts on the 5 VAX computers dominates the maintenance cost of our data acquisition and analysis computing facility as reflected in Table I.8. In Table I.9 a detailed list of the cost of supplies is given. Magnetic tapes in the table are predominantly used in a regular disk backup data dump; these tapes are then stored for a period of years so that data, codes, etc. can be retrieved at a later time if needed.

Table I.1Ø presents estimated costs for operating and maintaining the beamline and experimental apparatus and mainly consists of vacuum equipment maintenance and repair.

Table I.11 shows costs for several additional peripheral equipment items needed for reliable K5ØØ operation. The beam identification equipment is required for ascertaining beam purity when an analog beam can be present, i.e. when beams with nearly identical Q/M are possible (for example, $^{20}Ne^{+5}$ and $^{16}O^{+4}$). The equipment consists of silicon detectors, a beamline target chamber, associated electronics and a pulse height analyzer. An improved and permanent dee voltage X-ray calibration system will use the same pulse height analyzer and requires only additional electronics

TABLE I.1

FACILITY OPERATIONS

	K$	K$	
PRINCIPAL INVESTIGATORS &CO. PI.'S	62.8		
FACULTY & SENIOR ASSOC	236.4		
OTHER PROFESSIONALS (18.5 FTE)	339.7		
SECRETARIAL AND CLERICAL (1.Ø FTE)	15.Ø		
OTHER (2.6 FTE)	41.4		
	695.3		
LESS MSU CONTRIBUTION	1Ø3.8		
NSF CONTRIBUTION TO SALARIES	591.5	591.5	
FRINGES (18.9%)		111.8	
UNDERGRADUATES (14 @29hrs/week)		85.5	
TRAVEL SUPPORT		12.Ø	
ION SOURCE (TABLE I.2)		1Ø7.5	
CRYOGENICS (TABLE I.3)		1Ø2.Ø	
RF UPGRADE (TABLE I.4)		96.Ø	
RF AND DEFLECTOR MAINTENANCE (TABLE I.5)		37.4	
CONTROL SYSTEM (TABLE I.6)		21.5	
LCW, ELECTRICAL, HYDRAULICS (TABLE I.7)		12.Ø	
UTILITIES		33.3	$\Sigma = 699.5$
COMPUTER MAINTENANCE (TABLE I.8)		1Ø7.7	
COMPUTER SUPPLIES AND SOFTWARE (TABLE I.9)		31.1	
BEAMLINES (TABLE I.1Ø)		19.2	
K5ØØ EQUIPMENT (TABLE I.11)		34.3	
O. H. (39.5% of Non-equipment items)		474.2	
TOTAL		$1877.ØK	

TABLE I.3

CRYOGENICS

	K$
CTI 1400 HE REFRIGERATION MAINTENANCE, PARTS AND SUPPLIES	6.5
HELIUM GAS COSTS	8.5
LN_2 FOR K500 OPERATION, CRYOPUMPS AND REFRIGERATOR (3.5×10^5 GAL. AT 0.25 $/GAL.)	87.0
TOTAL	$102.0K

TABLE I.5

RF AND DEFLECTOR MAINTENANCE (MATERIALS)

	K$
RF MAINTENANCE & REPAIR	
RF CONTROL PARTS	4.0
RF AMPLIFIERS	2.0
POWER SUPPLIES	6.0
COUPLER REPAIRS	1.5
MISC. (TUBES, FINGERSTOCK,ETC.)	6.0
	19.5
DEFLECTOR MAINTENANCE & REPAIR	
2 DEFLECTOR SHOES @ 4.8K	9.6K
8 SPARKING PLATES @ 0.3K	2.4K
8 TUNGSTEN SEPTUMS	0.9K
72 INSULATORS	5.0K
	17.9K
TOTAL RF AND DEFLECTOR MAINTENANCE	$37.4K

TABLE I.7

LCW, ELECTRICAL AND HYDRAULICS MAINTENANCE

	K$
LCW FILTER AND CHEMICALS	3.0
ELECTRICAL MAINTENANCE	4.0
(SUPPLIES, REPAIR, WIRING MODIFICATIONS,ETC.)	
HYDRAULIC MAINTENANCE	4.0
MISCELLANEOUS	1.0
TOTAL	$12.0K

TABLE I.9

COMPUTER SUPPLIES ONE YEAR PROJECTED BUDGET

AMOUNT	ITEM	COST PER UNIT $	COST K$
12MO.	029 Keypunch Rental	137./MO	1.65
12MO.	129 Keypunch Rental	267./MO	3.32
12MO.	VAX/VMS Software	300./MO	3.60
12MO.	VAX Fortran	44./MO	0.53
12MO.	VAX Basic	44./MO	0.53
12MO.	VAX Graphics	65./MO	0.78
12MO.	VAX Network	180./MO	2.16
12MO.	VAX ADE Software	75./MO	0.90
125K	Data Processing Cards		0.65
400	Magnetic Tapes	16./EA	6.56
120	Printronics Ribbons	119./DOZ	1.19
60	Diablo Ribbons	60./DOZ	0.30
24	Keypunch Ribbons	16./DOZ	0.03
12	Decwriter III Ribbons	51./DOZ	0.05
6	VT100 Screen Filters	30./EA	0.18
6CTS	Tektronix 4612 Paper	28./CTS	0.17
6BTLS	Dry Copy Toner for 4612	22./EA	0.13
4BOX	4 Across Mail Labels	59./BOX	0.24
4BOX	H.P. Plotter Paper	34./BOX	0.14
	Laser Printer Paper[1)]		4.00
	Line Printer Paper		1.90
	Calcomp Plotter Supplies		0.10
	Economy Tape Storage (Racks)		0.90
	Tape Drive Cleaning Supplies		0.10
	Miscellaneous		1.00
	Total Budget		$31.1K

[1)] Based on Xerox copy machine paper usage.

TABLE I.11

K-500 CYCLOTRON EQUIPMENT

	K$
RADIATION MONITORING COUNTERS	4.8
BEAM IDENTIFICATION SYSTEM	12.0
DEE VOLT X-RAY CALIBRATION	2.0
ION SOURCE VACUUM UPGRADE	2.8
FAST RESPONSE ION SOURCE GAS SYSTEM	5.3
EMITTANCE MEASURING EQUIPMENT	7.4
TOTAL	$34.3K

II. USER SERVICES AND SUPPORT

II. USER SERVICES AND SUPPORT

This section specifies the costs of supporting the research needs of users, where these costs are defined in accord with the NSF guidelines of Appendix AP-1. The proposed budget is given in Table II.1, supported by supplementary Tables II.2-5.

The distribution of FTE's associated with user support was given in the Proposal Introduction, and is converted into the equivalent salary costs in the first part of Table II.1. The contribution of PI's and Co PI's is to be identified in large part with the efforts involved in developing the Phase I facility in a way that is valuable to all users; a part is also associated with the administrative tasks of making the facility efficient and convenient to the user community. Another Ø.6 FTE of effort is included for the activities of Post-Docs in the development of the Detector Laboratory. A total of 5.6 FTE comes from the contributions of Faculty and other Senior Associates who are also connected with the above activities, as well as the effort devoted to 1) design, maintenance and repair of nuclear electronics, 2) service provided by the Computer Group to users, and 3) design of improved equipment for the Phase I facility. The 4.Ø FTE in the category of Other Professionals comes mainly from the necessary mechanical and electrical technical support. The Secretarial and Clerical category carries Ø.8 FTE, a large part of which is associated with work on user communications, and mailings. Finally the Ø.7 FTE classified as Other, includes a contribution for purchasing, drawing and general help in the Laboratory in areas of receiving and messenger services.

Proposed staff additions with an important User support role are a Nuclear Electronics Engineer/Scientist and a Systems Programmer. The first of these is in response to the growing realization of the complexity of the types of experiments which are now necessary as a consequence of evolving perceptions as to the significant scientific issues to be addressed; innovative concepts in electronics and instrumentation will clearly be a controlling factor relative to both cost and effectiveness of the needed multiparticle experiemnts. A Senior Electronics Physicist or Engineer is essential if a forefront research capability is to be maintained in this area.Additional programming support is similarly very important in order to respond to the needs of users for modifications to data taking and data analysis programs for particular experiments.

Table II.2 shows the level of funding requested for costs of visits by the Executive Committee and the Program Advisory Committee and for support of visitors and unfunded outside users. The funds requested for support of three summer visitors for a period of approximately two months will partially implement a recommendation of the Users' Executive Committee, by working to provide a means for outside users to become involved in development of the facility. Funds are also requested for travel support for users with approved experiments at NSCL, but who are not supported by other grant funds (See Table II.2), this item also being a Users' Executive Committee recommendation.

Funds amounting to 14K are requested for the adaptation of beamlines, in cases where users need to install special pieces of apparatus. In the first months of running with the K500, two such requests have come up and been handled and we have, as indicated in the preceeding section, provided a general purpose beam-line where users can install equipment for experiments which are not compatible with the capabilities of standard facility apparatus.

The budget in Table II.1 includes 146K for upgrade of the Laboratory's electronics pool to partially alleviate a pressing problem which has become apparent in the running of experiments in the first scheduling period. This problem comes from the fact that many of the most significant experiments (in the perception of the PAC) require a larger number of electronics modules than was anticipated at the time when the original long term proposal for the Laboratory was formulated, this being primarily a consequence of the greater than anticipated experimental complexity of the science as it has evolved. Also, as experiments were first being attempted in the present K5Ø0 running period, we learned that many of the older electronics modules were bought for experiments with the K5Ø cyclotron have an unacceptably high rate of failure. (A high failure rate becomes a critical problem in a large scale experiment where hundreds of modules are in use--the intricate and tedious process of locating and repairing or replacing defective modules can totally take over the assigned running time when failures are frequent). We have then experienced serious problems in instrumenting complex multi-detector experiments and many such experiments were approved for the first scheduling period including:

1) Energy Dependence of Light Particle Production (82008, Westfall et al.)
2) Studies of Light Fragments from ^{12}C and ^{20}Ne Induced Reactions (82009, Anantaraman et al.)
3) Studies of Evaporation-Fission Competition for Highly Excited Lanthanides and Actinides (82012, Schröder et al.)
4) Search for Multiparticle Jets in Heavy Ion Collisions (82015, Hasselquist et al.)
5) Linear Momentum Transfer in Incomplete Fusion Reactions followed by Fission (82020, Viola et al.)
6) Fusion and Fission Properties of Nuclei with Vanishing Liquid Drop Fission Barrier (82023, Vandenbosch et al.)
7) Study of Momentum Transfer through Continuum γ-Ray Multiplicities in Heavy Ion Reactions (82029, Moretto et al.)
8) Neutron and γ-Ray Emission in Deep Inelastic Collisions (82032, Galonsky et al.)

9) Light Particle Correlation Measurements in Heavy Ion Induced Reactions (82Ø25, Lynch et al.)

The evolving directions of scientific issues also clearly point to an increasing complexity of experimental set-ups in future scheduling periods as more groups beome involved in probing detailed characteristics of nuclear reactions in this new energy regime. This trend towards increasingly complex multiparticle experiments is also apparent from ongoing and planned experiments at other leading laboratories working in this field (GANIL, GSI, ORNL, LBL,...). The situation is further exacerbated by the fact that resources available for upgrading the NSCL pool of modular electronics have been at a minimal level in a number of recent years, these being years when no in-house experiments were run and when large outside user experiments of the MSU group were primarily instrumented by the host laboratories. In summary there is then a clear and definitive need for a step increase in the Laboratory's electronics inventory in order to meet the minimal needs of large user experiments. This issue has been noted on several occasions in communications from users and from the Users' Executive Committee. The proposed electronics upgrade of 146K will substaintially alleviate the problem of insufficient modular electronics, although still not to a level where standard set-ups can remain in place when large scale multi-particle coincidence experiments have to be instrumented. The proposed purchases will, however, make a very significant improvement for users, making it possible to set up approved experiments with adequately reliable equipment. The purchases as presently contemplated are itemized in Table II.3, while also noting that this (and all other) major purchases of nuclear electronics will be (and are) discussed in detail with the Users' Executive Committee just prior to the placing of actual orders. The list of items in Table II.3 is then a tentative proposal to be reviewed and finalized; requirements of the next round of approved experiments will of course be a further important source of information affecting the final choice.

The item for additional computer terminals (Table II.1) is for completion of the data taking and analyzing stations, at a cost of 6.ØK. Finally, the requirements for the Target and Detector Laboratories are detailed in Tables II.4 and II.5 and represent basic needs. The largest requests are for 1) three gas handling systems to allow parallel use and/or testing of several of the rapidly expanding array of gas based charged particle detectors, 2) the development of a large ion chamber for heavy fragment identification, and 3) the purchase of a foil rolling mill for the Target Laboratory.

TABLE II.1

USER SUPPORT

	K$	K$	
PRINCIPAL INVESTIGATORS &CO. PI.'S	51.8		
FACULTY & SENIOR ASSOC	155.1		
POST DOCS (.6 FTE)	11.8		
OTHER PROFESSIONALS (4.0 FTE)	72.0		
SECRETARIAL-CLERICAL (.8 FTE)	11.85		
OTHER (.7 FTE)	10.0		
	312.5		
LESS MSU CONTRIBUTION	59.0		
TOTAL	253.6	253.6	
FRINGES (18.9%)		47.9	
EXPENSES FOR PROGRAM ADVISORY COMM, USER'S EXEC COMM, VISITORS AND UNFUNDED USERS (TABLE II.2)		41.0	
ADAPTATION OF BEAMLINES, PROVISION OF BEAMLINE ELEMENTS		14.0	
UPGRADE OF ELECTRONICS (TABLE II.3)		146.0	256.5
COMPUTER TERMINALS FOR GENERAL USE		6.0	
TARGET AND DETECTOR LABS (TABLES II.4 AND II.5)		49.5	
OVERHEAD (39.5% on Non-Equipment Items)		144.6	
TOTAL		$702.6K	

TABLE II.2

SUPPORT FOR PAC, EXECUTIVE COMMITTEE

OUTSIDE USERS AND SUMMER VISITORS

	K$
EXECUTIVE COMMITTEE (2 visits per year of 4 people)	3.0
PROGRAM ADVISORY COMMITTEE (3 visits per year of 4 people)	5.0
SUMMER VISITORS PROGRAM (3 people for 2 months, travel (2K) and salaries (23K))	25.0
SUPPORT FOR UNFUNDED OUTSIDE USERS (5 people for 2 visits)	8.0
TOTAL	$41.0K

TABLE II.3

UPGRADE OF ELECTRONICS POOL

	ITEM	COST K($)
5	Nim Bins (@ $1.4K)	7.0
10	Fast-slow charged particle preamps (@ $650)	6.5
5	Scintillation preamps (@ $220)	1.1
4	Low noise preamps for ion chambers (@ $650)	2.6
4	Proportional counter preamps (@ $620)	2.5
10	Spectroscopy amplifiers (@ $800)	8.0
5	Delay amplifiers (@ $500)	2.5
8	Timing filter amplifiers (@ $800)	6.4
5	Linear gates and stretchers (@ $600)	3.0
3	Quad Constant fraction disc (@ $1500)	4.5
5	Constant Fraction TSCA (@ $650)	3.3
3	Octal discriminators (@ $1200)	3.6
2	Time-to-amplitude converters/SCA (@ $1100)	2.2
4	4-fold majority logic units (@ $1200)	4.8
3	Triple 4-fold coincidence units (@ $1200)	3.6
1	32 input multiplicity logic unit (@ $1200)	1.2
5	Logic Fan-in/Fan-outs (@ $700)	3.5
4	LeCroy dual gate generators (@ $1200)	4.8
8	Ns-delays (@ $360)	2.9
5	Dual solid state detector supplies (100 V/1000 V) (@ $1000)	5.0
1	Multi-output HV supply (@ 8K)	8.0
5	Ge-Li, proportional counter supplies (@ $650)	3.3
2	Quad Linear Fan-in/Fan-out (@ $850)	1.7
5	Dual prescalers (@ $600)	3.0
1	Random pulsers (@ $2000)	2.0
1	485 Tektronix oscilloscope (@ 8K)	8.0
3	High resolution ADC's (@ 2.5K)	7.5
2	Camac TDC's (@ 2.0K)	4.0
3	Camac Scalers (@ 1.5K)	4.5
2	Camac charge integrating ADC's (@ 2.5K)	5.0
	Cables and connectors, misc.	20.0
		$146.0K

TABLE II.4

DETECTOR LABORATORY

	K$
GAS DETECTOR DEVELOPMENT, CONSTRUCTION AND MAINTENANCE	
Detector Wire - 5,000 ft. @ .30	1.5
Thin foils, support screens	1.0
Detector gasses	2.0
Detector housing, fittings, feed thru's	4.0
Pressure control and purification systems 3 systems @ 3K	9.0
Prototype development of large ion chamber	8.0
SCINTILLATION DETECTOR CONSTRUCTION	
Scintillation Phosphors	2.0
Photo-Multipliers	3.0
Light guides, housings, bases and magnetic shields	2.0
	$32.5K

TABLE II.5

TARGET LABORATORY

	K$
EQUIPMENT FOR FACILITY UPGRADE	
POWER SUPPLY FOR ELECTRON GUN	4.0
FOIL ROLLING MILL	8.0
TARGET PRODUCTION	
TARGET MATERIALS, ISOTOPES	4.0
SUPPLIES, BOATS	1.0
TOTAL	$17.0K

III. MAJOR SPECIAL ITEM

III. MAJOR SPECIAL ITEM

After a careful reading of the National Science Foundation Guidelines (Section AP-1 of the separately bound appendix) we have assigned the several facility upgrading efforts to one or the other of the previous two sections and as a consequence no "major special item" is proposed. Reading the NSF Guidelines, the distinguishing attribute between a routine upgrade and a major special item upgrade hinges on whether the upgrade is one which is necessary to stave off obsolescence, make the facility easier to operate, etc. or, on the other hand, whether it adds a significant new capability to the overall characteristics of the facility. The assignment of an item such as the electronics upgrade is a borderline issue which some might view as an appropriate major special item. The electronics upgrade will certainly improve the capabilities of the facility in an important way and yet primary characteristics such as beam energies, mass regimes, etc. are unchanged. Weighing this we have therefore judged none of the proposed upgrades to be appropriate for the major special item designation. If there is significant disagreement with this judgement, the discussion accompanying the proposed upgrades can be viewed by the reader as appropriate for this section.

IV. STAFF RESEARCH

Introduction

The K500 Cyclotron is one of the few accelerators in the world capable of delivering high intensity beams of nuclei at energies up to 50 MeV/nucleon. Over the last few years several exploratory studies in this intermediate energy regime have been conducted at the Bevalac and at CERN which have clarified some of the important directions for further study. It is already clear that the understanding of phenomena at intermediate energies will require many detailed experimental studies as well as new theoretical approaches. The high energy, precise beams from the Phase I Cyclotron also allow new studies of many traditional problems in nuclear science, particularly in nuclear structure. Our research program description is organized into four major sections, namely 1) Nuclear Reactions, 2) Nuclear Structure, 3) Fundamental Interactions and Astrophysics and 4) Nuclear Structure Theory and Analysis of Spectroscopic Data - there is of course in reality considerable overlap between the topics.

The Nuclear Reactions section focuses on new processes that may occur in the energy regime of the Phase I accelerator, ranging from the evolution of the established low energy phenomena of deep-inelastic scattering, fusion and fission to reactions dominated by many fragments in the final channel. In this energy range little is known about the mechanisms of energy dissipation and momentum flow; the experiments may give a signature of hydrodynamical behavior in contrast to the mean field phenomena characteristic of low energy nuclear collisions. Inevitably the associated experiments call for large arrays of detectors and electronics. The measurement of processes with very small cross sections may be crucial, and such experiments will become feasible with the Phase I beams. For example the measurement of pion production below the nucleon-nucleon threshold can be extended to much lower energies.

The Phase I accelerator also provides new opportunities for the study of Nuclear Structure. A major effort will be devoted to the field of giant resonances, exploiting the possibilities for charge exchange reactions and high energy inelastic scattering of light and heavy ions. The facility also promises a major advance in the exploration of nuclei far from stability, both through the high energy, high intensity beams that become available for exotic transfer reactions, and also through novel apparatus such as the Reaction Product Mass Separator. A new thrust in gamma-ray experiments will become possible if the multi-detector array of anti-compton shielded germanium detectors proposed by the Pittsburgh - Carnegie-Mellon - ORNL - MSU collaboration becomes available at NSCL.

Some experiments in nuclear science are important not only for their intrinsic interest, but also for the impact on other fields. The section on Fundamental Interactions and Astrophysics addresses a number of current topics which are interdisciplinary in nature; the experiments make imaginative use of the new beams at NSCL, as well as the capabilities of the RPMS and S320 Magnetic Spectrometer.

It has long been a goal of our laboratory to advance the theoretical understanding of the experimental results obtained. An important component of this aspect of our program is described in the section on Nuclear Structure Theory and Analysis of Spectroscopic Data. This group and their research are also strongly coupled to many of the activities described in other sections. In particular, the work has a key relationship to the studies of exotic nuclei through shell model calculations of level and decay schemes, to the studies of giant M1 and Gamow-Teller data, to nucleon transfer reactions and fundamental interactions and to a variety of other topics relevant to interpretation of experiments both inside and outside the laboratory. In this context the strong interaction between the separately funded nuclear theory group (Bertsch, Scholten, Stocker, and Toki)and almost all areas of experimental research should be strongly noted. In particular, members of the Theory Group play a major role in giant resonance studies, in the interpretation of the complex behavior exhibited by intermediate energy nuclear reactions through hydrodynamical and statistical models, and in sub-threshold pion production. For cases where the collaboration is particularly close, the names of theorists are included on the experimental project.

Many of our proposals demand the use of accelerators at other facilities. Over the last two years, while the Phase I Facility was being completed, the Research Staff at MSU have made use of many different accelerators. Most of these outside user programs evolve naturally into the experimental research at NSCL, although several areas of research will continue to benefit from parallel work with beams available at other facilities. It is, for example, frequently of interest to compare the behavior of light and heavy ion induced reactions; this is true in the research on charge exchange and inelastic scattering where it is desirable to continue work at Indiana and Orsay. Similarily in the study of nuclear reactions, the heavier mass beams at intermediate energy which are available at the Bevalac and GANIL, may be important in adding to our understanding of the mechanisms. In the past, we have found that the experience gained in reaction mechanism studies at the Bevalac was helpful in planning the research and instrumentation for the Phase I facility. Similarly, experience with the Streamer Chamber facility will be important in intelligent planning of the instrumentation for Phase II.

The relevant outside user activities are mentioned in each of the project descriptions. The associated costs are detailed in Table IV.1, sub-section IV E, of this Staff Research section. In each research proposal the names of the staff involved are given, underlined in cases where the effort constitutes a major component of the research project; the distribution is also indicated in Table IV.1 of sub-section IV E. Names of individuals working on projects, but for whom the research is not a major thrust, appear on the write-ups without underlining.

The discussion of each topic usually consists of a combined review of the highlights of recent work and an anticipation of how the research leads into programs with the new K500 Superconducting Cyclotron over the next three years. In some cases anticipated extension of the research into the Phase II domain is also described.

A. NUCLEAR REACTIONS

A 1. EVOLUTION OF REACTION MECHANISMS

(a) Fusion and Fission

(b) Deep Inelastic Scattering

(c) Nuclear Fragmentation

(a) Fusion and Fission

A. Galonsky, C.K. Gelbke and D.K. Scott

The limits of compound nucleus formation, the energy dependence of incomplete fusion reactions, and heavy ion induced fission or multi-fragmentation reactions are of particular interest for our understanding of the dynamics of nucleus-nucleus collisions. In order to span a maximum range of energies and projectile-target combinations, we plan to make optimum use of the special capabilities of the heavy ion accelerators at Michigan State University, Argonne National Laboratory, Oak Ridge National Laboratory and possibly G.A.N.I.L.

(i) Fission and Fast Fission following Capture Reactions

The concept of compound nucleus formation and decay is expected to become invalid for angular momenta exceeding the value $\ell_{Bf=\emptyset}$ for which the fission barrier vanishes. However, the cross sections for fusion-fission-like processes may considerably exceed[1] the sharp cut-off limit for compound nucleus formation, $\sigma_{CN}^{max}=\pi \lambda\!\!\!^{-2}\, \ell_{Bf=\emptyset}^{2}$, as calculated from the rotating liquid drop model.[2] A new reaction mechanism, "fast fission", was suggested[3] to set in for partial waves greater than $\ell_{Bf=\emptyset}$ but less than ℓ_{cr}, where ℓ_{cr} is the maximum angular momentum for which capture of the projectile by the target nucleus occurs. In the context of more general considerations on the dynamics of fusion of two nuclei [4], fast fission corresponds to reactions that overcome the conditional saddle point (corresponding to frozen entrance channel mass asymmetry) but not the true fission saddle point.

Although fast fission appears to be well justified theoretically, its experimental signatures are less well established. In order to search for possible experimental signatures of this process we have studied[5] fission following capture reactions induced by ^{32}S on ^{208}Pb over the energy range of E_{lab} = 180 - 270 MeV. Over this range of energies, the maximum angular momentum for capture ℓ_c, obtained in the sharp cut-off approximation, increases from values considerably smaller to values significantly larger than the value of $\ell_{Bf=\emptyset}$ predicted by the rotating liquid drop model.

The experiments were performed at the Argonne National Laboratory Superconducting Linear Accelerator, taking advantage of the excellent time structure of the beam pulses for time-of-flight identification of the outgoing fission fragments.

From measurements of the distribution of folding angles between coincident fission fragments it was confirmed that the reaction proceeds via the capture of essentially the entire projectile by the target nucleus. The widths of the fission fragment mass distributions, ΔM_{FWHM}, were found to increase rather smoothly with increasing beam energy. In Fig. 1, ΔM_{FWHM}

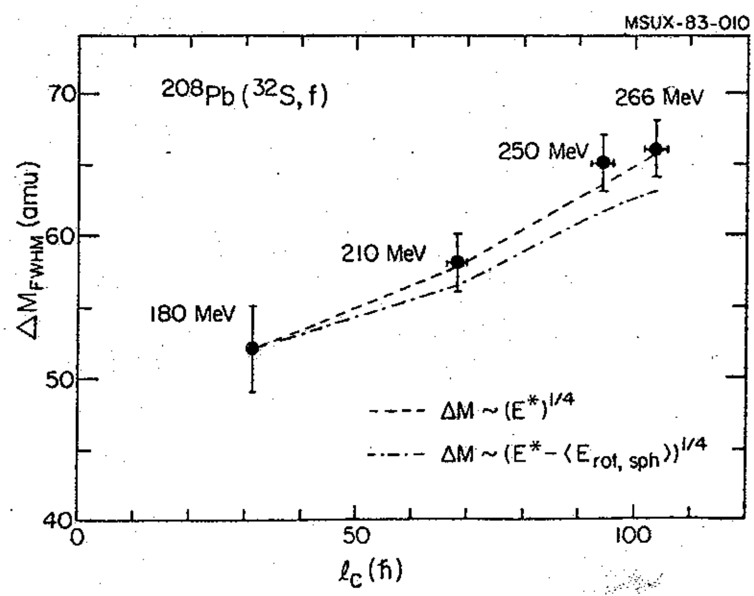

Fig. 1.

is plotted vs. the sharp cutoff angular momentum for capture which was determined from the measured fission cross section via the relation $\sigma_f = \pi\lambda\!\!\!^{-2} (\ell_c + 1)^2$. In contrast to the suggestions of Ref. 3, we do not find positive evidence for an abrupt increase of ΔM_{FWHM}, for $\ell_c > \ell_{Bf=\emptyset} \simeq 6\emptyset\hbar$. Rather, our observations are consistent with the expected variation of ΔM_{FWHM} with temperature, $\Delta M_{FWHM} \simeq T^{1/2}$, as is shown by the dashed and dot-dashed lines in the figure.

The fission fragment angular distributions were analyzed by making the assumption that the final total helicity distribution corresponds to a statistical equilibrium distribution of K-values at some intermediate stage of the reaction.

The fission fragment angular distribution is then given by

$$\frac{d\sigma}{d\Omega}(\theta) = \pi\lambda\!\!\!^{-2} \sum_{\ell=\emptyset}^{\infty} (2\ell+1)\, T_\ell$$

$$\frac{\sum_{K=-\ell}^{+\ell} \tfrac{1}{2}(2\ell+1)\, \left|\mathcal{D}^{\ell}_{M=\emptyset,K}(\theta)\right|^2 \exp\left(-\frac{K^2}{2K^2_{o,\ell}}\right)}{\sum_{K=-\ell}^{+\ell} \exp(-K^2/2K^2_{o,\ell})}$$

with

$$K^2_{\emptyset,\ell} = T\,\mathcal{J}_{eff}/\hbar^2 = T\left(\frac{\hbar^2}{\mathcal{J}_{\parallel}} - \frac{\hbar^2}{\mathcal{J}_{\perp}}\right)^{-1}.$$

Here, T_ℓ denotes the probability of capture for the partial wave of angular momentum ℓ, $\mathcal{D}^{\ell}_{M=\emptyset,K}$ is the symmetric top wave function, T is the nuclear temperature, and $\mathcal{J}_{\parallel}$ and $\mathcal{J}_{\perp}$ are the moments of inertia about axes of rotation parallel and perpendicular to the symmetry axis.

A consistent fit of the measured angular distribution was achieved by adopting a simple functional dependence of the effective moment of inertia on angular momentum

$$\mathcal{J}_o/\mathcal{J}_{eff} = \begin{cases} a-b\,\ell^2, & \text{for } \ell^2 \le \frac{a-c}{b} \\ c, & \text{for } \ell^2 > \frac{a-c}{b} \end{cases}$$

Here, we have used the rigid sphere moment of inertia $\mathcal{J}_o$ = 133 $\hbar^2$ MeV^{-1} to obtain the dimensionless numbers $\mathcal{J}_o/\mathcal{J}_{eff}$

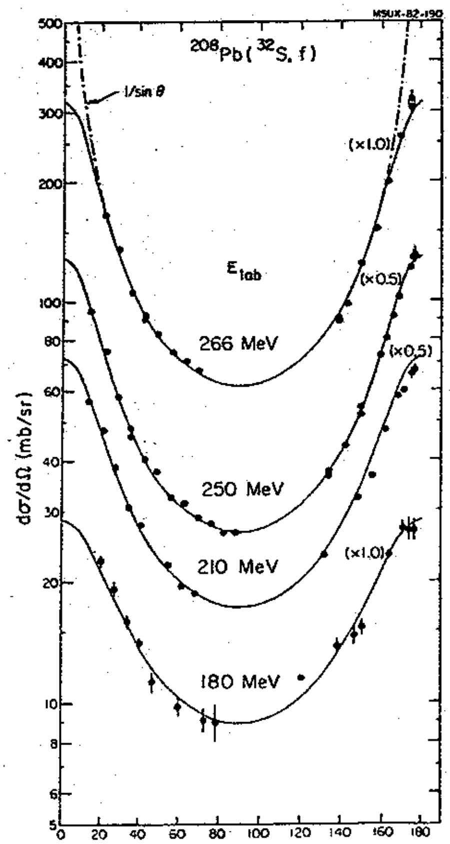

Fig. 2.

The resulting global fit to the measured angular distributions is shown by the solid curves in Fig. 2. The corresponding values of $\mathcal{J}_o/\mathcal{J}_{eff}$ are shown by the solid line in Fig. 3; they are in clear disagreement with the saddle point shapes predicted by the rotating liquid drop model.[2)] (The open and solid points in Fig. 3 show the results of a simplified analysis for which a constant value of $K_{o,\ell} = K_o$ was used to fit the angular distribution at a given energy, see ref. 5 for details.) The extracted values of $\mathcal{J}_o/\mathcal{J}_{eff}$ indicate that the distribution of K-values is frozen in at rather large deformations. Since these findings are difficult to understand in terms of the systematic trends established for compound nucleus formation and fission decay, it was suggested[6] that the present reaction might proceed via fast fission even at the lowest energies.

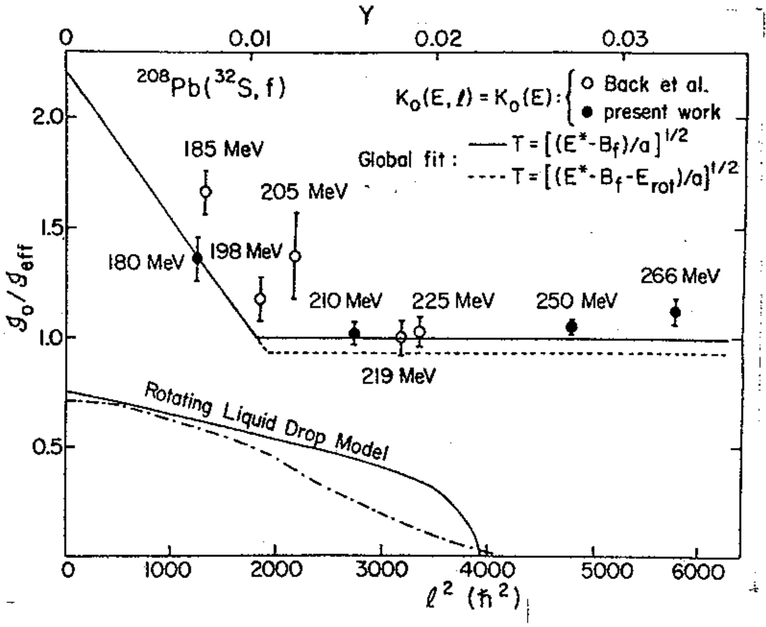

Fig. 3.

Obviously, more systematic investigations for different systems will be necessary to substantiate the assumptions on which the present analysis and interpretation are based. Of particular importance is the question whether the extracted narrow K-distributions correspond to equilibrium distributions of some intermediate stage of the reaction or whether they are governed by non-equilibrium dynamical effects. We plan to perform a more systematic study of the energy dependence of fission fragment angular distributions observed in heavy-ion induced capture reactions for various projectile-target combinations in order to test the general range of validity of the transition state model[7] for compound nucleus fission.

Our analysis is based on the assumption of first chance fission. Since recent investigations[8] cast doubt on the reliability of statistical model predictions at higher excitation energies and angular momenta, we plan to perform an independent study of the energy dependence of pre- and post- fission neutron evaporation. By comparing cases corresponding to conventional compound nucleus fission to cases for which fast fission is expected to take place, one might obtain information about the relative time scales for the two processes. This proposed series of experiments will use large area position sensitive parallel plate detectors for the detection of fission fragments and about ten liquid scintillators for the detection of neutrons. The excellent time structure of the beams delivered by the Argonne National Laboratory Superconducting Linear Accelerator will be of critical importance for the experiment where all kinematic quantities will be derived from velocity and position measurements.

(ii) Linear Momentum Transfer

For fissionable target nuclei, information about the linear momentum transfer to the target residue may be obtained[9-12] by measuring the two fission fragments resulting from the decay of the target residue. Increasing linear momentum transfers correspond to smaller folding angles (see Fig. 4 for illustration).

For peripheral reactions induced by ^{16}O on ^{238}U at 315 MeV, significant deviations from two-body kinematics were established[10] by detecting projectile residues in coincidence with two fission fragments resulting from the decay of the target residue. The dependence of the average value of the target recoil momentum $\langle P_R^{||} \rangle$ on the average momentum of the projectile residue $\langle P_3^{||} \rangle$ is shown in Fig. 5 (only momentum components parallel to the beam direction are given.) The observed large linear momentum transfer to the target residue provided clear evidence that the reactions do not proceed via a simple participant - spectator breakup mechanism, but involve significant interactions between projectile and target. It will be interesting to perform similar studies at the higher beam energies available at

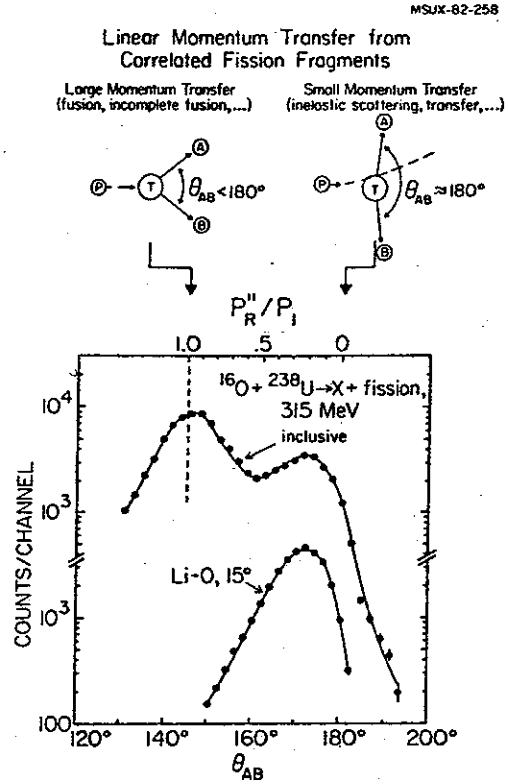

Fig. 4.

Michigan State University, in order to investigate whether the participant-spectator model becomes more realistic at higher energies.

Folding angle measurements allow the distinction between "central" or fusion-like reactions from "peripheral" or transfer-like reactions, (see Fig. 4 for illustration). The angular distributions of energetic protons, deuterons, tritons, and alpha particles observed[11)] in "central" and "peripheral" $^{16}O + {}^{238}U$ collisions at E/A = 20 MeV are shown in Fig. 6. At forward angles, both processes contribute. With increasing detection angle of the coincident light particle, the relative contribution of transfer-like "peripheral" collisions decreases rapidly. Except at very forward angles, the cross section for non-equilibrium light particle emission is dominated by fusion-like reactions (see ref. 11 for more details). In future experiments, we plan to investigate in- and out- of- plane light particle

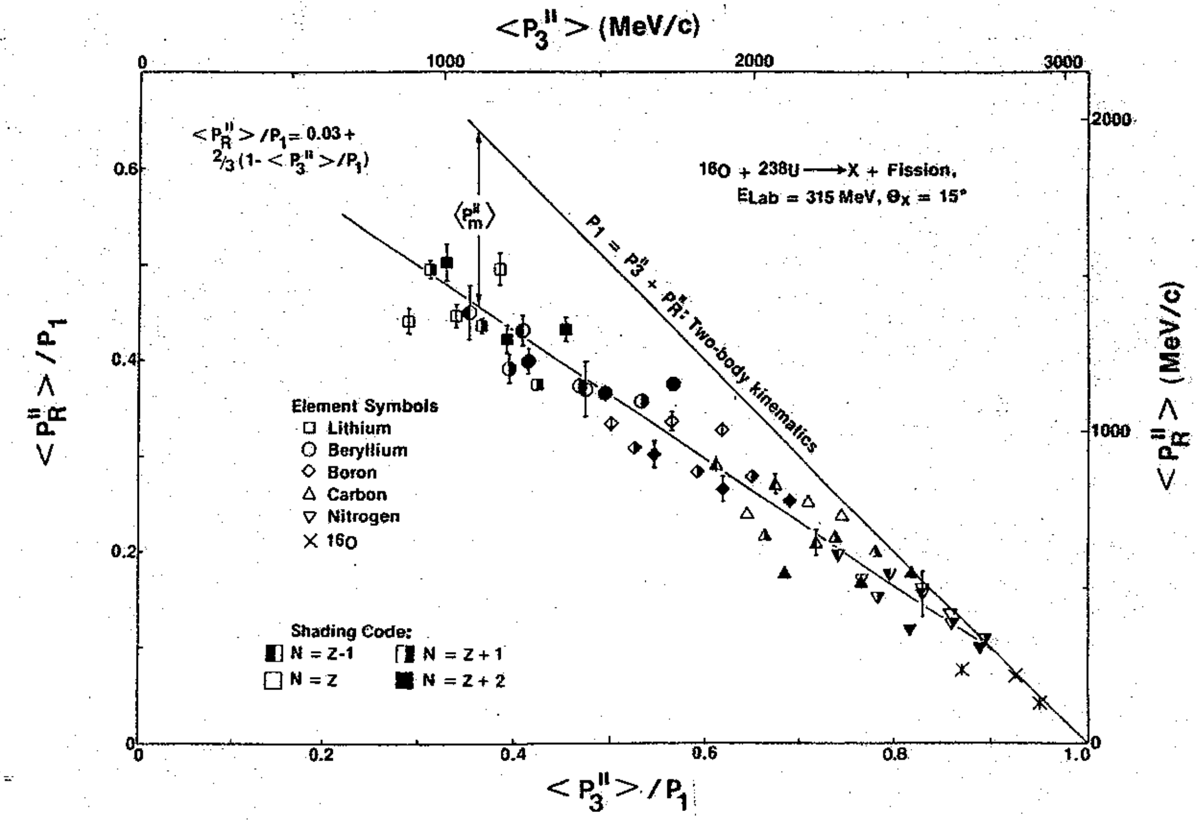

Fig. 5.

correlations by using the fission fragment coincidence technique to suppress the contribution of light particles from "peripheral" or transfer-like collisions for which the rather trivial process of the sequential decay of excited projectile residues makes an important contribution to the yield of energetic light particles.[13)]

For heavy ion induced reactions at E/A = 20 MeV, pre-equilibrium light particle emission is an important aspect of the reaction mechanism.[11)] As a consequence, the composite nucleus produced in fusion-like reactions recoils with a linear momentum Δp which is smaller than the beam momentum p. Published data exhibit a rather universal trend[12)] of the most probable fraction, $\Delta p/p$, of the projectile momentum that is transferred to the composite system in fusion-like reactions (see Fig. 7). For incident energies per nucleon larger than about 10 MeV, the data are consistent

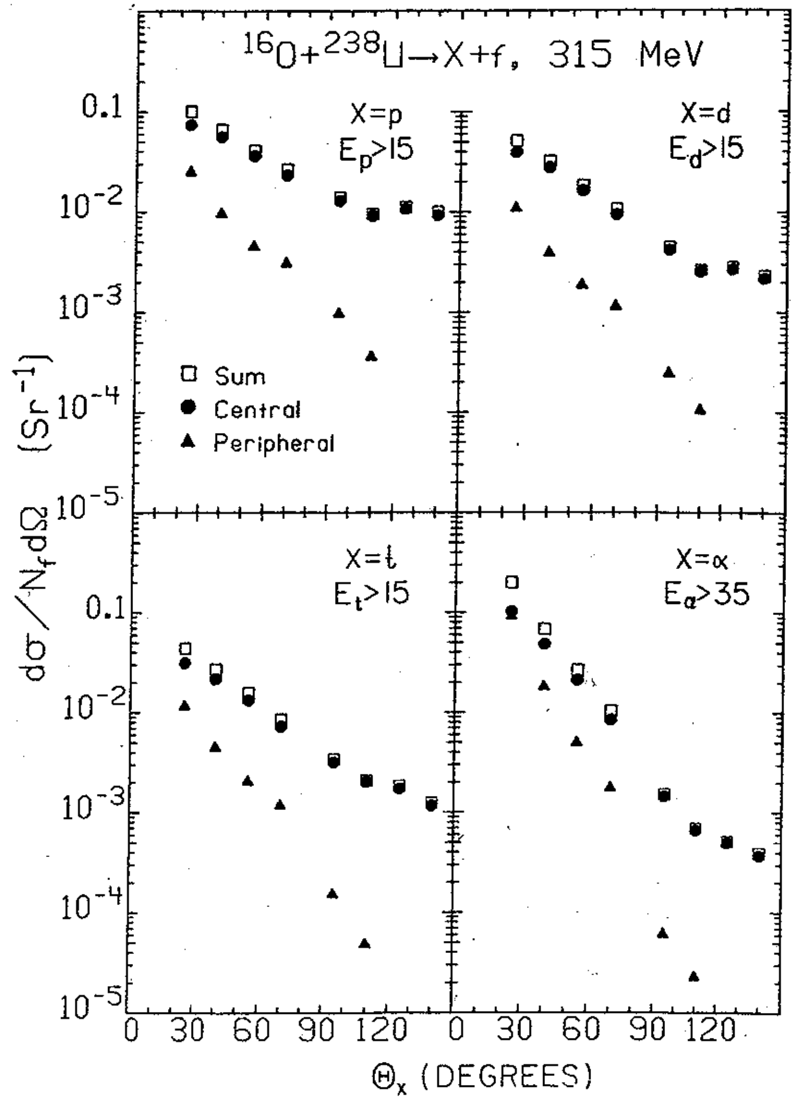

Fig. 6.

with a linear decrease of $\Delta p/p$ which is approximately proportional to the beam velocity. A similar trend has been observed[14)] for ^{16}O induced reactions on light target nuclei for which the recoil velocities of evaporation residues were measured with time-of-flight techniques. It is clearly desirable to pursue those measurements towards higher beam energies. We plan to use both direct time-of- flight measurements for reactions on lighter targets and folding angle measurements for reactions on heavy targets to determine the energy dependence of the average linear momentum transfer in fusion-like reactions. In this context, it is worth while mentioning that recent folding angle measurements[15,16)] for

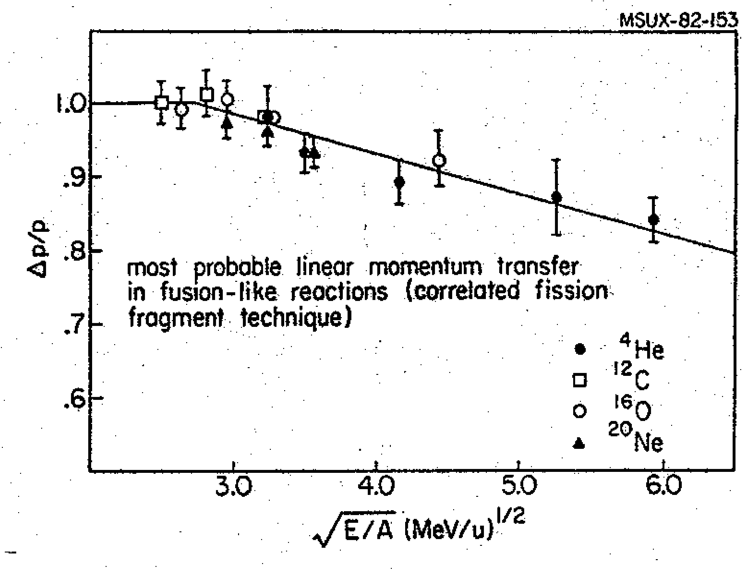

Fig. 7.

^{12}C induced reactions at E/A > 60 MeV indicate that the observed fisson yield is predominantly due to low momentum transfer peripheral collisions. At present, these findings are not understood. We plan to take advantage of the large range of projectile energies that will be available at MSU to study the energy dependence of heavy ion induced fusion-fission reactions. In particular, we plan to address the question whether the increasing importance of preequilibrium charged particle emission produces nonfissile target residues or whether more complex multi-fragmentation processes set in at higher energies.

(iii) Production of low-energy complex fragments

There is growing theoretical evidence that nuclear matter at high temperature becomes dynamically unstable. However, the exact nature of the instability and its effect on the subsequent disintegration into constituent nucleons and complex fragments is not clear.

The fused composite system formed in nucleus-nucleus collisions has been predicted[17)] to break up immediately if the longitudinal energy per nucleon is greater than 2 MeV per nucleon in the center of mass system. At higher energies a number of theoretical calculations predict the occurrence of a liquid-gas phase transition[18,19].

The consequences of these predicted instabilities are expected to be observable via the relative abundance of complex fragments emerging in the exit channel. Previous measurements of complex particle yields for proton induced reactions at high energies have revealed a simple power law dependence[20] of the observed fragment yield, $Y(A_f) \simeq A_f^{-\tau}$ with $\tau \simeq 2.6$. This power law dependence was interpreted in terms of a phase transition near a critical point.[20]

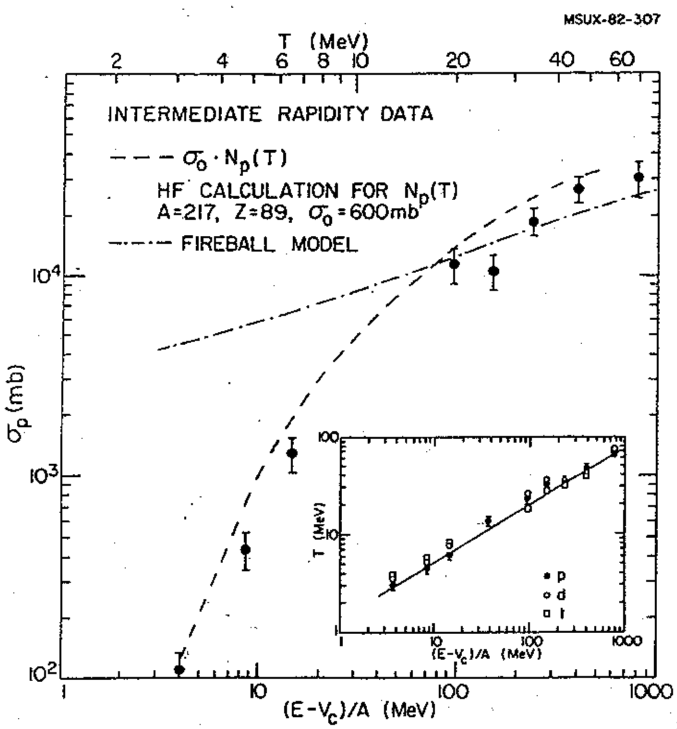

Fig. 8.

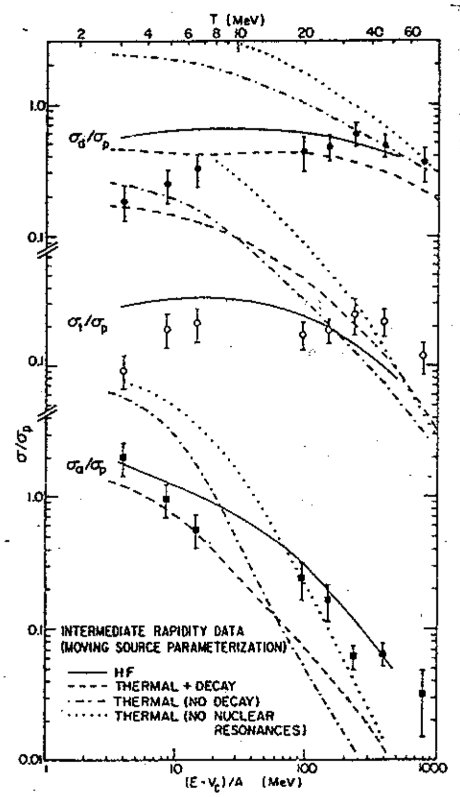

Fig. 9.

Recently, Hauser-Feshbach calculations have been successfully applied to the interpretation of light particle emission in intermediate energy nucleus-nucleus collisions. Examples of such calculations are given in Figs. 8 and 9 by the dashed and solid curves respectively (see Refs.21,22 and

23 for more details). Extensions of these calculations predict a dramatic increase in the emission of Z>3 complex particles as a function of the initial nuclear temperature. The competition between complex particle and proton emission is predicted to exhibit a strong energy dependence with a characteristic maximum near T≃1Ø MeV; (see Fig. 1Ø for illustration). More surprising is the predicted transition of the fragment yields from an exponential to a power law dependence as the temperature is raised from 4 to 8 MeV.

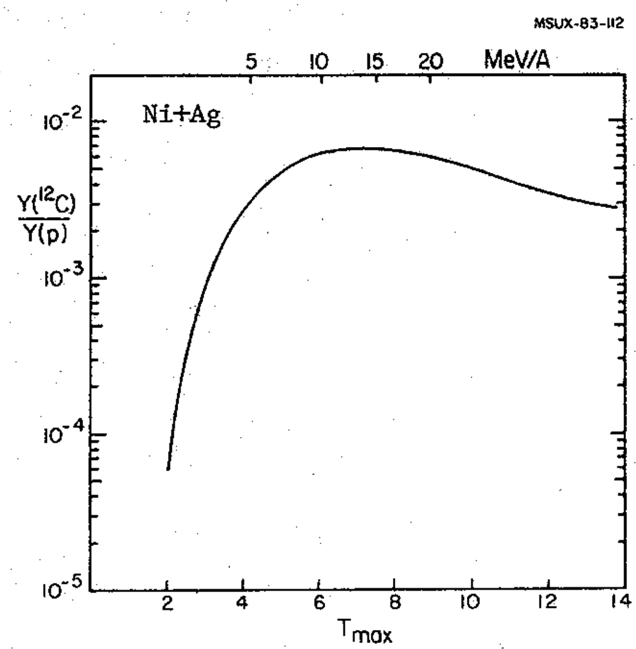

Fig. 1Ø.

At present, little experimental information is available that could be used to test the assumption of thermal emission of composite nuclei heavier than alpha particles. Such data could be decisive for testing our present concepts of intermediate energy nuclear collisions and of crucial importance for our understanding of the properties of hot nuclear matter.

The predicted rapid increase of the cross sections of complex nuclei heavier than alpha particles and possible manifestations of a critical point are accessible to experimental verification for the energies available at MSU, Oak Ridge National Laboratory and G.A.N.I.L. Since it is not clear that complete fusion is achieved at these high energies we plan to perform singles and coincidence light particle measurements in order to obtain independent and complementary information on the nuclear temperature achieved in these reactions. Furthermore, we plan coincidence measurements between complex particles and heavy recoiling nuclei in order to obtain information about the question whether two or more heavy particles emerge in the exit channel.

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(b) Deep-inelastic Scattering

A. Galonsky, M. Mallory, D.J. Morrissey

Investigation of the energy-dissipation process at K500 energies, namely in the region around the Fermi energy of nuclei (~20 MeV/u) is of considerable interest, because at these energies qualitative changes in the characteristic heavy-ion interactions are expected to occur. By observing neutrons, gamma rays and fission fragments in coincidence with the fragments of the collisions we can learn much about the nature of these collisions--about the disposition of the excitation energy and about the amount and orientation of the angular momenta of the fragments. We have three different classes of experiments underway, each focusing on a particular aspect of the deep-inelastic reaction mechanism.

Important contributions to the understanding of the sharing of the excitation energy between reaction partners have come from measurements of the neutron spectra in coincidence with the deep-inelastic fragments. These experiments have been completed at the Berkeley SuperHILAC for ^{56}Fe + ^{156}Ho,[1] at the GSI laboratory for ^{86}Kr + ^{166}Er,[2] and at Orsay for several interacting pairs.[3] In all cases the results were consistent with a reaction mechanism in which a mass flow equalized the neutron-to-proton ratio in the two final fragments; the excitation energy of each fragment was proportional to its mass; and the temperature at which neutrons were evaporated was the same in each fragment. The neutron spectra could be interpreted as being purely evaporative, that is, the contributions due to any "hot spot" or other non-equilibrium neutron source were negligibly small. Of course, the energy in these experiments exceeded the Coulomb barrier by at most 4 MeV/u. An extension of the ^{86}Kr + ^{166}Er experiment to E/A = 12 MeV has resulted in the first observation[4] in a heavy system of neutrons which could not be explained by the above equilibration process.

The first measurements of neutron emission at NSCL will use the higher-mass beams such as ^{20}Ne and ^{40}Ar. At the lower energies mentioned above the reaction is essentially binary, and this fact has been used to reconstruct the kinematics from measurements on only one fragment. However, reactions in which 100 MeV or more of kinetic energy is converted into excitation energy result in a many particle final state which one cannot hope to determine in detail. The best we can hope for is to measure M,Z,E, and direction for the two major fragments. We will determine these quantities for the projectile-like fragment. If one neglects the momentum carried off by light particles, i.e. assumes emission from a constant velocity source, this is sufficient to define the kinematics. For deflections near the grazing angle, the slower, target-like fragment is difficult to detect. However, for the higher excitation energies it should be possible to get some over-determination of the kinematics by measuring the direction and velocity of the target-like fragment with a position sensitive avalanche counter (PSAC). Indeed, in reactions with a large center-of-mass velocity[2,4) the fragment detection was accomplished with a PSAC for each fragment. In a later round of experiments, when ^{40}Ar beams of higher energy are available, heavy-fragment detection will be feasible over a range of Q-value and scattering angle.

The geometry of the experiment is shown in Figure 1. Deep inelastic scattering is concentrated into forward angles, thus allowing us to place the target at the entrance, rather than the center, of the scattering chamber. This positioning creates longer flight paths for better velocity and angle determination. The large acceptance angles of the avalanche counter (AC) and of each PSAC render angle changes unnecessary or at least infrequent. Timing signals from the light-fragment AC and PSAC determine the fragment velocity and the time of the event in the target; the latter is used for determining the neutron flight time. The thin ionization chamber (IC) and stopping solid state detectors (SSD) are used for ΔE-E measurement and Z determination. Outside the chamber are 10 NE213 scintillation neutron detectors (1 shown).

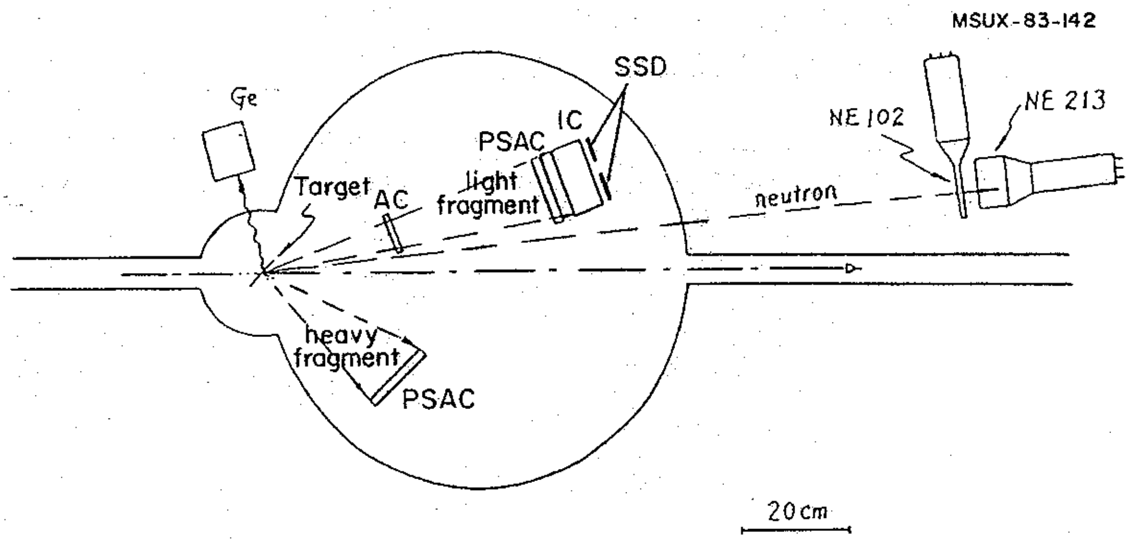

Fig. 1. Set up for fragment-neutron coincidence measurements. Only one of the ten neutron detectors and one of the four Ge detectors are shown.

To minimize spectrum distortion from neutron interactions in the chamber, the chamber is deep and it has thin walls. Indeed, the proton cut-off is below 50 MeV. Above 50 MeV, protons will also reach the neutron detectors; they will be distinguished from neutrons by thin NE102 scintillators in front of the neutron detectors and, as for neutrons, their spectra will be measured by time of flight. Comparison of neutron and proton spectra is most informative at the higher energies where the influence of the Coulomb barrier is small. We have made such a comparison in a ^{16}O + U fission experiment[5] at Berkeley.

The experimental geometry for observing neutrons and protons emitted in a fission event requires little modification from the geometry of deep inelastic reactions. With the variability of projectile type and energy given by the K5ØØ, we will be studying both the classical fusion-fission regime and the regime of fast fission[6,7,8] where a critical angular momentum is exceeded.

The inclusion of a set of gamma-ray detectors will lead to additional useful information. Besides fragment identification, this information is the gamma-ray multiplicity, of course, and would enable us to calculate the spin transferred in the reaction process. Several determinations of the magnitude of transferred angular momentum have been made by measuring gamma-ray multiplicities[9] and angular distributions of sequential fission fragments.[1Ø-12] There is, in general, an increase in the transferred angular momentum with increasing negative Q-value, and there is evidence that sometimes the statistical equilibrium sticking limit of rigid rotation is attained.[9] A systematic study of a reaction system that includes information on the creation of excitation energy (from neutron spectra) and intrinsic spin angular momenta (from the gamma-ray multiplicities) would be very valuable.

Another important aspect of the reaction mechanism is the alignment of the transferred angular momentum, since components of this angular momentum are, in general, present both perpendicular to and in the reaction plane. Measurements of the in-plane to out-of-plane ratio of continuum gamma-rays have shown that a relatively simple arrangement of three continuum gamma-ray detectors can be used to extract the details of the variation of the alignment of the spin angular momentum.[13] By a suitable arrangement of the gamma-ray detectors used in the multiplicity measurements we can simultaneously extract the angular distribution of the gamma-rays. We have started to develop this line of research by measuring neutron-discrete gamma-ray coincidences, in a ^{12}C + ^{16}O fusion-evaporation experiment[14] at Notre Dame.

We are also involved in a continuing study of the role of angular momentum transfer in deep-inelastic scattering in collaboration with the Moretto group at the Lawrence Berkeley Laboratory. In particular, we are in the process of completing a series of measurements of sequential fission of ^{197}Au and ^{238}U targets induced by ^{20}Ne, ^{32}S and ^{40}Ar projectiles. Such measurements yield information on the magnitude and orientation (or alignment) of the intrinsic spin of the heavy fragment as a function of kinetic energy damping and mass transfer.

The measurement of the sequential fission angular distributions has provided the most detailed information on the average angular momentum of the reaction products from deep inelastic scattering. This is the only technique that can differentiate between the components of the spin of the reaction product that are in the scattering plane. These in-plane components of the angular momentum cause the misalignment of the fragment's spin from the entrance channel orbital angular momentum. The in-plane components can be generated by some feature of the reaction mechanism or by statistical fluctuations of the angular momentum bearing modes of the dinuclear complex. Moretto, Schmitt and Pacheco have shown that statistical equilibrium predicts a difference in the in-plane components of the angular momentum whenever the reaction partners are mass asymmetric.[15,16]

The results from our work lend strong support to the statistical equilibrium picture of the misalignment of the spin. We have recently published our measurements of the ^{20}Ne induced sequential fission which demonstrated the largest in-plane anisotropy observed for a deep-inelastic reaction (2:1).[11,12] The study of the ^{40}Ar induced sequential fission is nearly complete, and it shows a smaller but still substantial in-plane anisotropy (1.5:1). This anisotropy can be seen in Fig. 2. Data for ^{32}S induced sequential fission are presently being analyzed.

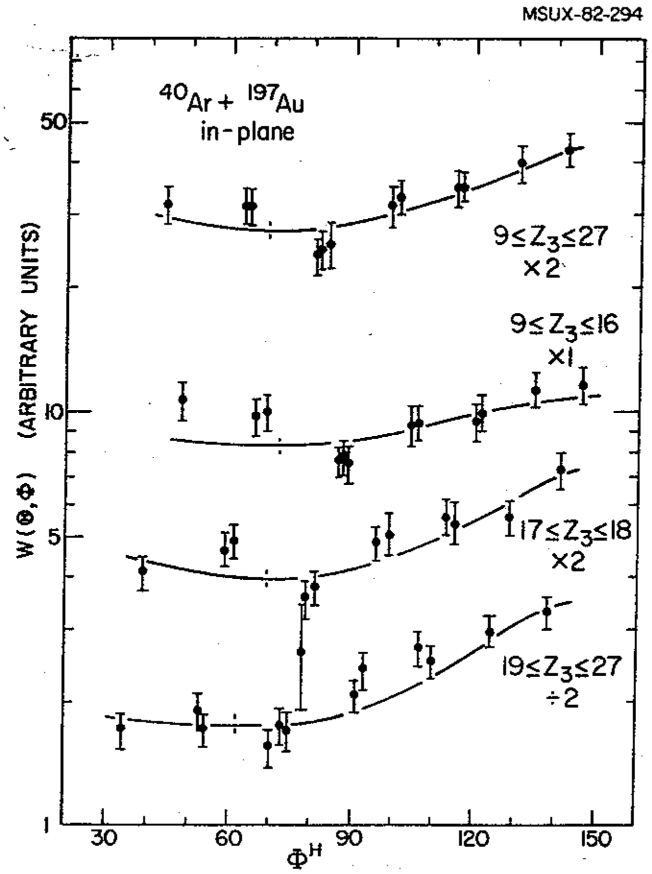

Fig. 2. The in-plane sequential fission angular distribution for the reaction of ^{40}Ar with ^{197}Au is shown. The average Q value is 140 MeV. The angle is measured with respect to the laboratory target recoil angle.

The preliminary results indicate that the anisotropy will lie between the two established values, as expected. However, an intriguing feature of the in-plane anisotropy that we found in the ^{40}Ar induced sequential fission is that the anisotropy decreases with exit channel mass asymmetry, given the fixed entrance channel mass asymmetry. This feature is shown by the Z-gated angular distributions in Fig. 2. The statistics of the two other data sets do not allow a similar analysis. Thus, the global magnitude of the anisotropy follows the mass asymmetry, but a fixed system seems to show the opposite behavior. We propose to remeasure the ^{40}Ar induced reactions in order to improve the statistics so that we can follow the in-plane asymmetry as a function of mass transfer. With these more complete data we hope to be able to separate dynamical influences from statistical equilibrium.

An important part of the experimental work at the NSCL will be the tracing of the connections of the low energy reaction mechanisms, such as the work just described, into the high energy stochastic processes. As the third part of the deep inelastic studies we are preparing for a series of approved experiments to measure the variation of transferred angular momentum with bombarding energy at the NSCL. The experiment consists of measuring projectile-like products in coincidence with continuum gamma-rays as a function of energy damping at several bombarding energies. The gamma-ray multiplicity can be used to calculate the spin created in the fragments as a function of energy damping and mass transfer. At low bombarding energies this conversion of orbital motion into intrinsic spin can be reasonably described in terms of particle transfer or mechanical torques. This experiment will follow the angular momentum transfer and will show when the reaction mechanism moves away from the expected behavior.

The reaction system we have proposed to study at the NSCL is ^{40}Ar + ^{165}Ho at a series of bombarding energies ranging up to the maximum available. The choice was dictated by several factors, notably, the projectile should be as massive as possible in order to maximize the entrance channel angular momentum. The product nuclei should be good rotational nuclei so that the conversion from gamma-ray multiplicity to fragment spin is straightforward. However, the projectiles that are available at NSCL, e.g. ^{40}Ar, are not good rotational nuclei; hence the target-projectile mass asymmetry was chosen to be large. This will concentrate statistically equilibrated angular momentum in the heavy fragment (which is a good rotor).

A 20" scattering chamber with a thin aluminum lid is being prepared for installation on the gamma-ray beamline at the NSCL for these experiments. The particle detectors will be small ion-chamber detectors (solid angles $\simeq 10^{-3}$ of 4π) that were obtained from Berkeley. These detectors will be used in the first experiments and will be replaced by higher efficiency gas ionization chambers that will be developed at the NSCL.

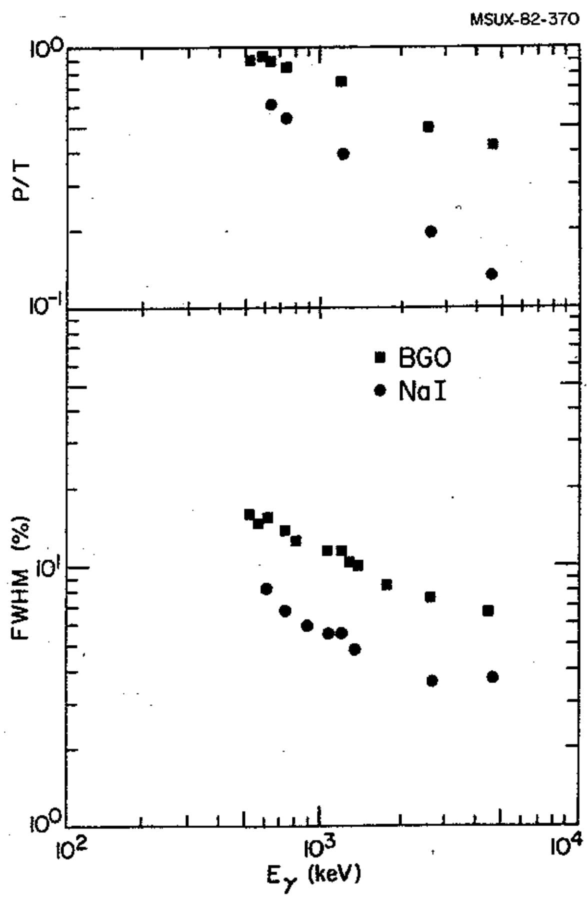

Fig. 3. The full-energy-peak to total-interactions ratio can be compared in the top for 7.6 cm x 7.6 cm BGO and NaI(Tl) detectors. The resolution of these two gamma-ray detector materials can be compared in the bottom.

The continuum gamma-rays will be detected in a set of 4 BGO detectors (7.6 cm x 7.6 cm). The BGO detectors have an advantage over NaI(Tl) detectors for continuum gamma-rays by virtue of their higher stopping power and thus higher photopeak efficiency. This difference is emphasized in Fig. 3. In preparation for using the new BGO detectors we have explored their sensitivity to moderately fast neutrons (≃5 MeV) which will be present in our experiments.[17)] We have found that BGO and NaI(Tl) have about the same sensitivity to these neutrons per unit volume. This is exactly opposite to the slow neutron sensitivity of the two materials (BGO being much less sensitive). Thus, the neutrons will have to be discriminated on the basis of their time-of-flight. The standard photomultiplier tubes supplied by Harshaw Chemical Co. do not have adequate time resolution for the discrimination and we are cooperating with Harshaw in specifying and testing a different PMT - BGO match.

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(c) Nuclear Fragmentation

N. Anantaraman, L.H. Harwood and G.D. Westfall

The study of projectile fragments produced in peripheral collisions of heavy ions has been very useful for an understanding of reaction mechanisms[1-2] as well for investigating the properties of neutron-rich nuclides.[3-4] The projectile fragments are identified on the basis of a characteristic peak, centered at approximately the beam velocity, in the inclusive momentum spectra of ejectiles emitted at forward angles. The bulk of the existing fragmentation data has been obtained with beams at incident energies between 100 and 2000 MeV/nucleon. These data show a reasonable agreement with the Goldhaber model[5], according to which the fragments are produced by a rapid shearing process, with a momentum distribution that samples the Fermi momentum of nucleons in the projectile. There are also some measurements in the energy range between 20 and 100 MeV/nucleon[6-10], where the delineation of the fragmentation process has been a subject of discussion for several years. In order to clarify the picture, we propose to undertake a series of measurements in the energy range up to 80 MeV/nucleon with the K500 beams, with extension to higher energies when Phase II beams become available.

Most analyses have focussed on the form of the momentum distribution of the emitted fragments, by comparing with the model proposed by Goldhaber.[5]. This model predicts that the fragment momentum distribution parallel to the beam can be characterized by a Gaussian shape with a width

$$\sigma_{||} = \sigma_{o||} \sqrt{\frac{M_p(M_p-M_f)}{M_p-1}} ,$$

where M_f and M_p are the fragment and projectile mass numbers, respectively. $\sigma_{o||}$ is proportional to the mean momentum of the projectile nucleons and appears to be a constant independent of projectile and energy at sufficiently high energies. Early studies[6] suggested that this "asymptotia" was reached by 20 MeV/nucleon. This observation provided the basis for many subsequent studies of additional transitional phenomena in the region of 20 MeV/nucleon. A later study concluded, however, that the asymptotic limit of the momentum distribution must occur at a higher energy.[7] A measurement with ^{20}Ne suggested that the high-energy limit is reached by 42 MeV/nucleon.[8] The measurements we propose will help to define the behavior in the transition region more precisely.

The velocity of sound in nuclear matter and the Fermi velocity of nuclear matter are both within the range of velocities available at NSCL. We shall be able to investigate any changes in $\sigma_{o\parallel}$ as we decrease the beam velocity below these two boundaries. It appears that at low energies $\sigma_{o\parallel}$ is not independent of beam velocity or projectile species but instead has a strong dependence on the beam velocity. This is illustrated in Fig. 1, which supports a relatively smooth transition in the reduced width.[10] One must be cautious when using the data of Fig. 1 as evidence for or against the occurrence of particular reaction mechanisms. A variety of reaction mechanisms could be contributing. For example, it is known that at the lower energies, processes such as direct and deeply-inelastic transfer become more important relative to the simple fragmentation process. Also at the lower energies, emission of secondary particles becomes more important in determining the widths of the distributions. By studying the energy dependence of the width of the momentum distribution, we should be able to unfold the primary and secondary interaction effects.

The angular distributions of nuclear fragments at intermediate energies--or equivalently the widths of the perpendicular momentum distributions--are governed not only by the ground-state motion in the projectile[5] but by its deflection in the nuclear and Coulomb fields of the

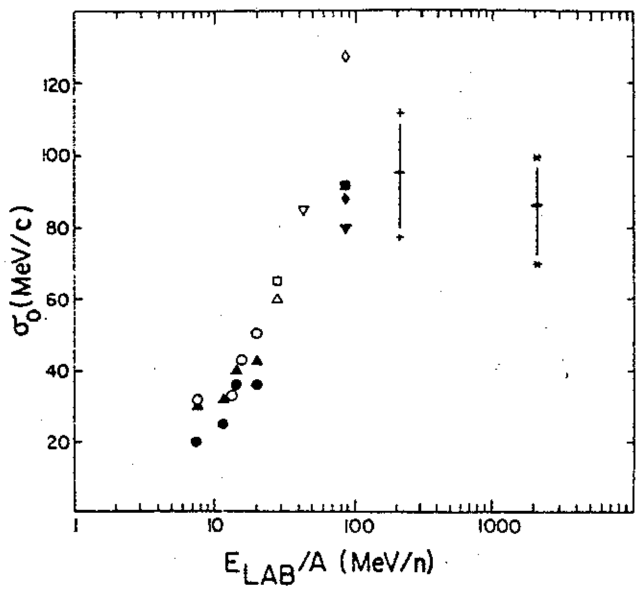

Fig. 1. A compilation of several different measurements of the reduced momentum widths of ejectiles from heavy-ion reactions (ref. 10). A large number of widths were measured at 213 and 2100 MeV/n; the figure indicates the range and mean value of the results.

target.[2)] By analyzing this phenomenon, it may be possible to sample the nuclear potential at much smaller radii than in transfer reactions.

The Goldhaber model has not been completely successful in explaining all the features of the data, even in the high-energy regime. We note, for instance, the differences in widths observed for nuclides of the same mass (Fig. 1). In a very recent reexamination of fragmentation data, Friedman[11)] has addressed these shortcomings of the Goldhaber model. He has attempted to explain the longitudinal momentum distributions of the fragments with a single parameter model based on absorptive effects (reminiscent of the optical model); the single parameter of the model is a radial scaling factor which, when multiplied by $A^{1/3}$, gives a "strong absorption radius." The model uses a simple cluster picture to arrive at a radial bound state wave function for the fragment relative to the part that is stripped away by the target. This leads to a localization in radial space which, in turn, leads to a width in momentum space obtainable with a Fourier transform. The predictions of this model are in much better agreement with the high-energy ^{12}C fragmentation data and are at least as good as the Goldhaber model for ^{16}O fragmentation. The variation in the widths observed for different isobars is automatically accounted for by Friedman: his prediction is that the momentum distribution width should be smaller than average for fragments formed by the removal of loosely bound clusters from the projectile. In addition, Friedman has attempted to estimate exit channel effects, such as the Coulomb distortion of the fragments' trajectories, which are important at lower energies (10-20 MeV/nucleon) and whose inclusion leads to agreement with the observed narrow widths.

The role of Pauli correlations in reducing the width of the momentum distribution has been studied by Bertsch.[12)] For a very heavy nucleus, such as ^{238}U, the calculated reduction in the dispersion is more than a factor of 2. It would be interesting to confirm the A dependence predicted by the Pauli correlations.

In order to better test these various models, we propose to extend the fragmentation data to much lower beam velocities and to expand the number of projectiles studied. The velocity range available at NSCL will be most interesting for this purpose. The wide variety of beam species will also allow us to greatly extend the scope of the data and our subsequent understanding of the reaction mechanisms. For example, the comparison of the widths for ^{22}Ne and ^{20}Ne beams will be interesting in view of the observed[5)] differences for ^{6}Li and ^{7}Li. An important point is that we will be able to measure the distribution widths for a given system from E/A=5 MeV to 80 MeV (and to 200 MeV with Phase II); the current data span a wide range of beams and ejectiles and thereby may have projectile, and certainly ejectile, effects folded into the velocity effects on the widths.

The projectile fragmentation process must be distinguished from the competing process of coherent projectile break-up in the Coulomb field of the target. The use of both light and heavy targets will help in this regard as well as in studying the target dependence of the fragmentation process itself. While the process is independent of the target at relativistic energies, there is some evidence for target dependence at energies below 100 MeV/nucleon.[13)]

Many of the measurements can be done with the K500 cyclotron; those needing to exceed 80 MeV/nucleon will have to await the K800. Some of the measurements will have to be done at the Bevalac; while they are not absolute necessities, data with very heavy projectiles would be the final test for any model. An example of such a beam only available at the Bevalac would be ^{238}U at 400 MeV/nucleon. Experiments with such beams as 100 MeV/nucleon ^{56}Fe could also be done at the Bevalac, but the much higher beam intensities projected for NSCL makes it a much more effective place to do such measurements.

At NSCL two instruments will provide most of the data. In Phase I, the S320 spectrograph will permit measurements of the fragments at and near zero degrees. In Phase II, the S800 will serve the same function for the fragmentation experiments. A detector system suitable for use with the S320 has been designed and is being built; the S800 detectors are still in the design process. Any experiments at the Bevalac would probably be done on the "Zero Degree Spectrometer."

In this section, we have focussed on the reaction mechanism aspects of the fragmentation process. However the fragments produced are interesting in their own right and a proposal to study their spectroscopy with the recoil product mass separator (RPMS) is discussed in section IVB4 (b). The measurements we have discussed here will obviously help in making effective use of the RPMS for the spectroscopic studies.

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A 2. TWO-PARTICLE CORRELATIONS

(a) Correlations between Light Particles

(b) Correlations between Light and Heavy Particles

(a) Correlations Between Light Particles

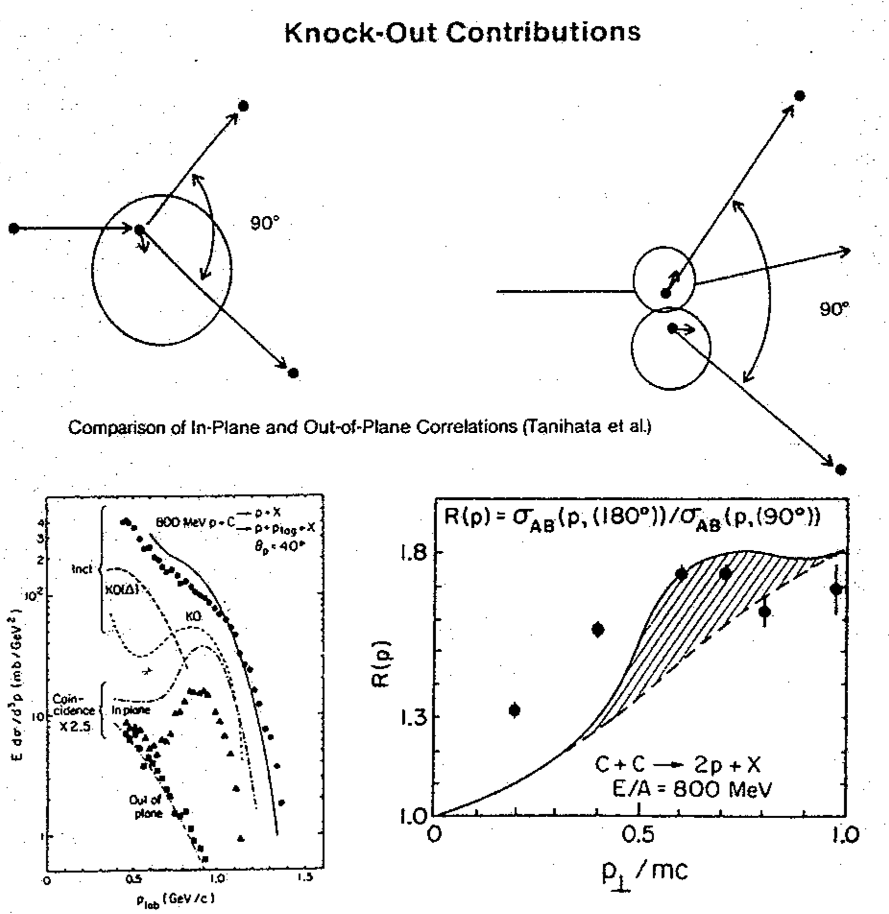
C.K. Gelbke and D.K. Scott

A variety of reaction mechanisms has been suggested leading to the emission of energetic light particles in intermediate energy nucleus-nucleus collisions. These mechanisms range from direct knock-out and breakup reactions on the one extreme to the attainment of local thermal equilibrium on the other. It should be clear that single particle inclusive measurements are, very often, not restrictive enough to discriminate between different models. The main reason for this lack of discrimination is the dominance of kinematic and phase space effects on the single particle observables.

Although light particle inclusive cross sections at sufficiently large transverse momenta can be rather well described in terms of thermal and hydrodynamical models, it is still a matter of debate whether local thermal equilibrium is indeed achieved for a single nuclear collision or whether the thermal character of single particle inclusive observables is primarily a result of ensemble averaging. According to the hypothesis of local statistical equilibrium, no dynamical correlations should exist between coincident light particles. The only remaining correlations should result from the phase space constraints imposed by the conservation laws for a finite ensemble or from final state interactions between particles leaving the statistical ensemble.

Up to the present, light particle correlation studies were stimulated by two motivations: (i) test the statistical assumption and search for possible dynamical correlations that could provide clues about the reaction mechanism; (ii) take advantage of final state interactions and try to obtain information about the space-time extent of the emitting ensemble.

If quasi-free knockout reactions are important in nucleus-nucleus collisions, an enhancement of the coincident proton-proton cross section will occur at the location corresponding to the free nucleon-nucleon kinematics. This enhancement will be broadened by the nucleon Fermi velocity distribution and there will be a damping due to a combinatorial background resulting from uncorrelated nucleon-nucleon scatterings. Such processes have been identified for proton-nucleus collisions[1)] at 800 MeV and for collisions between lighter nuclei[2)] at E/A = 400 and 800 MeV and between Ar and Pb at 800 MeV/nucleon[2)], as is shown in Fig. 1. Part (a) of the figure[2)] gives a comparison of single-particle inclusive and two-particle



(a) Fig. 1. (b)

inclusive proton spectra measured for in- and out-of-plane geometries at $\Theta_{lab} = 40^{O}$ for the reaction p + C at 800 MeV. The quasi-free scattering component is clearly identified in the coincidence spectrum measured in coplanar geometry.

Part (b) of the figure gives the ratio of in- and out-of-plane coincidence yields for the C + C reaction[2] at E/A = 800 MeV, showing an enhancement of the in-plane cross sections which is partly due to the knockout component but is likely to contain contributions from multiple scattering components.[3] Also included in the figure are the calculations from a geometrical phase space model[3] which reproduce the observed correlations rather well.

The random emission of light particles from a finite size source will, in general, still exhibit measurable correlations due to final state interactions or quantum statistical symmetries which affect the wavefunctions of particles that are emitted within small space-time intervals. These correlations can provide useful information about the space-time extent of the emitting sources.[4] At present, the effects of these final state interactions on the correlation function for two coincident light particles have been taken into account quantitatively for the case of proton-proton correlations[4]; however, distortions of these correlations caused by the interactions of the correlated pairs with the long range Coulomb interaction with the target residue have not been fully included.

In Fig. 2 two-proton correlations measured[5] for the reaction ^{40}Ar + KCl at E/A = 1.8 GeV are compared to the model calculations of ref. 4. The small size of the sharp sphere radius, R_s = 2.4 fm, which was extracted for nucleon emission at intermediate rapidities using a high multiplicity trigger ($1/2Y_B$,M>4 in the figure) is even smaller than expected from simple geometrical models; this striking result is not understood, at present.

Up to the present, correlations between two light particles have been investigated primarily at relativistic energies. Very little experimental information is available at lower energies. In Fig. 3 proton energy spectra are compared which were measured[6] in single- and two-proton inclusive experiments for ^{16}O induced reactions on

^{27}Al and ^{197}Au targets at the incident energy of E/A = 19.4 MeV. Within the statistical accuracy of these measurements, the shapes of light particle energy spectra

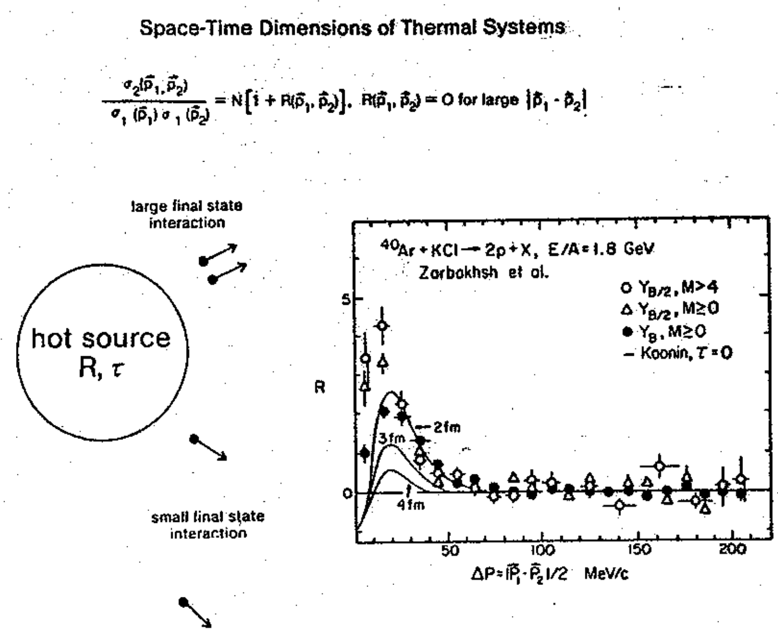


Fig. 2.

observed in coincidence with a second light particle were found to be very similar to the shapes of the singles energy spectra, indicating that the assumption of statistical equilibrium of a subset of nucleons is not strongly violated.

A more sensitive test for the existence of two-particle correlations is obtained from the correlation function $\sigma_{12}/\sigma_1\sigma_2$, as is shown in Fig. 4. The experimental correlations[6] exhibit sizeable variations which are more pronounced for the Al-target than for the Au-target. The correlation function has a minimum value for the emission of two light particles into the forward direction and exhibit a pronounced left-right asymmetry corresponding to the enhanced probability for coincident emission of the two

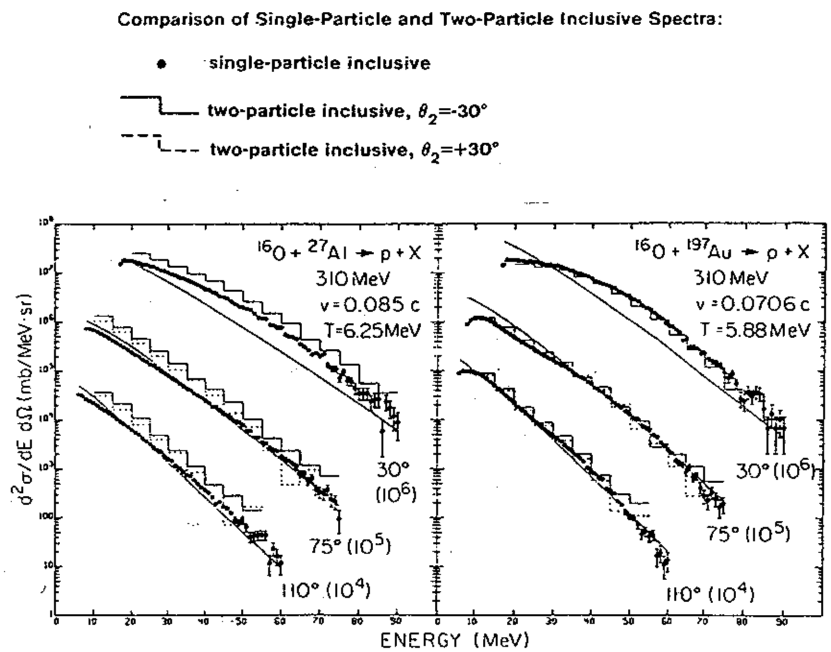


Fig. 3

light particles on opposite sides of the beam. Existing simple models of thermal light particle emission have not been successful in reproducing these correlations.[6)] Encouraged by the fact that sizeable two-particle correlations may indeed be observed at low to intermediate energies we have recently performed a more elaborate experiment in collaboration with Oak Ridge National Laboratory. In this experiment, coincidences between 13 light particle detector telescopes were measured for ^{16}O induced reactions on C, Al and Au targets at the incident energy of E/A = 25 MeV. In order to test the statistical assumption and search for possible dynamical effects, in- and out-of-plane correlations were measured for large relative momenta. In addition, a six-element hodoscope was placed at forward angles to investigate the correlations at small relative momenta caused by final state interactions. At present, the data are being analyzed. We plan to improve our detection system and expand it to a total of about 15 telescopes with which we plan to perform a systematic investigation of large and small angle light particle correlations over the entire range of

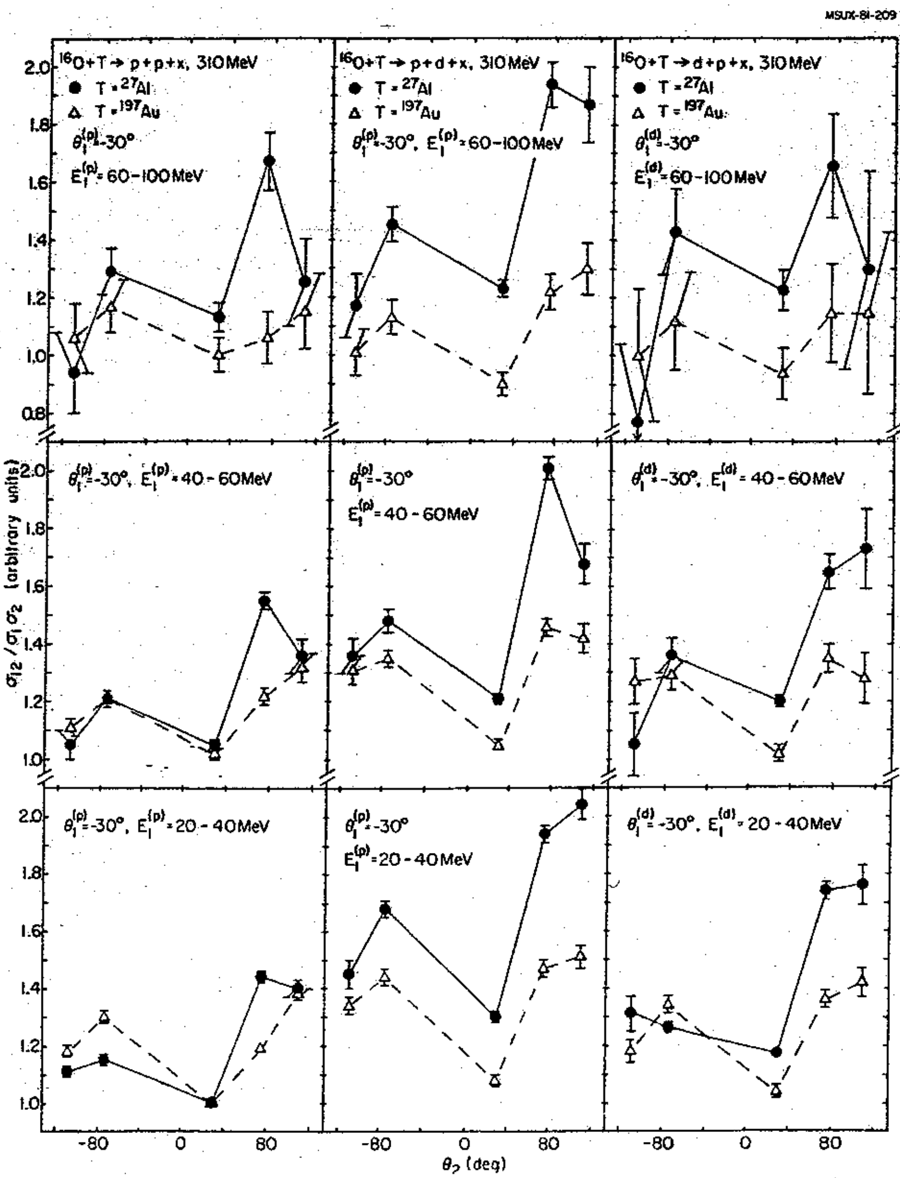


Fig. 4.

energies available at Michigan State University and, possibly, G.A.N.I.L.

To provide maximum flexibility, we propose to purchase 15 light charged particle telescopes that have good energy resolution over a maximum possible range of energies. In previous experiments, a good compromise between solid angle, energy resolution, dynamical energy and particle range was achieved by using 400 micron, 450 micron surface barrier ΔE detectors backed by thin window (7.5 micron Havar) NaI detectors of 2" diameter and 4" thickness. These detectors can be operated in high vacuum. They have better energy resolution than plastic scintillators and the additional advantage of being sufficiently efficient to detect high energy (~4 MeV) γ-rays that may be used for calibration purposes. We propose to buy a total of 15 similar telescopes for a total cost of $35,000.

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(b) Correlations Between Light and Heavy Particles

G.M. Crawley, C.K. Gelbke and D.K. Scott

There is growing evidence for the formation of a localized zone during collisions of heavy ions over a wide range of energies.[1] At high incident energies of several hundred MeV/nucleon, this source manifests itself as a participant zone with high temperature. As the incident energy is reduced the participant zone could evolve into a hot-spot, the observation of which would give information on the transport properties of nuclear matter[2] at finite temperatures. At low bombarding energies, i.e. at low temperatures (of a few MeV), in the energy domain where the TDHF approach has proved to be successful, the mean free path of a nucleon is comparable to or larger than typical nuclear dimensions. At higher temperatures, the mean free path may become short enough for a hydrodynamical approach to be meaningful. The evolution of TDHF to higher temperatures is currently under study through the incorporation of collision terms, and in one approach a link has been established to hydrodynamical behavior.[3] Calculations of the mean free path as a function of temperature are currently in progress[4] at MSU, utilizing a realistic nucleon-nucleon potential with Pauli blocking effects included in a self consistent manner.

Phenomenological studies show that the evolution of the mean free path with temperature may be rather sudden. Fig. 1 illustrates the predictions of one model, in which the mean free path decreases rapidly as $T \simeq 10$ MeV is approached.[5] Other studies based on quite different approaches indicate that the mean free path in nucleus-nucleus collisions may be short at energies of ~35 MeV/nucleon,[6] (1-3.5 fm) and then increase at higher bombarding energies. This behavior, if substantiated, could influence the formation of hot-spots in nuclear collisions in this energy domain.

We propose to perform coincidence experiments with ^{40}Ar induced reactions at the highest energy of 20 MeV/nucleon

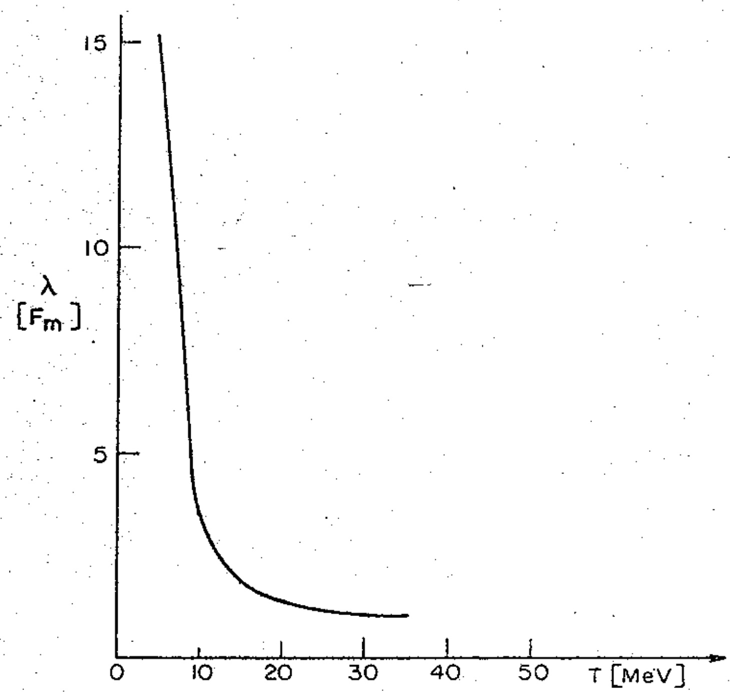

Fig. 1. Calculated variation of the mean free path as a function of nuclear temperature.

available at NSCL. Emitted light fragments (p,d,t, ^{3}He, alpha) will be detected in coincidence with projectile-like fragments; an asymmetry in the emission pattern of the light fragments will be sought, the detection of which will be indicative of local zone formation from the energy deposition on one side of the nucleus. A similar experiment was recently reported[7] using incident α-particles of 140 MeV. From the angular distribution of coincident protons, an angular dependent temperature was deduced (Fig. 2(a)). A schematic picture of the mechanism which could cause this asymmetry is shown in Fig. 2(b), suggesting that protons emitted to the right hand side of the direction of the transferred momentum, traverse less nuclear matter than those emitted to the left. From a theoretical analysis, of such observations it may be possible to deduce information on the transport properties of nuclear matter at finite temperature.[2]

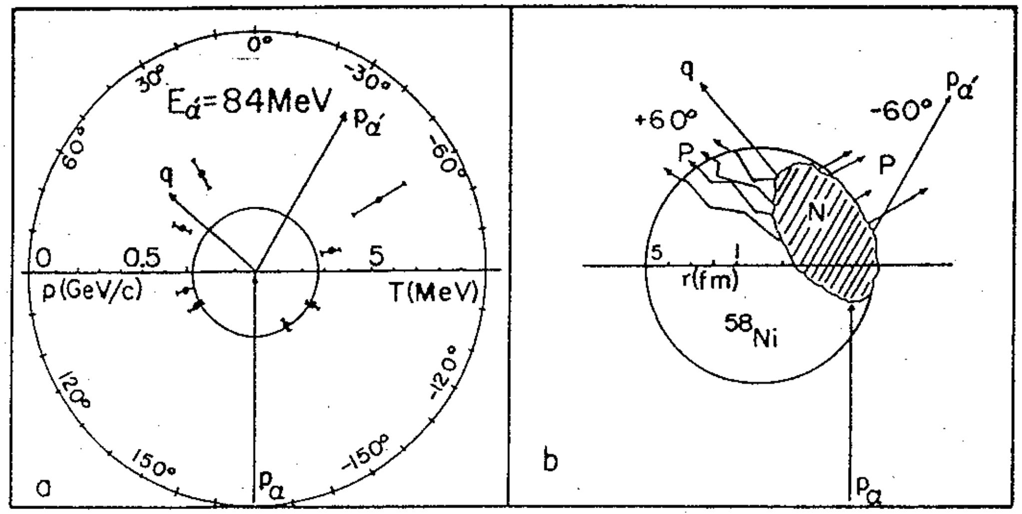

Fig. 2. In part (a) the temperature variation is shown as a function of emitted proton direction, where the protons are observed in coincidence with inelastically scattered α-particles in the direction P_{α}'. A possible interpretation is given in (b), where the protons are assumed to be emitted from a localized zone.

Earlier studies with heavy ions have been inconclusive because of the difficulty of disentangling the contributions of sequential excitation and decay. With a light heavy ion the direction of the intermediate excited fragment changes with changing light particle detection angle, so that asymmetries can be generated from the variations of the angular distribution of the excited fragment. (For an early study of this phenomenon, see Ref. 8). These problems are less acute in the case of a heavy projectile such as ^{40}Ar.

Similar studies have already been conducted with ^{40}Ar and ^{32}S at incident energies below 10 MeV/nucleon,[9,10)] which are suggestive of the emission of light particles from the neck between the colliding nuclei, and of shadowing of fast non-equilibrium α-emission caused by the proximity of the colliding nuclei. These observations are also indicative of emission from localized regions. We expect that the zone of emission should be much better developed with the higher energy beams of ^{40}Ar available at NSCL.

If the asymmetries due to emission from localized regions can be confirmed, then it may be possible to deduce information on the transport properties of nuclear matter at finite temperature using the methods of Ref. 2.

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A 3. HIGH MULTIPLICITY REACTIONS

(a) **Production of Composite Particles**

(b) **Streamer Chamber Experiments**

(c) **Experiments with Charged Particle Multiplicity Array**

(a) Production of Composite Particles

G.M. Crawley, C.K. Gelbke, D.K. Scott,
H. Stöcker and G.D. Westfall

(i) Scientific Motivation

The formation of nuclear matter far from normal densities and at high excitations can provide information on the equation of state of nuclear matter. It may be possible to create nuclear matter in these states by colliding two nuclei and identifying particles emitted from the interaction zone between the two nuclei. By studying the energy spectra and production cross sections for nucleons and light nuclei from this interaction zone as a function of incident energy, it is possible to create a miniature laboratory for investigating nuclear matter in extreme states. Although most attention has been directed to the high density region, it is also of interest to study the properties of the system at low density after the expansion of the compressed zone has taken place.

In terms of statistical and hydrodynamical concepts, two interesting types of behavior could occur. At sufficiently high temperatures, the nuclear system exists only in a gaseous phase regardless of the density. This temperature is estimated to be approximately 20 MeV for nuclear matter[1)] but closer to 10-12 MeV for finite nuclei.[2)] Below this temperature both a liquid and a gaseous phase can coexist. The effect of the liquid-gas phase transition connecting these two phases is currently being investigated by means of hydrodynamical models in order to predict observable consequences[3)]; the observation of such effects would be important in demonstrating the relevance of hydrodynamical concepts in nuclear collisions, particularly in view of the interest in studying phase transitions of a more exotic nature. In actual nuclear collisions, the temperature is not expected to remain constant during the hydrodynamical expansion; however it appears that the entropy may remain more constant. Fig. 1 shows the region over which the liquid-gas coexistence may be observable.[4)]

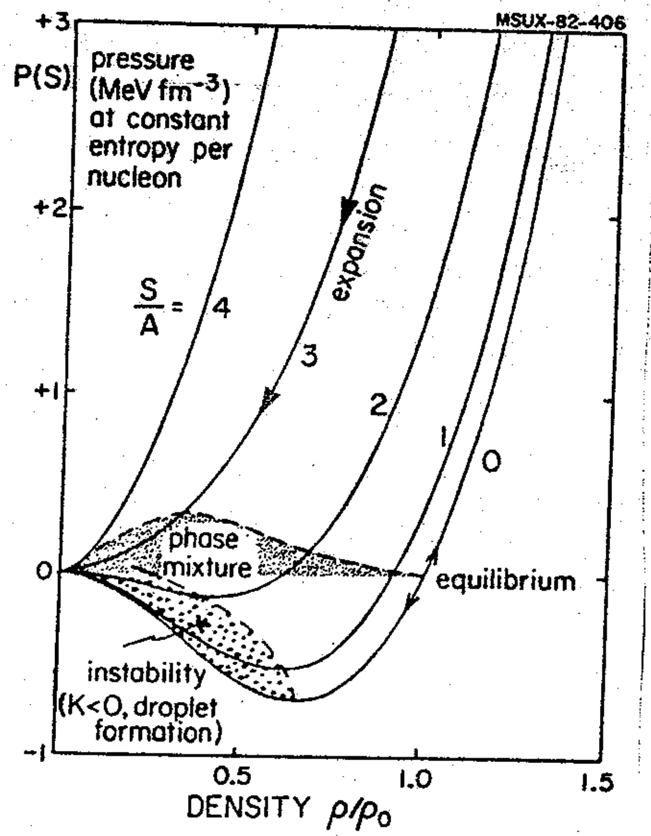

Fig. 1. Variation of the pressure in a nuclear system as a function of density relative to normal density, for different values of specific entropy S/A. During the expansion following the creation of a compressed, heated nuclear zone, the entropy stays approximately constant, as indicated by the arrows on the curve for S/A=3. The regions in which a mixture of nuclear gas and liquid phases coexist, as well as the region of mechanical instability (K<0), are indicated.

The dynamical evolution of the nuclear system may occur too rapidly for the equilibrium to be established across the phase boundary. This point has been discussed by Curtin[5)], who shows that the establishment of phase equilibrium depends on the interplay of the temperature dependence of the evaporation times and of the damping times relevant to the dynamical evolution of the system. However, a phase separation can also occur on a short time scale,[6)] if the expanding system develops a mechanical instability, i.e. if the nuclear compressibility becomes negative. This region is indicated in Fig. 2, together with the overstressed zone from which the unstable region can be reached by an expansion at

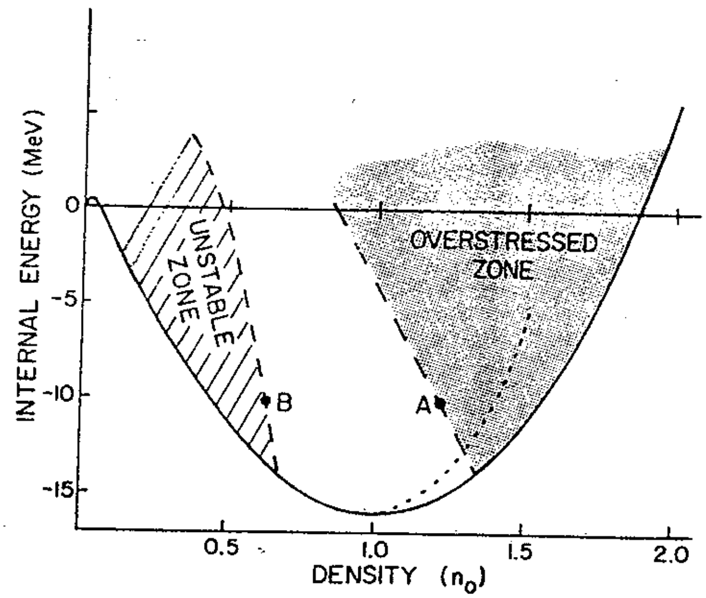

Fig. 2. The region of instability (as shown in Fig. 1) is delineated here in an internal energy, density plot, along with the corresponding overstressed zone, created for example in a nuclear collision, from which the unstable region becomes accessible in an expansion at constant entropy.

constant entropy. The required energy per nucleon is higher in a hadron collision which induces no compression than in a heavy ion collision with compression. The observation of this difference may be useful in studying compressional effects in heavy ion collisions and we shall investigate experimental possibilities in the near future.

In both types of phase transitions - the slow chemical or the fast mechanical instability - one expects a change in the production of nucleons and light particles as some critical excitation energy is exceeded. Recent calculations incorporating the effects of critical phenomena predict sudden changes in the relative abundance of light composites and nucleons at the critical temperatures.[7)] So far there are insufficient data to confirm or rule out the above ideas, but it appears that beam energies from the NSCL Phase I Cyclotron in the range 20-60 MeV/nucleon, supplemented by experiments at higher energies up to 100 MeV/nucleon at the Bevalac, are well suited to such an investigation.

(ii) Recent Experiments

We have been pursuing these ideas through an analysis of ^{16}O and ^{20}Ne induced reactions on heavy targets where the contribution from the interaction zone is identified with a source moving in the laboratory with a velocity intermediate between that of the projectile and target nuclei.[8)] Production cross sections and apparent temperatures were extracted for p,d,t and alpha particles. The variation of the temperature for protons is shown in Fig. 3 but similar temperatures are found for different emitted particles, thereby reinforcing the validity of the thermal model. The point plotted at 35 MeV/nucleon comes from an analysis of the first experiment performed at NSCL with a ^{12}C beam. In Fig. 4 the mean mass of fragments (protons -> alphas) emitted from the source are shown as a function of incident energy. The data seem to indicate a change in behavior around 35 MeV/nucleon. Above 100 MeV/nucleon the temperatures and production cross sections have been described in terms of a model incorporating thermal and chemical equilibrium among nucleons in the interacting region.[8)]

In more recent experiments at the Bevalac we are studying heavier emitted fragments in ^{40}Ar induced reactions on Ca and Au at E_{LAB} of 50, 100 and 150 MeV/nucleon. The following particles were observed at velocities intermediate between those of the projectile and target:p,d,t, $^{3,4,6,8}He$, $^{6,7,8,9}Li$, $^{7,9,10,11}Be$, $^{10,11,12,13}B$, and $^{11,12,13,14}C$. Similar measurements will be carried out at the NSCL with 20-60 MeV/nucleon ^{4}He, ^{12}C, and ^{20}Ne beams. The observed

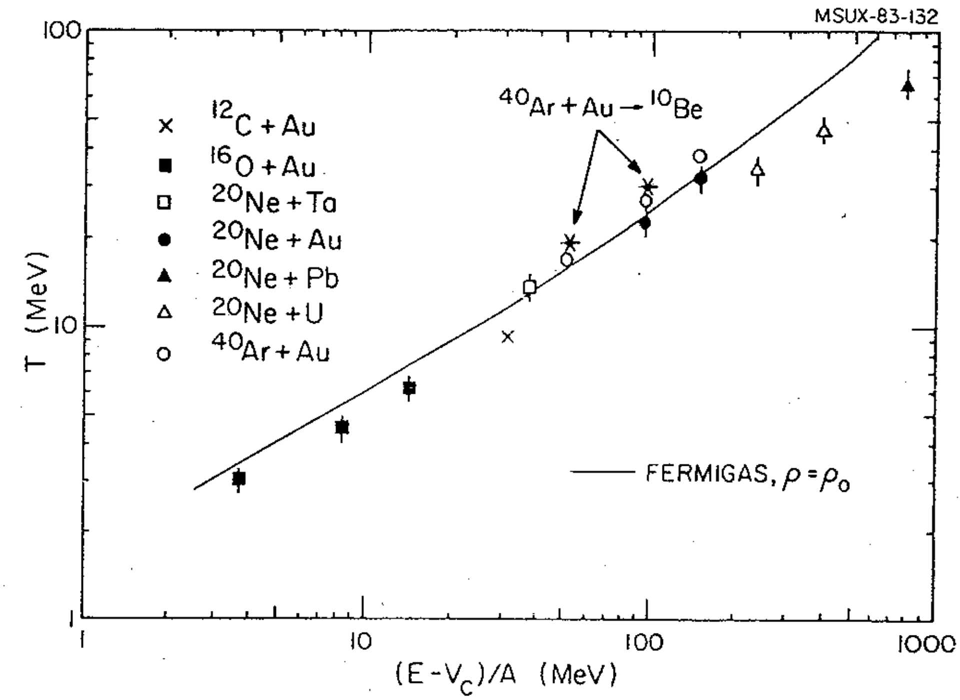

Fig. 3. Variation of the temperatures extracted from the energy spectra of protons believed to be emitted from sources moving with velocity between those of projectile and target (intermediate rapidity source). Most of the data are from systems of ^{16}O and ^{20}Ne on heavy targets of Au and U. Results for heavier emitted fragments of Be emitted in Argon induced reactions at approximately 50 and 100 MeV/nucleon also appear to follow these systematics.

energy spectra and angular distributions are analyzed as in Ref. 8 and production cross sections, temperatures and composite/proton ratios are extracted. Sample energy spectra for Be fragments are shown in Fig. 5, for incident energies of 50 and 100 MeV/nucleon, together with theoretical curves derived with a moving source model. The corresponding temperatures are also shown in Fig. 3, where it is seen that they follow the trends of the lighter fragments. These results indicate that the heavy fragments are also created in a thermal process, which is a topic of great current theoretical interest[9].

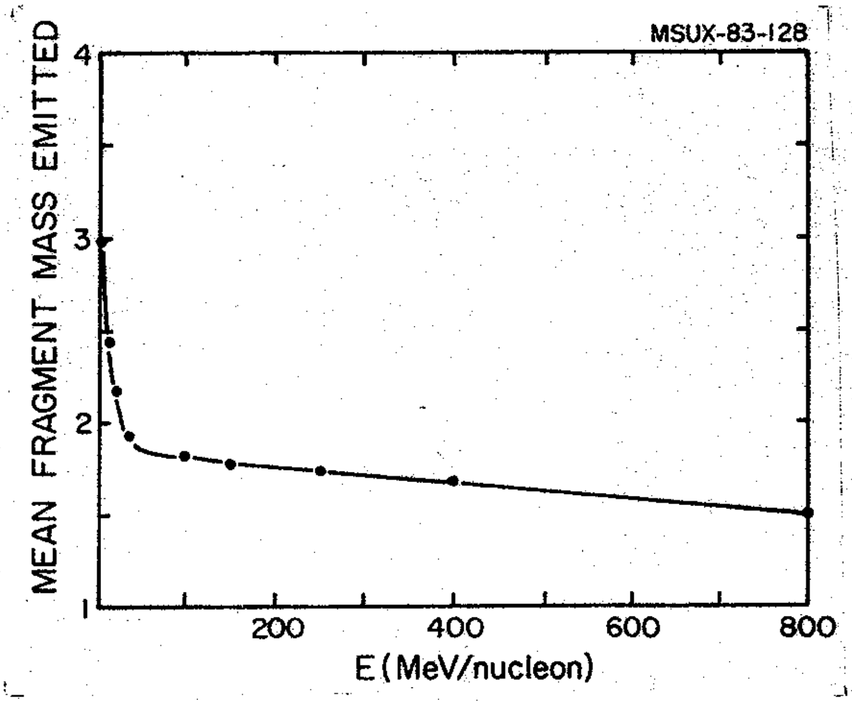

Fig. 4. Variation of the mean fragment mass (protons -> alphas) emitted by intermediate energy sources as a function of incident energy.

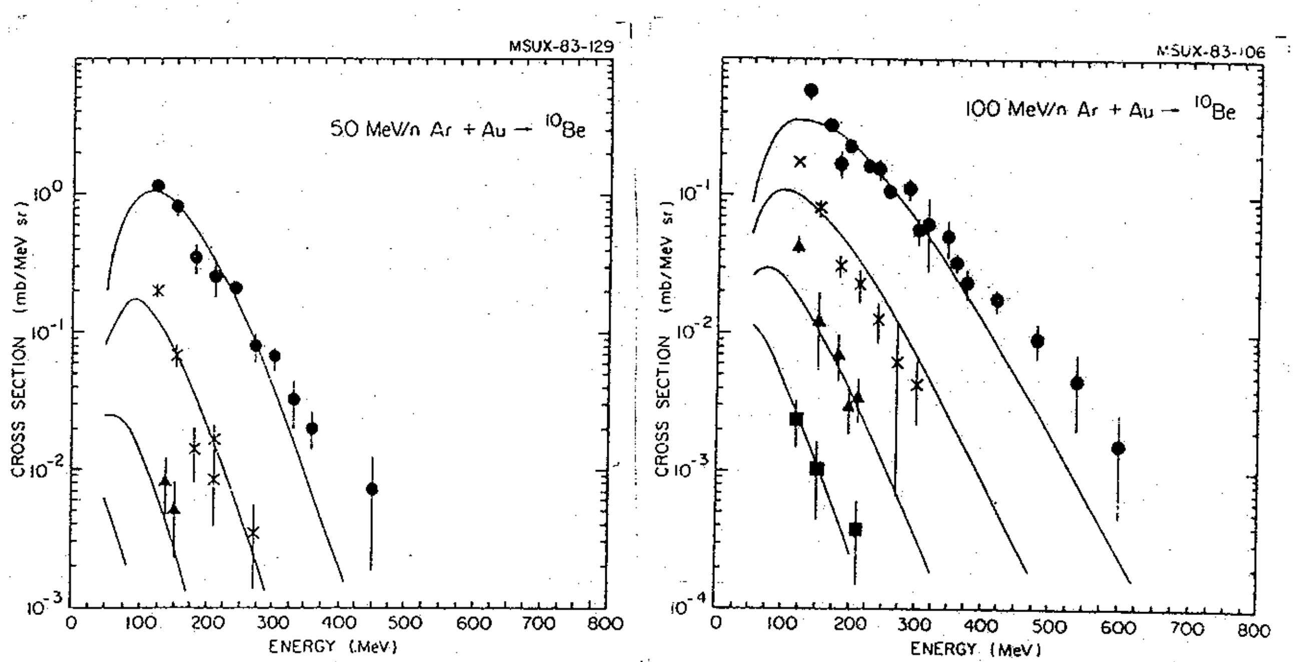

Fig. 5. Energy spectra for ^{10}Be fragments emitted in collisions of ^{40}Ar on Au at 50 (left) and 100 MeV/nucleon. The spectra are fitted with a moving source model, the extracted temperatures of which are plotted in Fig. 3.

Our preliminary results indicate that at E/A = 100 and 150 MeV/nucleon, the cross sections decrease monotonically as a function of the fragment mass number, but at 50 MeV/nucleon the cross section decreases up to mass 6, and then increases for heavier masses. A similar effect has been observed in emulsion experiments[10] with ^{12}C at E/A = 85 MeV. These observations could be indicative of a condensation phenomenon. Calculations using hydrodynamical and cascade models are in progress, as well as approaches based on a thermodynamic model incorporating quantum statistics.

(iii) Future Experiments

To establish convincingly the existence or nonexistence of critical phenomena, one must measure a global set of data over a wide range of projectile and target nuclei, and beam energies. Combinations of light, medium, and heavy mass symmetric systems as well as asymmetric light-heavy mass systems will be studied. The energies and particles available from the Phase I facility at NSCL supplemented by measurements at the low energy beamline of the Lawrence Berkeley Laboratory Bevalac, are ideal for these studies since existing data[8] indicate that the critical temperature of 20 MeV is reached in reactions near 100 MeV/nucleon. Beams up to 60 MeV/nucleon will be available at NSCL, and we have already undertaken experiments at the Bevalac with beams of 50 MeV/nucleon. In future experiments, a better selection for central collisions will be imposed through an array of scintillator telescopes which will be used to signal an absence of beam projectile fragments in the forward direction.

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(b) Streamer Chamber Experiments

N. Anantaraman, A. Galonsky, D.K. Scott
H. Stöcker and G.D. Westfall

Central nuclear collisions at intermediate energies offer the possibility of studying a wealth of new phenomena related to the bulk properties of nuclei and of nuclear matter (see, for example, the recent review by Stöcker et al.[1]) The identification of many of these phenomena will require the observation of emission patterns, multiplicities and correlations of the reaction products. For this purpose, single-particle inclusive measurements, although very productive in the previous generation of experiments, are clearly insufficient. Instead, exclusive detectors are needed with nearly 4π solid angle, high multitrack efficiency, good angular and momentum resolution, and a capability of detecting a wide variety of emitted fragments. The streamer chamber operated in the avalanche mode[2] meets these requirements, and we propose to undertake a program of streamer chamber experiments at the Bevalac using intermediate-energy heavy ion beams. We plan to continue this program at the NSCL when the Phase II beams become available, by undertaking the construction of a streamer chamber as recommended at the Phase II Workshop of December, 1982.

High-multiplicity ^{12}C-induced reactions on Ag(Br) at energies as low as 60 MeV/A are found to be dominated by complete disintegration of the projectile and target nuclei into light and medium mass fragments.[3] Fig. 1 shows an emulsion picture of a typical event. A ^{12}C nucleus enters from the left with an energy of 70 MeV/A. It undergoes a reaction with an Ag or Br nucleus, which

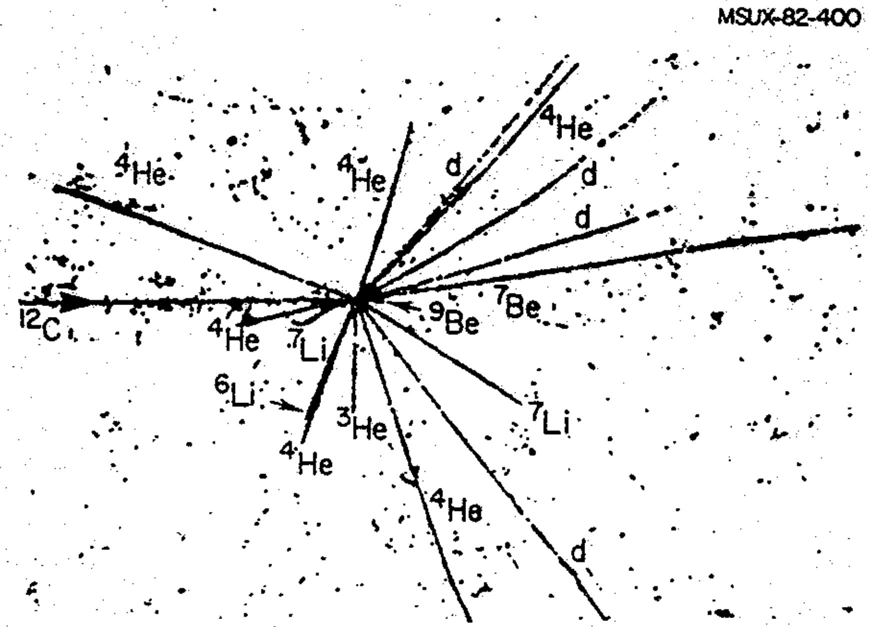

Fig. 1. A collision of ^{12}C on nuclear emulsion at incident energy of 70 MeV/nucleon. If the target nucleus is Bromine, this event corresponds to complete disintigration of the system in fragments with A$\leq$11.

results in the emission of 16 visible charged particle tracks (4 deuterons, 7 alpha particles, 3 lithium and 2 beryllium fragments) containing a total of approximately 71 nucleons. In the case of a C + Br event this corresponds to a complete breakup of the system into fragments with A $\leq$ 11. If the target is Ag, a fragment with Z = 18 should be added. It is noteworthy that this is not a rare type of event; in a sample of 73 events with multiplicities exceeding 11 (corresponding to 20% of the total reaction cross section), several events with even higher charged particle multiplicity and/or number of emitted charges have been observed. These findings yield direct evidence for the transition from fusion to "multifragmentation" in the intermediate energy regime. In these events, "leading particles" (fragments in the forward direction with a speed close to the beam velocity) are not observed.

The data described above were obtained with emulsions. The use of a streamer chamber brings the added capability of triggerability, so that the data selected for recording can be enriched in the multifragmentation events. All but one of the fragments visible in Fig. 1 have energies below 15 MeV/A. These particles could be detected in the streamer chamber, which has a minimum energy cut-off well below 5 MeV/A and is limited (for sufficiently small target thickness) only by the requirement that the fragments must have several (>8) cms of track length in the chamber gas. With thin targets, however, one must be prepared to reject a large fraction of recorded events as corresponding to interactions in the gas rather than in the target. For particles that stop in the gas, we get information on both the momentum (from the curvature of the tracks) and the energy (from the range).

The study of medium-mass fragments (A = 6 to 60) produced in the central collisions appears to be essential[1)] to clarify the reaction mechanism and to yield information about condensation effects and a possible liquid-vapor phase transition,[4)] or a fast mechanical instability leading to break up of overstressed nuclear matter[5)]. The charge identification capability of the streamer chamber, via the computer digitization of photographic information on ionization density, has recently been demonstrated for both light and moderately heavy collision products.[6)] The integrated intensity per unit length is capable of separating fragments of charge 17 from those of charge 18 when they have a restricted range of rigidities. It is expected that the technique can be extended and improved by operating the chamber in the avalanche mode (so that there is a better proportionality of the track brightness to the ionization) and by using a charge-coupled device instead of film as the recording device (so that there is a linear response to the brightness and a large dynamic range).

One of our objectives will be to develop these techniques, particularly the use of the charge-coupled device (CCD). The CCD is a solid-state image sensor with a two-dimensional array of electron-collecting zones. CCD's of adequate resolution (e.g. 390 x 584) and large dynamic range (e.g. 925) are commercially available. With film a higher resolution can be achieved, but the dynamic range is much more limited (typically 20). The large dynamic range of the CCD is important because in intermediate-energy collisions one expects appreciable production of fragments with a wide range of charges and velocities and therefore a wide range of primary ionization. Other advantages of the CCD over film are its linear response and greater (perhaps by an order of magnitude) sensitivity to light. Furthermore, use of the CCD eliminates the slow, expensive processing of photographic information by manual scanning.

One prediction of the fluid dynamical model is that, for central collisions, the projectile is essentially stopped in the target and the subsequent explosion of the combined system results in a predominant sidewards emission of the fragments due to collective flow effects. Even for intermediate impact parameter collisions, a substantial transverse momentum transfer to the remnants of the projectile is predicted--the bounce-off effect. This means that particles with large velocities should be observable at rather large angles. The emission patterns predicted for these collisions are obviously well suited to observation in a streamer chamber.

Our first measurements will be directed towards a search for condensation phenomena by studying the charge distribution Y(Z) of fragments emitted in high multiplicity events in the collision of a heavy projectile on a heavy target. The limited data available on lighter systems[3] (where the phenomena are expected to be less well developed) indicate a nearly exponential falloff in Y(Z) up to Z=10, followed by a rise at larger Z's (see Fig. 2). A possible explanation of this rise as being due to fission is ruled out by missing mass considerations--the data indicate that no residual nucleus is left to fission once the light and medium mass fragments are subtracted from the sum of projectile and target masses. Quantum statistical calculations reproduce the observed trend: the slope of the exponential falloff is directly related to the entropy and the rise at Z=10 is explained as a condensation phenomenon.[1] (The massive fragments are taken to be related to the liquid phase.)

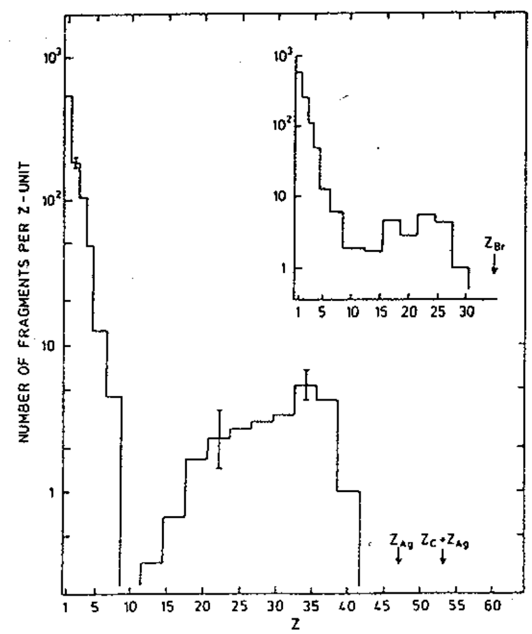

Fig. 2. The charge distribution of all emitted particles, from the emulsion experiment of ref. 3. The heavy fragment group is indirectly determined, under the assumption that all targets are Ag (large figure), as well as under Br target assumption (small figure).

Possible projectile-target systems for the measurements are Kr + Au and Au + Au. (The heavier the system, the better, since critical phenomena are based on nuclear matter calculations which neglect effects of the nuclear surface; hence it is desirable to deal with as large a participant zone as possible. However, the heaviest beam used up to now in the Bevalac streamer chamber is Kr, and we want to gain experience with this beam before turning to heavier, and more highly ionising, projectiles.) Beams of about 10^3 particles/sec of U have recently been accelerated at the Bevalac, and the intensity of the Au beam is expected to be about 10^6 pps. These intensities are adequate for streamer chamber measurements. Since the condensation phenomenon is predicted to occur only at low temperatures ($T \leq 20$ MeV),[4)] we shall study the bombarding energy dependence of the Y(Z) distribution by measurements at energies of 50, 100, 150 and 200 MeV/A. Possible fission contributions to the rise at $Z>10$ can be monitored not only by missing-mass considerations but also by the distinct signature of two fission fragments moving in opposite directions. Target fragmentation contribution will be excluded by means of rapidity plots; only intermediate rapidity particles will be considered in the search for the condensation bump.

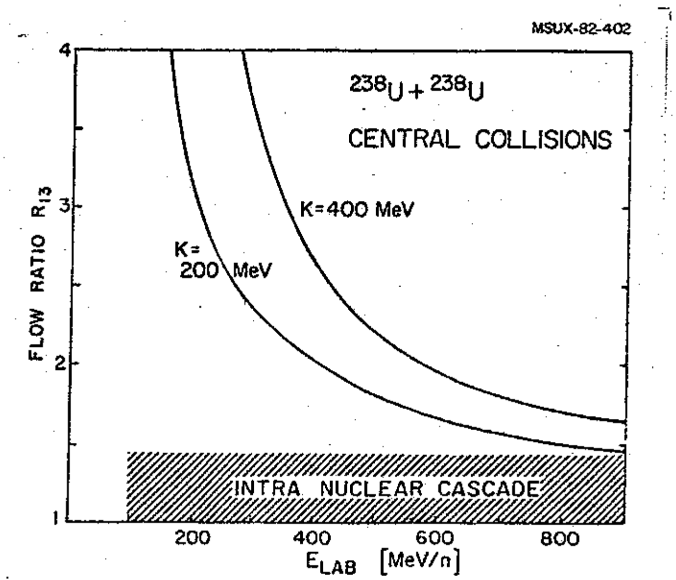

Fig. 3. Plot of the aspect ratio as a function of incident energy for a collision of U+U, where the predictions of a cascade model are compared with a hydrodynamical model for two different equations of state.

These measurements will also be analyzed in terms of global variables such as thrust, kinetic flow and sphericity. This will require event-by-event analysis of <u>all</u> emitted particles. A comparison of the results with cascade and hydrodynamic model calculations can establish the relative merits of the two models,[1] and the sensitivity of the global variables to the collision dynamics. Much larger transverse momenta are generated in the hydrodynamical calculations. In Fig. 3 the aspect ratio, representing the ratio of the maximum and minimum axes of the kinetic energy flow tensor, is shown as a function of incident energy for central collisions of U+U. We see that in the region from 50-200 MeV/nucleon there is great sensitivity to the model prediction, and also to the values of compressibility used in the equation of state.

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(c) Experiments with Charged Particle Multiplicity Array

G.M. Crawley, C.K. Gelbke, H. Stöcker and G.D. Westfall

(i) Scientific Motivation

One of the goals of high energy nucleus-nucleus reaction studies is the investigation of collective effects. In these reactions it may be possible to create and study nuclear conditions that cannot be observed in ground state nuclei and that may have relevance to the understanding of such topics as the big bang and neutron stars. The aim of these experiments is to study collective, dynamic effects in nucleus-nucleus collisions at intermediate energies (from 20 to 200 MeV/nucleon). At these incident energies, one expects nuclear densities of 2 to 3 times normal and excitations of up to 50 MeV/nucleon to occur. It is expected that this energy regime will be appropriate to observe compression effects at moderate entropy since the large backgrounds arising from particle production in reactions at relativistic energies will be much smaller. In recent years experiments have established the importance of measuring γ-rays, π's, neutrons, protons, light nuclear fragments (A<5), medium mass nuclear fragments (A<50), fission fragments, and projectile-like fragments resulting from the collisions of high energy nuclei. A great deal of information concerning high energy nucleus-nucleus collisions has been obtained using single particle inclusive measurements.[1,2,3] A difficulty arises when these data are compared with theoretical predictions and it is found that disparate models produce similar results. Thus experimenters are turning to devices that can simultaneously detect many particles from each reaction. Examples of such devices are the Plastic Ball/Plastic Wall at LBL, the HISS facility at LBL, and the charged particle array at GANIL.

An example[4] of a multi-particle measurement that is able to discriminate between various models is that of protons, observed at angles from 20 to 130 degrees and tagged with the multiplicity of charged particles emerging from the reaction of 393 MeV/nucleon ^{20}Ne+U. In Fig. 1 double differential cross sections are shown for protons associated with high and with low multiplicity. For high multiplicity the forward

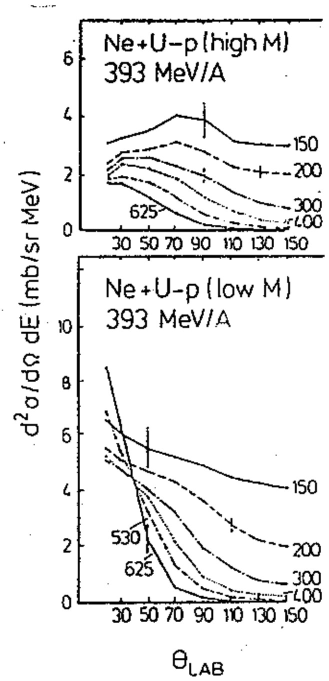

Fig. 1. Differential cross sections for proton emission in Ne+U at 393 MeV/nucleon with high multiplicity selection (top) and low multiplicity selection (bottom).

emission of low energy protons is suppressed. Calculations such as firestreak, nuclear cascade, and rows-on-rows fail to reproduce this suppression while a hydrodynamical calculation[5] successfully predicts the sidewards peaking as shown in Fig. 2. There remains a question of whether this effect originates in Coulomb interactions of the emitted protons with the residual target nucleus. Neutron measurements are in progress to settle this point.

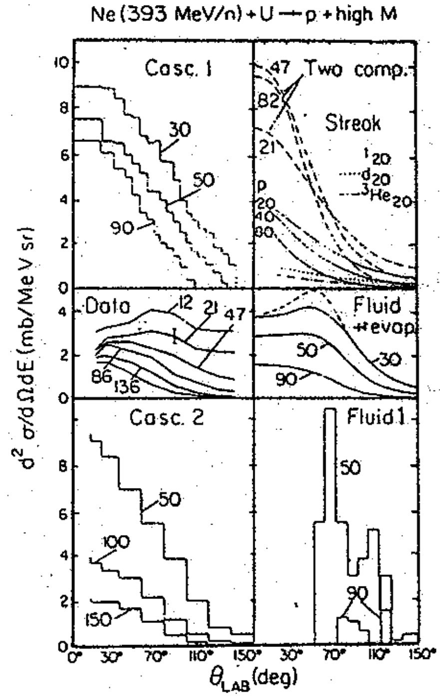

Fig. 2. Comparison of different model predictions for proton emission in Ne+U collisions at 393 MeV/nucleon. The forward suppression of the data (middle left section) is best reproduced with the fluid dynamical model including evaporation.

(ii) Multi-Particle Detector

At NSCL energies it is important to study not only light particles and projectile-like fragments, but intermediate rapidity medium mass fragments, fission fragments, and neutrons. Therefore we have proposed a device that is capable of simultaneously detecting most of the particles emerging from nuclear collisions occurring at the intermediate energies of the NSCL facility. The basic component of this device is the "logarithmic" detector. Its response is designed to increase logarithmically in stopping power with the range of penetration of the observed fragment. Thus fission fragments would be detected in thin front elements and highly energetic light particles would be observed using thick range-energy telescopes. This array of counters will have sufficient granularity to handle light particle multiplicities up to 100 with reasonable efficiency and slow, highly ionizing particles with somewhat lower multiplicities of approximately 15.

We propose that this device be composed of 32 heavy fragment detectors each comprised of a Parallel Plate Avalanche Counter (PPAC), a Bragg Curve Counter (BCC) and 180 CaF_2-plastic scintillator telescopes covering 92% of the total solid angle. The heavy fragment detectors would be shaped as two concentric truncated icosahedrons having 20 regular hexagons and 12 regular pentagons as faces. The light particle telescopes would consist of triangular sections with six telescopes behind the hexagonal faces and five detectors backing the pentagonal faces. Each light particle telescope would contain a 2 mm thick CaF_2 ΔE detector backed by a 30 cm plastic scintillator E detector. The preliminary design discussed at the Phase II Workshop in December, 1982 is shown in Fig. 3.

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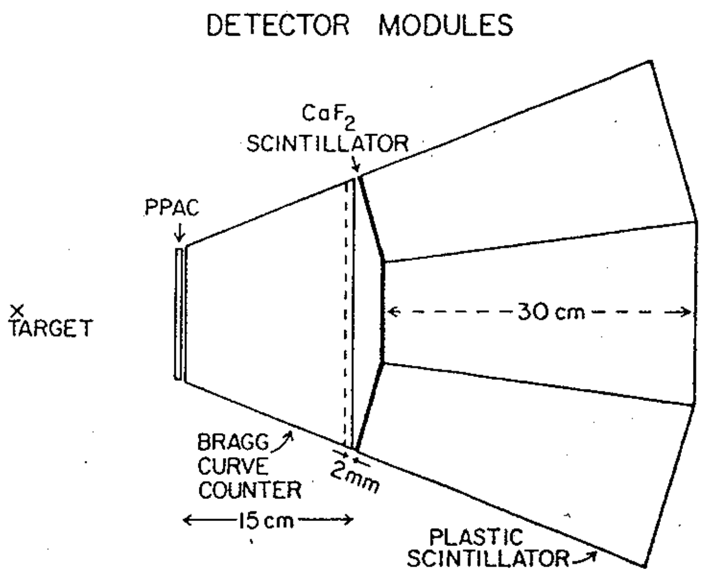

Fig. 3. Schematic layout of multidetector array module.

(iii) Planned Experiments

To gain operational experience with multi-particle experiments we have, in collaboration with Professor Robert Tickle from the University of Michigan, constructed a hit detector array consisting of a three plane multi-wire proportional chamber backed by seven CaF_2-plastic scintillator telescopes. This array will be used to detect jets of particles in conjunction with trigger particles such as projectile-like fragments, light and medium mass fragments at intermediate rapidities, and target-like fragments. At present we have two approved experiments with this device, one at Lawrence Berkeley Laboratory and one at NSCL. Some of the scientific goals of these future experiments are described below.

Nuclear collisions at intermediate energies are predicted to exhibit a large momentum transfer at certain impact parameters[6)] - the bounce-off effect. A jet of light particles should occur in the forward direction, accompanied by recoiling target fragments in the opposite azimuthal direction. In our set-up we can look for this effect by placing a heavy ion trigger detector at 90 degrees azimuthally anticorrelated to the hit detector placed at a forward angle. An analogous case can be studied by placing a projectile fragment telescope at forward angles and measuring multiparticle jets at 90 degrees on the opposite side of the beam with the hit detector. The hydrodynamical description[5,6)] also predicts a preferential sidewards emission of medium mass particles to large angles for small impact parameters. Hence we must impose additional trigger conditions to select events with more than one particle entering the hit detector. By varying the angle of the hit detector and by selecting the type and energy of particles in the jets, it will be possible to detect any preferential angle of emission for multiparticle jets.

High energy nucleus-nucleus reactions are also often described in the nuclear cascade model, which assumes that nuclear collisions proceed as a sequence of independent, free nucleon-nucleon collisions. The simplest approximation is to assume that the major contribution to the light particle spectra is due to first generation nucleon-nucleon scattering.[7,8)] To test the direct single scattering contribution to light particle production, a light particle telescope will be used as a trigger. The hit detector will be placed such that it encompasses the angles to which a free nucleon would be scattered. The large angular acceptance of the hit detector allows the measurement of the coincident particle even though the kinematical region where it should be observed is large because of the Fermi momenta of the two nuclei.

We are constructing a section of the multi-particle detector described earlier consisting of a PPAC, a BCC, and six CaF_2-plastic scintillator telescopes. This module will be used to test techniques for constructing the full 4π array as well as being used in coincidence with the MWPC-telescope array and various trigger detectors. The results of these measurements will be of interest in their own right and will enable us to prepare for experiments using the full Phase II beam capabilities.

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A 4. EXPERIMENTS INVOLVING PIONS

(a) Sub-Threshold Pion Production

(b) Anomalons as Pineuts; Pion Binding in Nuclei

(a) Subthreshold Pion Production

W. Benenson, G.M. Crawley and E. Kashy

The production of pions at beam energies per nucleon below 290 MeV, the free nucleon-nucleon threshold, is called subthreshold pion production, and in recent years has received quite a bit of study at the four or five laboratories in the world capable of producing the required beam energies. In this section of the proposal we outline our plans to extend our measurements with composite particle beams to higher masses and lower energies and also into the exclusive region.

(i) Inclusive Measurements:

The MSU-LBL project to study heavy ion pion production began about six years ago when virtually the only existing data were the 1948- 1950 alpha beam experiments performed at the Berkeley 184" cyclotron.[1)] The goal of our project was to try to understand the reaction mechanism and via this knowledge to search for exotic effects such as pion condensation. These effects were expected to show up as deviations from the predictions of the basic models for the process. Several significant deviations were found, but these were finally attributed to inadequacies in the model and represented important contributions to the understanding of the collision process. For example, the Coulomb effect of the charged remnants was found to be very large[2)] and to require a cold object moving at beam velocity after the collision.An example of these data is shown in Fig 1. Theories[3)] for the π^-/π^+ ratios at 0^o can now be used to determine the average Z of the projectile fragment.[4)] Likewise, it seems that the data require a hot equilibrated object moving at the center-of-mass velocity even at

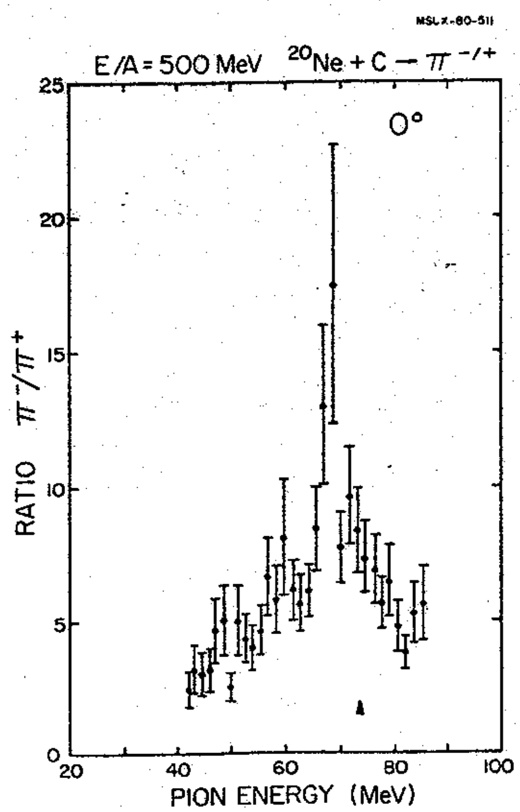

Fig. 1. Ratio of the $\pi^{\pm}_{o}$ spectra from $^{2\emptyset}$Ne on C at E/A=5ØØ MeV and 0^{o}.

the lowest beam energies. The failure to observe exotic effects thus far is neither discouraging nor unexpected since the beams typically are A=2Ø, nuclei that are mainly surface and not at all like the chunks or infinite slabs of nuclear matter which were used in the original calculations. This year we are going to perform experiments with beams of A=139, which is as high in mass as is practical for sub-threshold production at the Bevalac, and when MSU Phase II comes into operation, we will go to higher masses and lower energies.

The state of the data for subthreshold production with heavy ions is summarised in Fig. 2. In this graph our A=2Ø data have been scaled down to match up with the CERN A=12 data at lower energies.[5] Although falling rapidly with decreasing beam energy, these data show that experiments with the K500 cyclotron, although challenging, are definitely feasible. The first series of experiments will consist of a comparison between beams

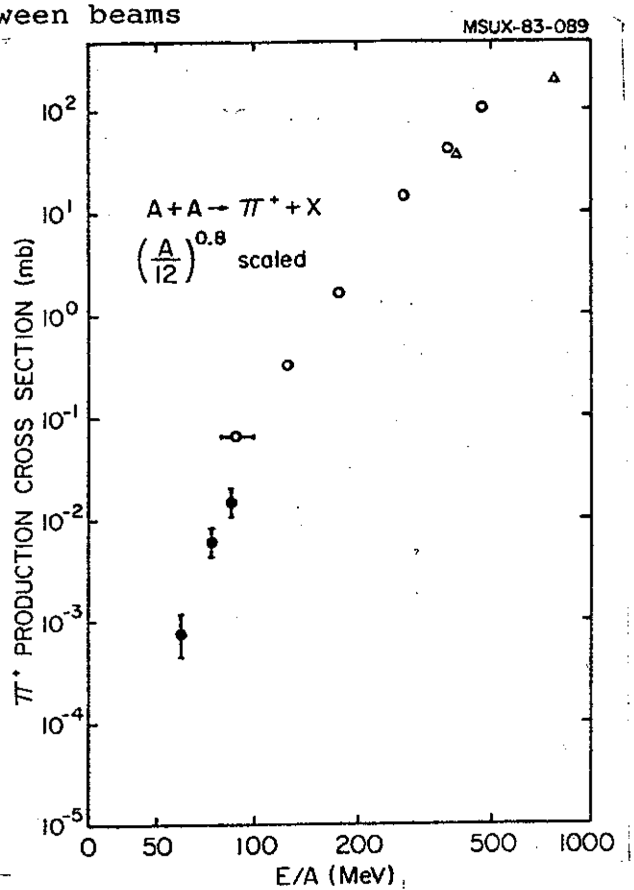

Fig. 2. Total cross section for pion production versus beam energy. Data are from CERN (dark circles) and LBL (open circles and triangles).

of the same E/A but with as wide a range of A as possible, for example ^{4}He, ^{6}Li, ^{7}Li and ^{12}C at E/A= 50 MeV. These cross sections and momentum distributions should be very sensitive to the Fermi motion of the nucleons in the projectile.

The inclusive pion experiments at NSCL will utilize the Enge Split-Pole spectrograph. This device is an acceptable spectrograph for inclusive experiments, making up for its moderate solid angle by the large momentum acceptance. The focal plane detector will be a special multiwire proportional counter specially developed to solve the problems of this experiment, namely, low count rate and high room background. The geometry of this detector, called the Multi-Inclined-Wire (MIW) detector, is shown in Fig. 3. The pions are constrained as far as possible to travel along the length of the wires, which lie at an angle of 45° with respect to the focal plane. Only a few wires will

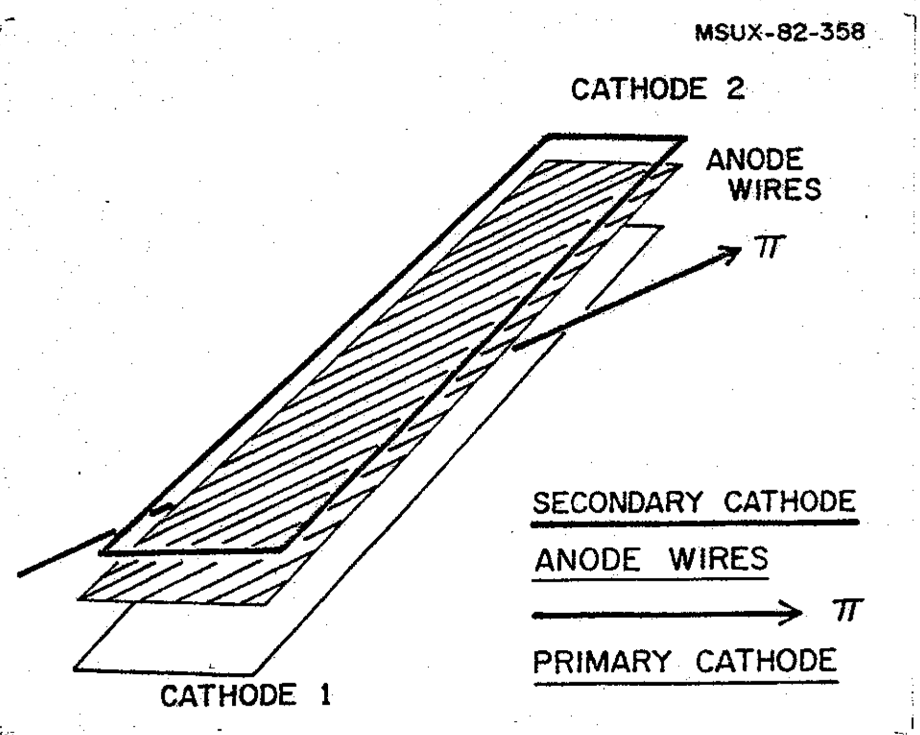

Fig. 3. The geometry of the MIW detector.

fire for a real event, and the pulse height will be maximised. Studies have shown that a conventional configuration would give an order of magnitude smaller signal spread over as many as nine wires. The final configuration is in the construction stage and consists of a pair of MIW planes separated by a few mm to provide angle information. Between the MIW and a plastic scintillator a wedge will be used to insure that all the pions stop in the scintillator. Our introduction of a wedge in exactly such a manner into the Indiana QQSP pion spectrograph[6] had a dramatic effect on the room background and made a very low cross section (p,π^-) experiment feasible. For a given scintillator thickness (which should be kept to a minimum) stopping pions give more light than any pions being transmitted through the scintillator. In addition the π^- star can enhance the light, and in the case of $\pi^+, \pi^+ \to \mu \to e$ decay can be observed for background suppression. The introduction of a wedge at IUCF reduced background to the point that a (p,π^-) cross section of 0.080 nb/sr was observed as a peak well above background as can be seen in Fig. 4.

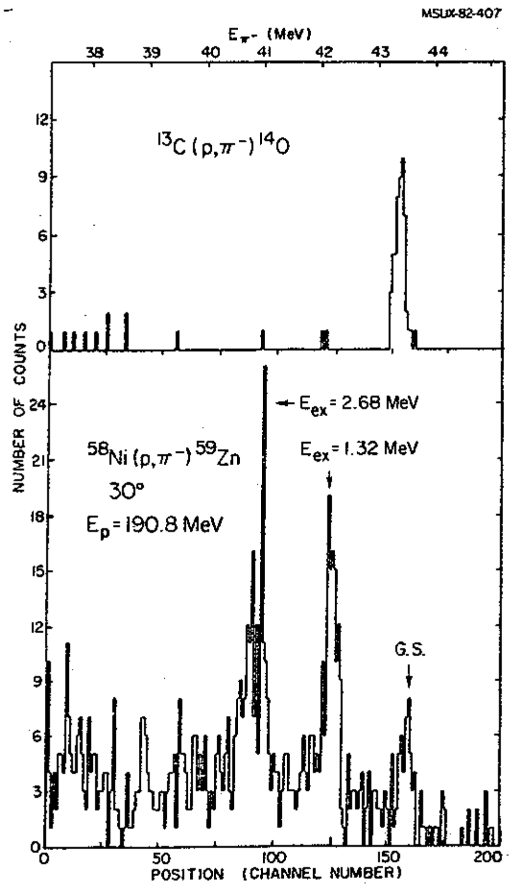

Fig. 4. Spectrum from a recent (p,π^-) mass measurement.

The A=139 experiments will be carried out at the Bevalac on the TASS spectrograph in collaboration with L. Schroeder, H.

Pugh, P. Kirk and others. The object of the experiment is to observe the onset of pionic instability predicted by Gyulassy[7] to be measurable near $P_\pi=2m_\pi$ and 90°. Even if this peak is not observed, as was the case for A=20 collisions,[8] the experiment will extend the data on subthreshold pion production to much higher mass beams than ever used before. Of interest will be the scaling laws obeyed by the cross section and the effect of the high A on the temperature. In addition we expect a very large Coulomb effect which can be used to determine the average Z of the projectile fragment.

(ii) Exclusive Measurements:

During the past few years light ion induced exclusive pion production data have begun to be measured at European laboratories, stimulated by the theoretical work of Huber and colleagues.[9] For the few measured cases, which involve H and He beams only, the agreement between theory and experiment is encouraging. A recent summary[10] of the present experimental situation points out how difficult it will be to expand the data into the region of heavier projectiles and targets. For the same target and beam energy per nucleon, the cross section drops almost four orders of magnitude in going from protons to ^{3}He. Likewise the target dependence of (^{3}He,π) reactions is three orders of magnitude in going from A=4 to 12. These facts point to the extreme difficulty of $^{12}C + ^{12}C \rightarrow \pi$ exclusive experiments, but we will try to approach exclusivity by looking at as high a pion momentum as feasible under the actual experimental conditions. The physics of the reaction does not require the resolution of the ground state but rather of a multiplet of states with a similar configuration. We are considering upgrading the solid angle of the Enge Spectrograph for these experiments since its wide momentum acceptance is not helpful in overcoming low count rate problems in this case. One method to accomplish this would be to introduce a quadrupole between the target and aperture and to change the curvature of the entrance pole piece.

Another approach to exclusive experiments is recoil detection. If the projectile is of a mass comparable to or greater than the target, then the recoils form a peak several MeV wide on the focal plane of the spectrograph at 0^{o}. If a π^{-} is produced in a two body final state reaction, then a unique product will be made. The Enge will be virtually 100 percent efficient for the total cross section of this reaction. The main problem with this idea is that light contaminants in the target could easily produce a yield of the species of interest so big as to mask the peak. This leads to the conclusion that recoil experiments are very well suited to Phase II operation with projectiles which are substantially heavier than the target. In this case the peak becomes narrower in energy and even more focussed at 0^{o}. We can test this idea with the K500 cyclotron by looking for ^{13}N's from 300 MeV ^{7}Li on ^{6}Li. This experiment will be proposed as soon as Li beams become available.

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(b) Anomalons as Pineuts; Pion Binding in Nuclei

Wm.C. McHarris

The most recent explanation for anomalons is the model that I formulated last year with John Rasmussen at Lawrence Berkeley Laboratory. This model considers them to be "pineuts", i.e., one or more negative pions bound hadronically to the neutron excess or cloud that extends out from a fragment formed in a high-energy nucleus-nucleus collision. The paper describing our model has just been published,[1] but already it has attracted considerable attention, extending even to the popular press.[2,3] Although our model necessarily is very qualitative at the present time, we think it is one of the more viable explanations for anomalons. In addition, it raises the question as to whether negative pions can account for other phenomena and whether, in fact, this sort of hadronic binding of mesons might be a rather general occurrence. We propose to refine our model and make it as quantitative as possible considering the general qualitative state of data concerning anomalons and higher-energy pion potentials. And, although we do not propose to become involved with the (very elaborate) emulsion and/or counter experiments now being performed to characterize anomalons, we do propose a fairly modest radiochemical experiment. Here we summarize our basic "anomalons as pineuts" model, then outline some of our proposed refinements.

"Anomalons" is the name given to those projectile fragments that have anomalously short mean free paths immediately following their formation in relativistic nucleus-nucleus collisions. First seen in cosmic-ray experiments, they have recently been observed by groups working with emulsions exposed to beams from the LBL Bevalac[4,5] and by a group reexamining cosmic-ray emulsion data.[6] This past fall an independent confirmation was reported by a German group working with plastic track detectors.[7] Anomalons have attracted considerable interest, for they are very difficult to explain in any sort of straightforward terms. Indeed, the LBL group[4] concludes: "We are thus left in a predicament. Conventional nuclear physics as well as systematics fail to explain the observations..." Actually, there have been quite a number of explanations.[1] Most of these have focused on quark rearrangements and the possible existence of color non-singlet states, although others range from postulating quasi-molecular nuclei and "bubble" nuclei to postulating solitons and a new topological quantum number. The difficulty is that none of these can adequately explain even the current qualitative experimental observations.

Any adequate explanation must be able to account for essentially six experimental points:

1) The energy range of production, $E \approx 1\text{-}2$ AGeV.

2) The anomalously short mean free paths.

3) A time of existence $> 10^{-10}$ sec.

4) No charged particles seen from the "decay" of anomalons.

5) Enhancement of the anomalon effect at low Z values, but with a drop-off at or exclusion of $Z = 2$ and 1.

6) The anomalon memory effect, i.e., the enhanced tendency for anomalons to produce anomalons in subsequent generations.

Our model proposes that anomalons could result from a nuclear halo of "pineuts", hadronically bound states of a π^- plus a few neutrons surrounding a nucleus. Although the s-wave π^--n interaction is repulsive, the p-wave (and higher) is attractive. Thus, the possibility exists that neutron-rich nuclei (or nuclei having locally neutron-rich domains, such as the neck in a fissioning system) might have a sufficiently attractive velocity-dependent potential to allow π^--xn "polyneutron" systems. Relativistic nucleus-nucleus collisions provide the best opportunity for forming such states, for it has been found that not only are negative pions produced in copious quantities in such collisions, but also they are Coulomb-focused forward, bathing the target nuclei in a localized, intense π^- flux. Also, the excited nuclear fragments may have neutrons in barely-bound orbitals tailing out well beyond the normal nuclear radius--a neutron "splash" extending out beyond the protons, which are prevented by the Coulomb force from forming an analogous "splash". Thus, conditions are optimal for forming a nuclear stratospheric halo enriched in pineut clusters.

This explanation of anamalons meets the six requisite points as follows:

1) The production energy range is satisfied. The π^-s are produced abundantly above the $\Delta(1232)$ threshold. Note that this is below the region of abundant associated production of kaons and lambdas and below the threshold for producing anti-protons, leading to rather serious difficulties in those explanations involving quark rearrangements. (Also, some of the color non-singlet explanations have been shown to be non-physical.[8])

2) Our model invokes a π^--dineutron (or possibly a π^--polyneutron) cluster orbiting the nucleus at a distance such that the overlap with any proton wave-function is small. This larger object, in which the pions effectively stabilize the neutron halo, would clearly exhibit an enlarged cross-section, but it would cause reactions of the ordinary sort, consistent with anomalon observations.

3) The mean life of a free π^- is 26 nsec, and in a non-absorptive free pineut system, this would increase as the binding energy increased. (The phase space for weak decay would decrease until the binding energy reached the π-μ mass difference of 33.9 MeV, at which point the weak decay channel would close altogether.) In the proposed pineut/anomalon systems, however, there are protons, and the limiting factor becomes keeping the π^--p overlap as small as possible. In fact, as is discussed below, for

reasonable velocity-dependent potentials, one obtains a singularity in the effective mass, which serves to separate the class of inner solutions from the class of outer solutions, thus shielding the pions from most of the proton density. Thus, it becomes reasonable to expect lifetimes of $>10^{-10}$ sec for non-s-wave pineut orbitals outside the parent nucleus.

4) The predominant mode of decay of the orbiting pineut would be neutral, with the π^- mass given to a pair of neutrons (as occurs with pionic ^2H) or a pair of protons (as occurs with charge exchange, producing a π^o, seen with pionic ^1H and ^3He). (Annihilation with a correlated p-n pair usually is accompanied by some photon emission, as well.) Again, this is consistent with experimental observation thus far, including an experiment at the LBL Bevalac to look for photon emission downstream from the site of anomalon formation.[9]

5) A fairly constant anomalon interaction cross-section as a function of the charge on the fragment also follows, for the pineut halo would have the greatest effect as part of a small fragment. On the other hand, we predicted a diminution, perhaps an absence, of the effect for charges smaller than 3, because of the lack of the requisite neutron excess or tailing. (The cross-sections for producing fragments with appreciable neutron excess, such as ^6He or ^8He, in this region fall precipitously.) It is interesting that a study initiated after our model was introduced seems to confirm the lack of an anomalon effect at Z=2.[10]

6) The existence of a memory effect also follows straightforwardly from our model (and it is perhaps the most difficult phenomenon for any of the other explanations to account for), for the prime requisite of neutron excess in a fragment would be expected to persist more or less from generation to generation.

Follwing the prescriptions of Ericson and Myhrer[11] and Mandelzweig, Gal, and Friedman,[12] we have calculated π^-

binding, using the improved optical potentials of Carr, McManus, and Stricker-Bauer.[13] Using the same test nucleus ^{34}Na, we show some of our preliminary results in Fig. 1.

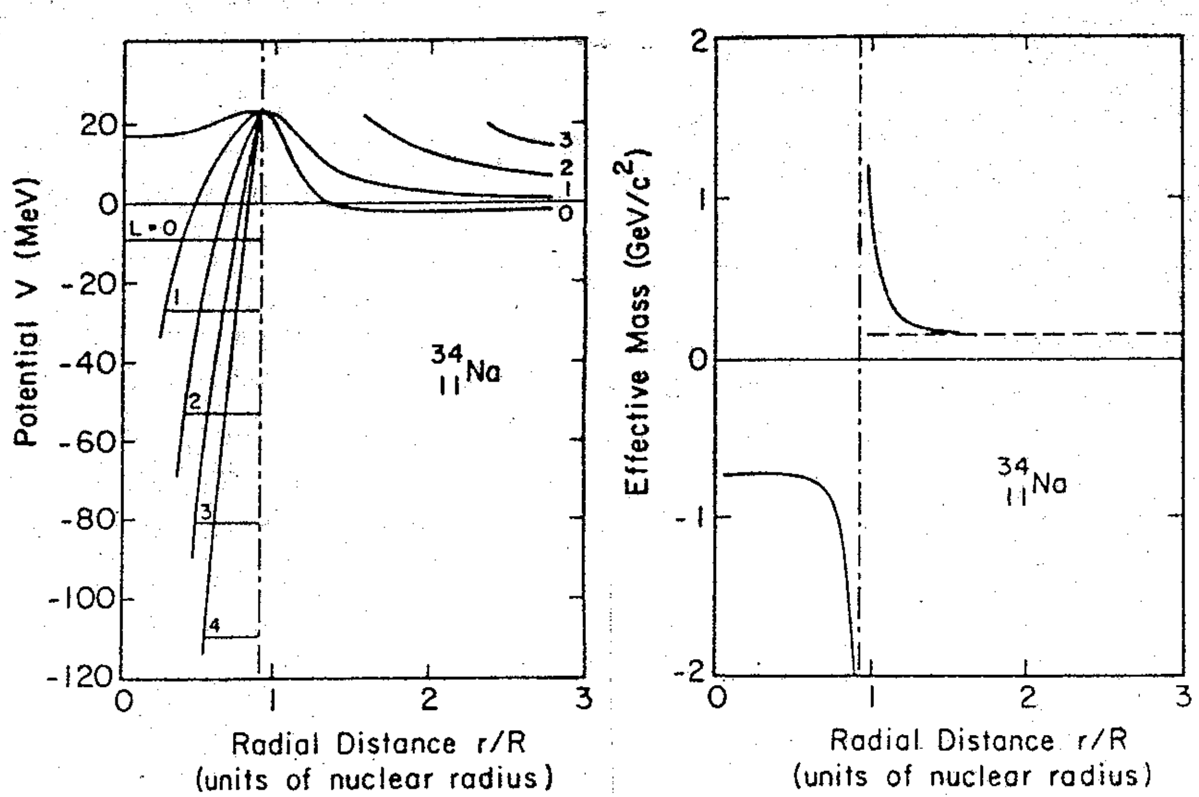

Fig. 1 The left side shows the radial potentials for a π^- in neutron-density-enhanced ^{34}Na for L values Ø through 4. The eigenvalues are indicated by horizontal bars at the appropriate energy running between the inner turning point and the mass singularity. The right side shows the effective mass dependence on distance.

For these calculations we used an enhanced effective neutron density brought about locally by the presence of the π^-. (It is this local neutron-density build-up that assures attaining a negative effective mass in the nuclear interior and which leads to our picture of "orbiting pineuts" to describe anomalons.) One can obtain deeply-bound solutions for a variety of reasonable parameters, and, of course, the binding is a sensitive function of the orbital angular momentum

L. (Also, since we wanted to look for the most deeply bound solutions, where all or most of the channels are closed for true pion absorption, the imaginary parts of the optical potential were set to zero for the solutions shown.)

We emphasize that our calculations (and indeed our model) are qualitative, but they indicate that one can obtain solutions that make physical sense for anomalons and that these solutions can be obtained with reasonable potentials and assumptions. (Recently another promising if preliminary study has been made of pions binding in nuclei, using a completely different approach, that of the relativistic Faddeev method.[14]) We propose to continue our calculations, performing them for many more examples, from the simplest "free pineuts" to heavier nuclei, and we would like to extend them as well by using more realistic (i.e., obtained at higher energies) potentials. We would also note that pionic states with two or more pions may gain added stability from admixtures of Δ pairs, which are predicted[15] to have very strong binding in spin-isospin (3,Ø) and (Ø,3) states.

We do not propose to become involved with the very elaborate track-detection experiments associated with anomalons, because they are already in progress in a number of laboratories around the world, and such experiments require great outlays both of finances and of manpower. However, during the next year we do propose to perform a relatively straightforward radiochemical experiment with a Bi target at the LBL Bevalac. (This experiment is planned in conjunction with John Rasmussen of LBL and Anthony Turkevich of the Univ. of Chicago.) Since pineut/anomalons are predicted to stabilize neutron excesses, exposing a Bi target (as a beam-stop) to relativistic heavy ion beams should enhance the production (at the appropriate target depth) of neutron-rich species, such as 6Ø.6-min ^{212}Bi, for which we have an extremely high radiochemical sensitivity. Such an experiment may or may not have a very high chance of success, but, considering its relative ease of being carried out, it would be a shame not to try it.

Finally, it should be pointed out that the phenomenon of pion (and other mesonic) binding in nuclei may prove to be more general than just for anomalons. For example, Rasmussen[16)] has predicted that the low-energy "bumps" found in the pion production cross-sections for Ne + NaF at the LBL Bevalac[17)] may well result from a similar π^- binding to excess neutrons. (And here one does not have to worry about the problem of protons and absorption.) Thus, it should be investigated as a possible general phenomenon. In passing, it should be noted that even if anomalons should turn out not to exist (and skeptics are fewer now than they were a year ago), they would have proved a virtual boon to the nuclear science community, because of the impetus they have given to creative speculation and calculation.

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B. NUCLEAR STRUCTURE

B 1. GIANT RESONANCES

(a) M1 Giant Resonances

(b) Excitation of Giant Resonances in Inelastic α Scattering

(c) Particle Response Function at High Excitation Energy

(d) Gross Structures in Reactions of Ca + Ca

(a) M1 Giant Resonances

N. Anantaraman, B.A. Brown, G.M. Crawley and A. Galonsky

Following the discovery[1] at MSU of the giant Gamow-Teller resonance in the ^{90}Zr(p,n) reaction at 45 MeV, it was studied at higher energy in many experiments[2] at Indiana University. With increasing energy up to 200 MeV the resonance became ever more prominent. A disturbing aspect of the interpretation of these charge-exchange experiments was the non-appearance in (p,p')[3] and (e,e')[4] experiments on ^{90}Zr and heavier nuclei of a charge analog (the $T=T_o$ component) of the resonance in the target itself. The location of the resonance in a given target and in its daughter nucleus should be related by the Coulomb displacement energy, and the relative strength excited in the target by (p,p'), and in the daughter by (p,n), should be given by isospin geometry coefficients.

The failure of the (p,p') experiment[3] could be understood in terms of the energy dependence of the nucleon-nucleon effective interaction as revealed in both experiment[1,2] and in modern theory.[5] These showed that transfers of one unit of spin and of isospin, as required for the related $0^+ \rightarrow 1^+$ (p,n) and (p,p') transitions, are relatively unlikely at 24 MeV, the energy of the (p,p') experiment.[3] On the contrary, at 200 MeV the M1 transition (i.e., $0^+ \rightarrow 1^+$) should be enhanced and not hard to observe at angles sufficiently small to take advantage of the forward peaking of this $\ell=0$ direct reaction.

After failing to obtain clean data at sufficiently small angles at Indiana, we formed an alliance with a group at Orsay (N. Marty et al.) that had a long-term common interest in this subject and suitable equipment. The revamped Orsay synchrocyclotron delivers $\simeq 0.1$ μA of 200-MeV protons, and with their large magnetic spectrograph and ray-tracing detection system we could obtain useable data down to 3°. Under these conditions the parent of the (p,n) resonance was quickly found[6]; its energy, width, and strength were all consistent with expectations. The (p,n) and (p,p') reactions were indeed revealing the same phenomenon, the former having $\Delta T_z=-1$, the latter $\Delta T_z=0$. Spectra at 4° showing the resonance in the even isotopes of Zr are given in Fig. 1.[7]

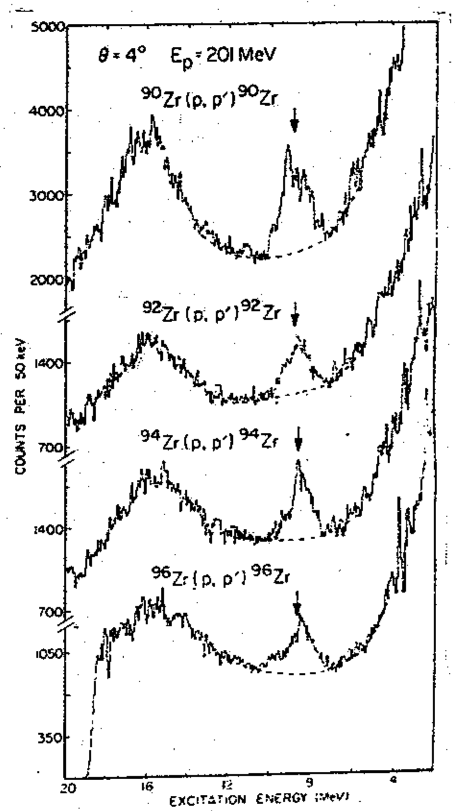

Fig. 1

By now, we have observed the resonance around 9 MeV excitation in many targets[8] within the mass range A=40-100 and possibly in targets of Sn and Ce. Figs. 2 and 3 show the resonance in some nickel targets and in some N=28 nuclei. The nucleon shell-model transition is between spin-orbit partners, in these cases mainly $f_{7/2} \rightarrow f_{5/2}$. Not unlike the Zr spectra, the Ni spectra have a broad, structured resonance centered around 9 MeV. In Ni, however, there is also a sharp peak whose excitation energy increases with increasing target isospin T_o. A sharp peak at high excitation requires a selection rule inhibiting particle

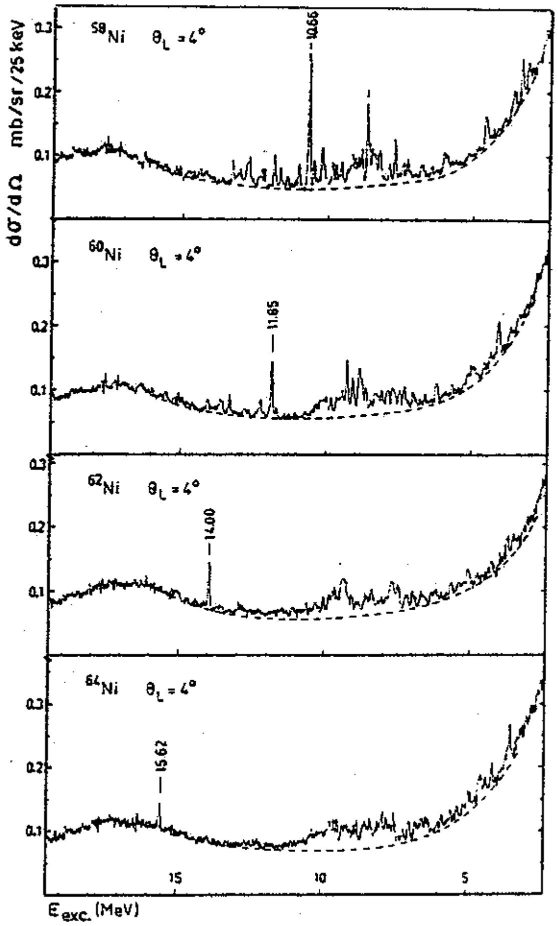

Fig. 2

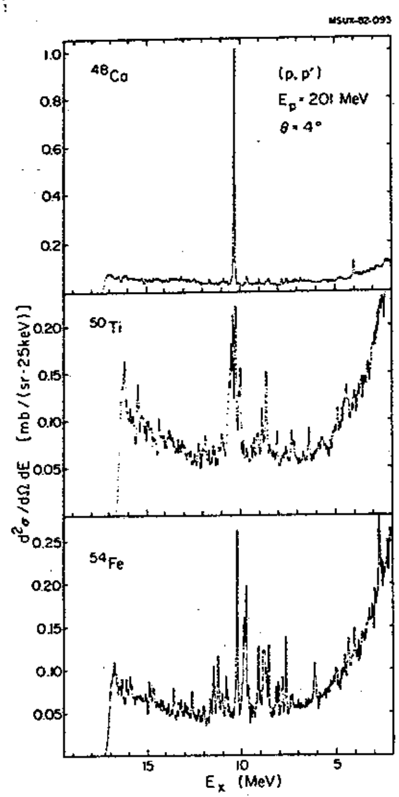

Fig. 3

decay. The angular distribution of the peak is the same as that of the main peak. We interpret it as the $T_o + 1$ part of the M1 resonance, its sharpness resulting from the suppression of neutron decay by isospin conservation. Corroborating evidence has now been obtained in a (p,n) experiment[9] on the same target nuclei. The 0^o spectra are shown in Fig. 4. Isospin geometry coefficients require that the $T_o + 1$ peaks be very small. Nevertheless, they are visible in the three lighter isotopes. Observation in such heavy nuclei of a $T_o + 1$ component of the Gamow-Teller resonance has not previously been reported. The strengths to the various 1^+ states observed in (p,p') and in (p,n) will help in testing and refining a detailed model of these states. That job is underway.

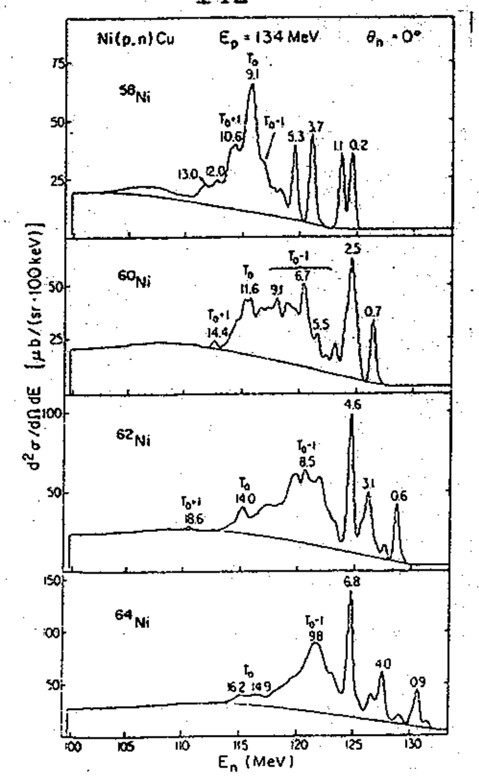

Fig. 4

Individual, sharp states characterize the spectra of Fig. 3, culminating in ^{48}Ca in the ultimate of simplicity - a single line. The theoretical 1^+ structure is also simple - a pure neutron $f_{7/2} \rightarrow f_{5/2}$ transition. A beautiful demonstration of the $\ell=0$ selectivity of small angles is afforded by the spectra of Fig. 5. The solitary line at 2^o and 4^o is joined by others at 8^o and is one of many at 12^o. The angular distribution of the 1^+ state at 10.2 MeV (the only place from 6 MeV to 18 MeV where we could find 1^+ strength) is given in Fig. 6 along with three theoretical distributions. All three match the data only in the first ten degrees. Each calculation relies on a knowledge of the nuclear interaction and of the ground state and 1^+ wave functions. The knowledge of these seems adequate to predict the shape of the angular distribution over a factor-of-ten fall off. However, the magnitudes are way off; the ratio of experiment to theory is only $\simeq$ 0.23 for the "Simple W-F" (closed shell ground state wave function) and 0.30 for the

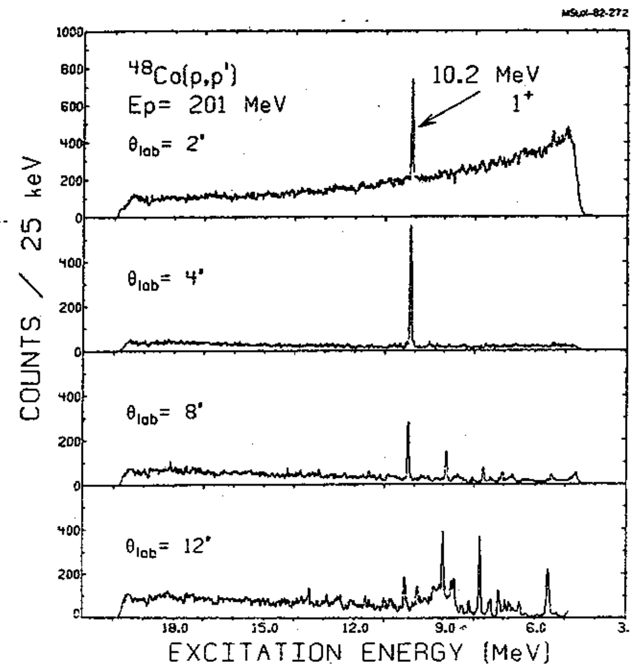

Fig. 5

"Full W-F" (wave function[10]) with neutrons in the f-p shell). This type of discrepancy, that of missing M1 strength, is now well known in (e,e') experiments.[11] In (p,n) experiments[2] we have the related missing Gamow-Teller strength. The extent of the discrepancy[12] is somewhat greater here, and it seems unlikely[13] that the popularly invoked Δ-nucleon hole excitation is sufficient to account for all of it.

The missing M1 and Gamow-Teller strength have not been found. Clearly, further investigation of the type discussed here is called for, and we intend to proceed. The failure in the case of ^{48}Ca is particularly perplexing because we should be able to deal properly with the wave functions via the shell model. Perhaps there is $T_o + 1$ strength at higher excitation energies. This could occur only if the ^{48}Ca ground state has some protons in the f-p shell, since a state of pure neutron excitation cannot have isospin

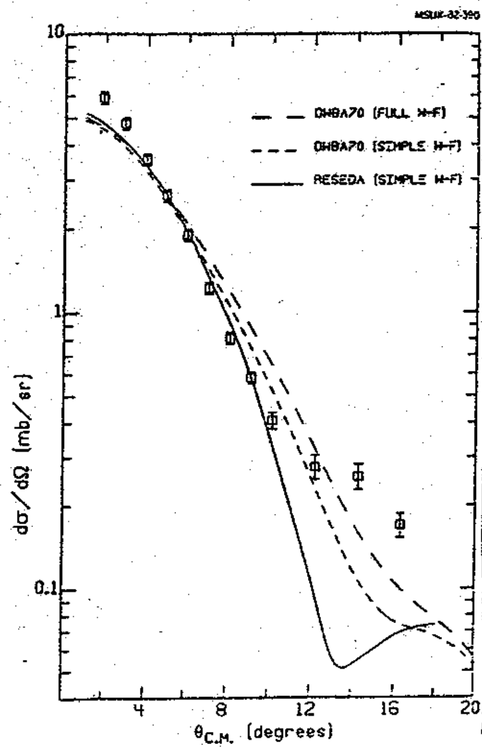

Fig. 6.

different from the ground state isospin. We will look for T_o+1 strength. Perhaps we will understand ^{48}Ca (p,p') better if we also study (p,p') on other calcium isotopes. We have, in fact, begun this study. We may also locate the M1 strength in ^{16}O and ^{18}O (nuclei which are analogous to ^{40}Ca and ^{42}Ca) to better test our use of the shell model. The simple shell model has two neutrons outside of a closed shell in both ^{18}O and ^{42}Ca, and we already have rather detailed oxygen wave functions. On the experimental side, we have preliminary ^{16}O data from a mylar target.

To investigate the nature and extent of the quenching of the M1 strength in light nuclei we shall study its mass dependence for sd-shell nuclei by means of the (p,p') reaction. While, as stated above, only about 0.3 of the predicted strength is observed for ^{48}Ca, all the predicted strength is found for the 15.11-MeV 1^+ state in ^{12}C.[14] It will be useful to trace the extent of the quenching through the sd shell. Results available from (e,e') and (p,n) studies show different trends for this mass dependence in the region A<4Ø (see Fig. 7): as one goes to very light nuclei, the M1 strength is progressively less quenched,[15] while the Gamow-Teller strength[16] stays quenched. Knupfer et al.[17] have interpreted this difference in behavior as being due to exchange

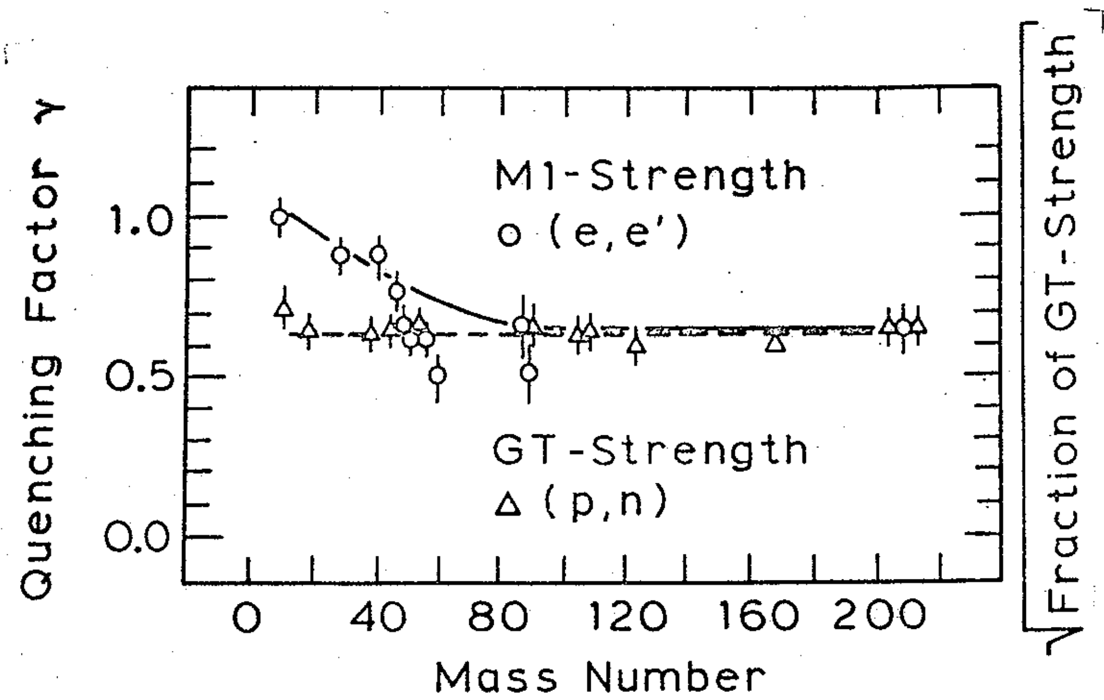

Fig. 7. Mass dependence of quenching factors for M1 transitions and Gamow-Teller transitions (from ref. 15). The solid and dashed lines are to quide the eye; they do not represent calculations.

currents which are absent in the Gamow-Teller process and which lead to an enhancement of magnetic dipole transition strengths over and above the same common quenching mechansim acting for both M1 and Gamow-Teller transitions. It will be interesting to see whether the (p,p') systematics follow the (e,e') trend. To extract quantitative information on the quenching from the (p,p') data accurate shell-model wave functions are needed. The recent work at MSU in creating improved shell-model descriptions of the sd-shell nuclei (section C2 (a)) will greatly help in this regard. The improved model wave functions should help in extracting quantitative information on the effects of non-nucleonic components of nuclear wave functions on the M1 strengths.

We have established the existence of the giant M1 resonance via (p,p') at 200 MeV in many nuclei, but we have had experimental difficulties with the heavier nuclei such as ^{208}Pb. We will explore the possibility of achieving greater sensitivity at smaller angles by requiring a γ-ray or neutron coincidence with the p'. A background, caused by slits, of elastically scattered, lower-energy protons should thereby be suppressed. If the M1 strength is not too finely dispersed, we might just find it.

We have discussed nuclei such as ^{48}Ca and ^{208}Pb where one has filled $j=l+1/2$ shells and empty $j=l-1/2$ shells and one can, therefore, expect strong M1 transitions. In some other nuclei, ground state correlations can greatly reduce the M1 strength. Hence, a measurement of M1 strength, in conjunction with good shell model calculations, bears directly on the ground state wave function. To name one case of current interest in this regard, we have the final nuclei in double beta decay - ^{48}Ti in the case of ^{48}Ca double beta decay and ^{76}Se in the case of ^{76}Ge decay, for example. These $0^+ \rightarrow 0^+$ decays go mainly by Gamow-Teller decay through intermediate 1^+ states, and their rates depend among other factors, on the ground state wave functions of the final nuclei. Cross sections for (p,p') to 1^+ states in the final nuclei are influenced by the same aspects of the (0^+) ground state wave function as are the beta decay amplitudes for the intermediate $1^+ \rightarrow 0^+$ part of the double beta decay. Our combined experimental-theoretical team we will be studying ^{48}Ti and ^{76}Se with the (p,p') M1 meter at Orsay and the shell model code at MSU.

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(b) Excitation of Giant Resonances by Inelastic α-Scattering

W. Benenson, G.F. Bertsch, G.M. Crawley, C.K. Gelbke, A. Galonsky, E. Kashy and J. Nolen

Progress in the understanding of giant resonance phenomena in nuclei has been very rapid during the last ten years. Much of this progress has been achieved by means of studies of light ion, particularly alpha particle, scattering. In general, increases in beam energy and technical advances permitting very forward angles to be measured have led to significant new results. There remain however a number of important questions to be answered. The combination of the K5ØØ cyclotron and the S320 spectrograph will permit a new series of experiments at angles near zero degrees and in the optimum energy range for these light particle scattering studies, and we expect that the results of these experiments will help to resolve some of the outstanding problems.

Inelastic alpha scattering in the energy range of the K5ØØ (up to 32Ø MeV) appears to be a particularly appropriate tool for the study of giant multipole resonances. The selection rules for one-step scattering reduce the contributions of some obscuring phenomena, e.g., the giant dipole resonance and other isovector states, and all the simple isoscalar excitations are expected to be increasing with increasing beam energy, as can be seen in Fig. 1. (There is however a limiting cross section which occurs when the beam energy is large compared to the Q-mismatch). This improvement with increasing beam energy has already been shown to hold for energies up to 18Ø MeV[1], and in the energy range from 18Ø to 32Ø MeV should result in an improvement in the peak to valley ratios which are so critically important to these studies. In fact recent work at Saclay[2] has shown that 34Ø MeV is close to the optimal energy. The spectrum in Fig. 2 is an example of measurements taken at this energy.

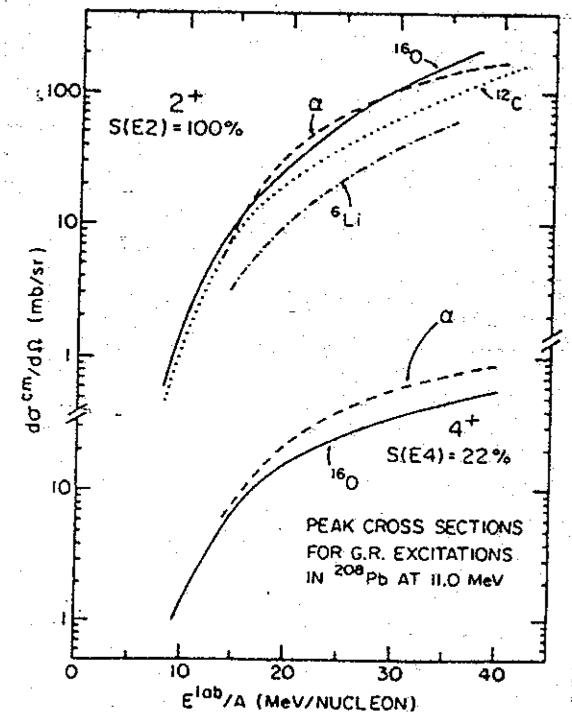

Fig. 1. DWBA predictions of the energy dependence of the peak cross sections for giant resonance excitations in ^{208}Pb at 11 MeV.

The spectra at 34Ø MeV are cleaner than at 48Ø MeV because the cross section is about the same at these two energies but the background increases at higher energies.

At energies above 18Ø MeV structures arising from the breakup of ^{5}He will occur in the spectra at excitations above 3Ø MeV and therefore will not interfere with the giant resonance peaks. The ability to vary the energy of the beam over a very wide range will permit the deconvolution of the overlapping resonances using the fact established in experiments at Jülich that the background and the ratio of yields will vary with energy. One problem with an energy-dependent analysis in this energy range is the absence of elastic scattering data. A necessary part of each experiment described below will be an elastic scattering run to establish the parameters of the optical model which will be used in the analysis. Some of the interesting giant resonance problems which can be attacked with beams from the K5ØØ are described below.

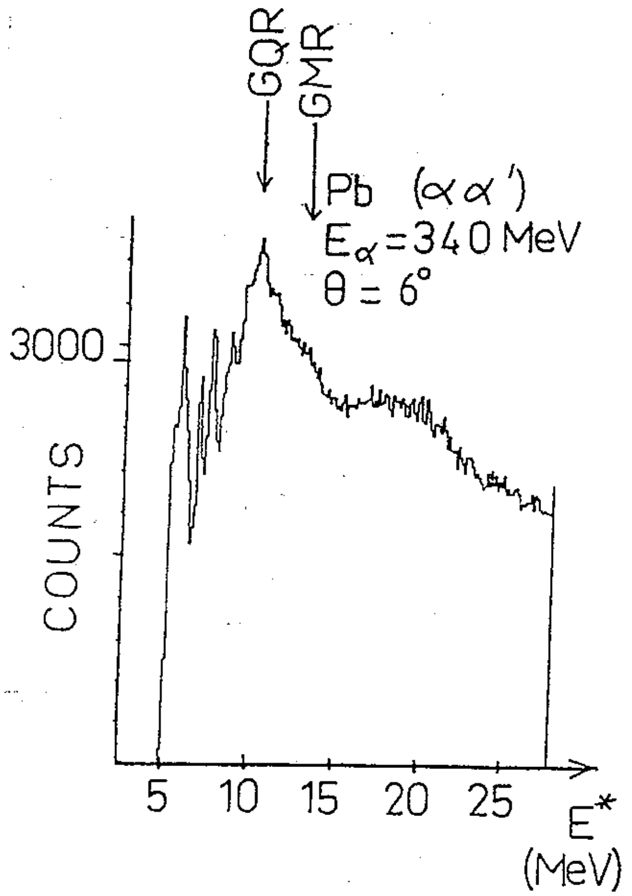

Fig. 2. A recent forward angle spectrum from Saclay for inelastic alpha scattering on ^{208}Pb at 340 MeV.

(i) <u>High Lying Giant Resonances.</u>

In spite of a very large number of experiments with a variety of probes, the giant resonance situation in ^{208}Pb remains unclear. In an alpha scattering experiment at 172 MeV[3)], two broad excitations were identified at 17.5 and 21.3 MeV which were suggested to be the isoscalar octupole resonance containing 60% of the sum rule and a isoscalar dipole state containing virtually all the sum rule strength. On the other hand, a (p,p') experiment at 800 MeV[4)] has shown only one bump with octupole character centered at 19.1 MeV. At lower excitation energy a suggestion of a new state between the quadrupole and monople has recently been made in a 480 MeV alpha scattering experiment at Saclay[5)].

The situation in ^{208}Pb certainly needs to be clarified, and alpha particle beams above 200 MeV appear to be an ideal tool for this. The ability to work at very forward angles and to vary the beam energy will be very valuable in establishing the multipolarity and strength of these new high lying giant resonances. If their existence is confirmed, then the next step clearly is to study them in as wide a range of nuclei as possible.

(ii) Giant Monopole Resonance in Light Nuclei.

The isoscalar monopole giant resonance has been definitively established in medium and heavy nuclei by the inelastic scattering of alphas[6)] and ^3He's[7)] at very forward angles. The excitation energy of the monopole resonance has considerable importance in nuclear physics and in astrophysics since it establishes the only measurement of the compressibility of nuclear matter. In heavier nuclei the remaining problem is the understanding of the width of the monopole resonance which is three times bigger than the theoretical prediction.[8)] Decay studies (see section iv.) may shed some light on this problem. For nuclei with A less than around 60 the monopole resonance seems to disappear, presumably because its strength is spread over a wide range of states. Experiments with ^3He's claim to observe monopole strength as low as A=27[1)], but alpha scattering experiments have failed to corroborate these results. The ^3He results give a very different A-dependence than usually observed for giant resonances, and it would be very worthwhile to be able to resolve this controversy. A good starting point would be ^{90}Zr, where there is agreement between the two experiments, followed by experiments with targets of lower A value, for example ^{40}Ca and ^{24}Mg.

(iii) Multipole Decomposition of Overlapping Resonances.

Although the excitation energy of most of the isoscalar giant resonances is now considered to be established except for the cases mentioned above, the strength contained is still open to question. Two difficulties arise in this determination. The first is the understanding of the background under the resonances, which is usually approximated by drawing a smooth line, and the second is the decomposition of overlapping resonances including some that may not have been previously considered. For example, the introduction of an E4 resonance with modest strength would throw estimates of the EØ and E2 strengths way off. Such a situation has in fact been predicted theoretically for ^{208}Pb[9].

Since different multipoles have different dependences on the bombarding energy for different particles, a systematic study over the whole range of energies and of light particle types may be the only way that this problem can be resolved. For example, for each of several beam velocities we could compare spectra taken with deuteron, ^{3}He, alpha and ^{6}Li beams. Performing all these experiments with the identical apparatus and calibrations would eliminate at least one source of confusion, and the very different background shapes should help also. Once again, the key ingredient is a high peak to valley ratio, and this we believe we will obtain with the S32Ø spectrograph and the K500 beams.

(iv.) Decay Studies of the Giant Resonances.

A powerful method to study the microscopic structure of the giant resonances is to use their particle decay. Except for the giant dipole resonance, very few experiments of this type have been undertaken. The remaining experiments have dealt mainly with the giant quadrupole resonance in light nuclei[1Ø]. Basically the question is whether or not the resonances decay in a statistical manner like the continuum or in the manner of states of simple character, which are very selective. The resonance width will actually be a sum of these two contributions , which are referred to as the spreading width and the direct escape width. In the case of the giant dipole resonance there is a dominance of the spreading width in heavy nuclei and a dominance of direct decay width in light nuclei[11]. For fission decay of the dipole resonance in actinide nuclei the decay is exactly like that of the continuum. For the decay of the giant quadrupole resonance the situation is less clearly understood. Calculations[12] are not in agreement with experiment which show a predominance of direct escape decay[13]. There also exist theories for the continuum which lies under the giant resonance peaks[14]. The quasi-elastic components of the continuum can be identified by coincidence experiments of the same type as used to measure the decay properties of the giant resonance peaks. Developing a data base in this manner for comparison and refining of these theories should make an important contribution to all giant resonance studies.

In the actinide nuclei one would expect a predominantly statistical decay similar to the continuum for the fission decay of the giant quadrupole resonance. Although this is a very controversial subject, the evidence now seems to be mounting that the fission decay of the quadrupole resonance is weaker than that of the continuum[15]. A definitive experiment is now needed in this field, one that would look at the fission decay of several actinides and over the whole giant resonance region of excitation energy. We plan to use high energy alphas to obtain the largest peak to valley possible for the resonances and to look at the decay products in large area position sensitive multiwire avalanche detectors.

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(c) Particle Response Function at High Excitation Energy in Medium Weight Nuclei

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The neutron hole state response function has been extensively studied experimentally by pickup reactions, both (p,d) and (^{3}He,d).[1-4] The proton hole states have also been studied but on fewer nuclei.[5] Calculations of the position and width of these states suggest that the simple states mix extensively with phonon states.[6-9].

On the other hand practically no information is available in the literature on highly excited particle states, either proton states or neutron states. The S320 spectrometer is an ideal tool for studying such excitations since it should allow clean spectra to be taken at very forward angles while removing count rate problems from elastic scattering. The additional advantage of the S320 is that its broad range will allow a wide region of excitation energy to be studied with one magnetic field setting.

More specifically the reactions we propose to investigate are the (d,^{3}He) and (d,t) reactions which populate neutron and proton particle states respectively. The targets to be studied include ^{40}Ca, ^{90}Zr, ^{144}Sm and ^{208}Pb. In each of these cases, there are high spin orbits which should be accessible with both proton and neutron transfer reactions. For example in ^{40}Ca, the distribution of l=3, $f_{7/2}$ and $f_{5/2}$, could be measured for both proton transfer and neutron transfer. In ^{208}Pb, proton transfer would populate states like $i_{13/2}$, $h_{9/2}$ and $f_{5/2}$ whereas neutron transfer would reach $i_{11/2}$, $g_{7/2}$ and possibly $j_{15/2}$ orbits.

One further advantage of the (d,t) reaction would be the study of isobaric analogue states in ^{209}Bi. Such states have been observed in lighter nuclei by the (^{3}He,d) reaction but this experiment becomes more difficult in heavy nuclei because of the large background from ^{3}He breakup. The measurements are, however, very interesting on heavy nuclei because of the intrinsic interest in spectroscopic information about the states.

The experiments will be performed in the S320 spectrograph. The (α,t) reactions will be carried out with the 120 MeV α-beam, since the tritons will be the most rigid particle emitted and could be detected very cleanly. The (α, ^{3}He) will be studied at the same bombarding energy and also at higher energy to test the selectivity of the process as a function of energy.

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