A. Project Summary

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University is the premier intermediate-energy heavy-ion user facility on the North American continent. Since its inception, the NSCL has played a significant role in nuclear and accelerator physics research, both in the US and worldwide. The two major research areas are: (1) The exploration of nuclear matter at high temperatures and at densities different from that of normal nuclear matter. This leads to a better understanding of the thermodynamic properties of finite quantum systems and of the liquid-gas phase transition of nuclear matter. (2) The exploration of the properties of nuclei with extreme ratios of neutrons to protons, including many of astrophysical importance. This area is undergoing a rapid expansion worldwide and at the NSCL due to the recent development of beams of short-lived nuclear species ("radioactive beams").

The NSCL proposes to continue operating as a national user facility for the five-year period from 11-1-1995 through 10-31-2000, providing a broad range of beams from its existing K1200 superconducting cyclotron. We envision significant improvements in our experimental capabilities during this time. The S800 magnetic spectrograph will add a new dimension to the NSCL nuclear structure program. Construction of this instrument has been a high priority for the National Science Foundation and the NSCL during the present operating period; commissioning is expected during the first year of the new operating period. The S800 will open new vistas for studies of reactions with unprecedented resolution, employing both stable and radioactive beams. Its availability will add further pressure for research time with beams from the K1200 cyclotron. A new capability of simultaneous event-by-event detection over the full solid angle of both neutral and charged particles will allow the incisive investigation of hot nuclei, including the liquid-gas phase transition in low-density nuclear matter and the equation of state of nuclear matter.

The NSCL has a proposal pending to upgrade its facility to provide beams of much higher intensity and higher energy for studies of nuclear structure and nuclear reactions, particularly those utilizing more intense radioactive beams. The upgrade plan consists of refurbishing the existing K500 cyclotron for high intensity operation, building a transfer line for injection of the K500 beams into the existing K1200 cyclotron, and replacing the present low-acceptance A1200 beam analysis system with a more powerful, higher-rigidity and higher-acceptance A1900 system. Since the proposed facility upgrade makes use of the existing K500 and K1200 accelerators, ion sources and experimental equipment, it is very cost effective. The proposed upgrade will provide a world-class radioactive beam facility, capable of delivering 100%-duty-factor beams of higher mass, intensity, and energy than available anywhere else in the world, and thus ensure US leadership in the rapidly growing area of nuclear physics with radioactive beams beyond the year 2000.

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C. Project Description

This proposal requests funds to operate the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU), for support of its users program, and for support of the research of the MSU staff in nuclear science and in accelerator and instrumentation physics. Experimental facilities at the NSCL include two superconducting cyclotrons, the K500 (the world's first superconducting cyclotron commissioned in 1982) and the K1200 (the world's most powerful cyclotron, commissioned in 1988). Three electron cyclotron resonance (ECR) ion sources provide beams for injection into the cyclotrons. Beams from the K1200 are extracted into an A1200 beam analysis system for the production of radioactive beams. The Laboratory has a modern and versatile complement of experimental apparatus, including a new high-resolution superconducting magnetic spectrograph, the S800, now nearing completion. High quality beams from the K1200 superconducting cyclotron cover the whole range of elements from hydrogen to uranium, with a wide range of energies from a few tens of MeV/nucleon to 200 MeV/nucleon (for fully stripped N=Z ions). They are also used for studies of the quantum-statistical properties of hot nuclei and the liquid-gas phase transition in nuclear matter, and for nuclear structure research with both stable and radioactive beams, including beams of nuclei at the limits of stability with unusual neutron density distributions. The NSCL facility is also used for multi-disciplinary research on problems in astrophysics, condensed matter physics, geophysical science, medicine, and biology. The Laboratory attracts many users from the US and abroad, and demand for beam time far exceeds that available. The NSCL research program continues to have a major influence in defining the directions of research with intermediate-energy heavy ions. A measure of this influence is the more than 170 invited talks given by NSCL users at national and international meetings during 1993-1994, as well as the 44 papers published during this period in Physical Review Letters and Physics Letters. The funds requested, together with the commissioning of new experimental apparatus, will continue to foster high quality basic research in nuclear science.

The NSCL has recently proposed a major intensity upgrade of its facility. If funded, large increases in beam intensities will be achieved [MSU94] in a cost-effective fashion by the coupled operation of the two existing superconducting cyclotrons, the K500 and the K1200. The K500 will accelerate high-intensity beams of low-charge-state ions (reliably produced by modern ECR ion sources) to modest energies ($E/A \leq 20$ MeV). After extraction from the K500 cyclotron, these high-intensity beams will be transported to the K1200 cyclotron, stripped to a higher charge state, and accelerated to full energy. Together with the installation of a high-acceptance, high-rigidity A1900 beam analysis system, the coupled cyclotron operation will provide large gains in the intensity of secondary (radioactive) beams, usually by two to three orders of magnitude, and thus ensure continued world-leadership in nuclear research with radioactive beams. The proposed facility upgrade is well matched to the existing NSCL beamlines and allows effective use of existing NSCL experimental apparatus, including the S800 magnetic spectrograph presently nearing completion. Michigan State University is presently providing a needed high-bay extension as a start-up contribution. MSU has further agreed to share the cost of the proposed facility upgrade, thereby reducing the need for new NSF funds to $11M (FY94 dollars) from a total cost of roughly $19M (which includes the high-bay addition). MSU's commitment assumes that the NSF operating support of the NSCL facility during the next five-year period will remain at least at the constant-effort FY94 funding level.

C-I: Results from Prior NSF Support

Historical Perspective of NSCL Facility

The nuclear physics program at MSU began in 1958 as an initiative of the Department of Physics. In 1961, the National Science Foundation (NSF) funded the construction of a 50 MeV cyclotron, which became the world's first high resolution isochronous cyclotron using new single-turn extraction techniques developed at MSU. In 1978, construction of the NSCL as a national user facility was recommended by the NSF/DOE Nuclear Science Advisory Committee (NSAC). In 1982, the first beam was extracted from the K500, the world's first superconducting cyclotron. The K1200 cyclotron was commissioned in 1988, and an interim research program was initiated. Concurrently, the remaining superconducting beam transport system was completed. The full experimental program began in 1990, after an 8-month shutdown for the installation of the superconducting beam transport system and the A1200 beam analysis system. Since then, the reliability of K1200 operation has steadily improved to better than 90%, while a large variety of beams and energies have been developed and extracted (see Fig. C-1, and also Table A1 of the Appendix).

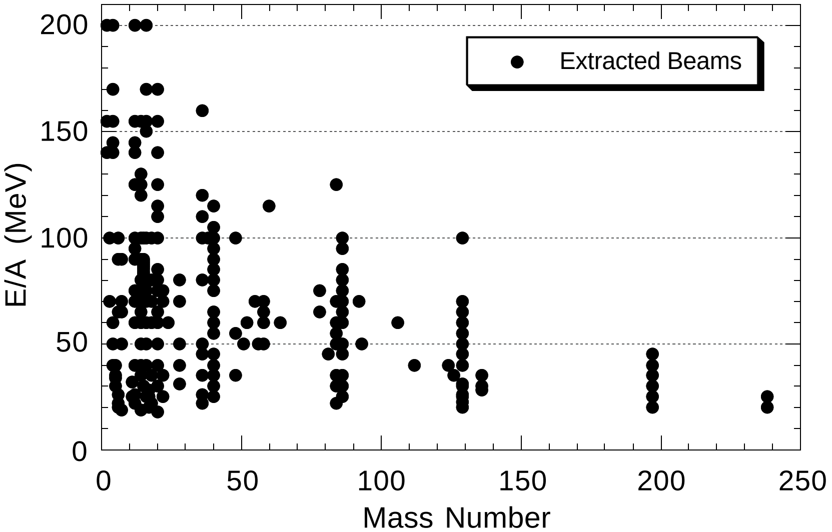

Fig. C-1: Energy per nucleon of beams extracted from the K1200 cyclotron. For Q/A = 0.5, the maximum theoretical energy of 200 MeV has been reached; for heavy beams, the original design goals of the NSCL facility proposed in 1978 have been exceeded. A beam list is given in Table A1 of the Appendix.

Major Instrumentation and Technology Developments:

- Development of iron-dominated beam-transport magnets with superconducting coils and construction of the superconducting beam line system.
- Development and construction of the A1200 beam analysis system to produce radioactive beams by projectile fragmentation.
- Completion and commissioning of gantry-mounted K100 superconducting cyclotron for radiation oncology at Harper Hospital.
- Proof-of-principle tribology studies which used the implantation of ^{7}Be and ^{22}Na for mechanical wear analysis.
- Development of ECR ion source technology. Design, construction and operation of ECR ion source with superconducting coils (SCECR) which now produces record beams of very highly charged ions.
- Completion of the large 4π-Array, a large-dynamic-range (protons to fission fragments) charged particle detector, plus several specialized forward arrays.
- Design and construction of a transportable low-threshold 4π phoswich array (Miniball).
- Commissioning of the 7-Tesla solenoid (Big Sol) for high-acceptance detection experiments with radioactive beams.
- Commissioning of the 17 m^3 Superball neutron multiplicity meter.
- Design of a novel ion optical technique which allows a spatially flat beam intensity profile, e.g., for proton cancer therapy treatments.
- Conceptual design of a superconducting 250 MeV proton cyclotron for cancer radiation therapy.
- Design and construction of an 8-Tesla magnet to push the frontiers of superconducting cyclotron technology.
- Development of the K500⊗K1200 coupled cyclotron facility concept.
- Design and construction (in progress) of the S800 superconducting spectrograph.

User Statistics (PAC 14 - 18)

Funded by the NSF and MSU, the NSCL serves a large national and international user community. Over the years, more than 450 scientists have used the NSCL to conduct their research. Beam time for research is allocated according to scientific merit with advice given to the Director by an external Program Advisory Committee (PAC) which meets and evaluates research proposals twice a year.

Pressure for beam time is high. The combined statistics over PACs 14 - 18 show that, since November 1992, 17,509 hours of beam time were requested and 11,318 hours (<65%) were approved. Almost half of the approved research time (5,120 hours) was allocated to collaborations led by outside spokespersons. The average numbers of inside and outside users per PAC period were 43 and 96, respectively. The average number of graduate students per PAC period from outside institutions was 21 as compared to the 19 graduate students from within the NSCL. More than half of the beam time requests are for experiments with radioactive beams, and pressure for significant increases in radioactive beam intensities is steadily mounting. With the commissioning of the S800 spectrograph, anticipated for early 1996, demand for beam time is expected to increase further.

Educational Impact and Outreach

The NSCL provides a unique research and teaching environment with an excellent faculty and a technical staff known for their high level of creativity and technical competence. The relatively small size of the laboratory and its flexible working groups offer a broad educational experience which forms an excellent basis for a future career both in academic research and in industry. Historically, the NSCL has provided the scientific and technical education of a large number of young scientists and engineers in undergraduate, graduate, and postdoctoral programs. Former students now occupy many important positions in universities, national laboratories, and industrial laboratories and contribute to society in many different areas. For example, recent NSCL graduates now work on cancer therapy, airport anti-terrorist safety, environmental protection, weapons safeguards, nuclear fusion, and radiation effects on space travel.

Undergraduate, graduate and postgraduate education: Most NSCL faculty have joint appointments with the Department of Physics and Astronomy with normal-load assignments in teaching undergraduate courses, and they have an excellent reputation for high quality instruction and innovation. For example, a very successful Computer Assisted Personalized Assignment program (CAPA) was recently developed and brought into the classroom by NSCL faculty [Kas93, Mor95]; the program has been adopted at several universities. Three NSCL faculty members have an NSF ILI grant to employ advanced computer techniques in undergraduate physics labs. The NSCL also plays an important role in undergraduate education by providing experience for undergraduate students in a stimulating environment where they are exposed to basic physics research and related technologies ranging from applied superconductivity to accelerators designed for cancer therapy. For many years, the NSCL has also provided summer internships to talented undergraduate students via an NSF and MSU funded REU (Research Experience for Undergraduates) program.

Most importantly, the NSCL plays a major role in training the next generation of nuclear scientists for the United States. Currently, more than 60 graduate students from MSU and other universities work at the NSCL on PhD programs in experimental or theoretical nuclear physics, nuclear chemistry, or accelerator physics. Typically 10 postdoctoral research associates reside at the NSCL, supported by funds from MSU, the NSF, and foreign institutions. NSCL graduate students and postdocs have earned excellent reputations for being well trained, and many young scientists from the NSCL now hold important positions in industry, academia, and national laboratories in the US and abroad.

Precollege education outreach: The NSCL plays an important role in pre-college and community education. NSCL faculty participate in the Science Olympiad and the Math, Science and Technology program for gifted middle school students administered by the MSU Honors College. The NSCL also conducts a Summer Research Intern Program for middle school and high school teachers with lectures, training in physics demonstrations, and problem solving. Part of the program requires the teachers to apply their new knowledge by teaching middle school and high school students enrolled in the program. The teachers can still call on expert faculty advice should they need or desire to do so.

This year a Science Challenge outreach program has been initiated. It challenges high school students to solve problems and enter their solutions via the internet into the CAPA system using an NSCL computer. The students experiment with several puzzling physical phenomena (materials are provided) and thus gain a deeper understanding of the underlying physics principles. Currently eight teachers and approximately three hundred students from Michigan, Ohio, and Illinois are involved in this pilot program.

On a less formal basis, the NSCL conducts guided tours of the facility for interested groups of the public. Before seeing the facility, the groups are shown a special video (produced at MSU), which explains and illustrates major technical and scientific issues in lay terms. Typically 1500 - 2000 persons take such tours each year. Many NSCL graduate students are active participants in "Science Theater", an organization which attempts to convey the excitement of science through performances at schools and in the community, including the 1994 Michigan Festival. Science Theater won the Physics and Astronomy Department Outreach Award in 1991 and the 1993 Award for Public Understanding of Science and Technology from the American Association for the Advancement of Science.

Cross-disciplinary research and technical outreach: Approximately 5-10% of the NSCL effort has been devoted to support a broad and diverse program of applied and cross disciplinary topics, and the NSCL will continue to seek new opportunities to foster cross-disciplinary research and societal applications. Recent and/or ongoing activities include atomic physics measurements which test quantum electrodynamics [Che93], studies of electron transfer and ionization mechanisms [Zah93], tests and calibrations of various radiation detectors used in space flights and dosimetry applications [Lav94], non-destructive wear analysis studies using implanted ^{7}Be ions [Mal89, McH90], flux pinning and possible material modifications via irradiation of high T_c superconductors with heavy ions, accelerator mass spectroscopy of rare gas isotopes [Kut94], problems in radiation biology, and the development of fast on-line PET imaging techniques for radiation therapy [Lit92]. As a spin-off from nuclear theory, a theorist from the NSCL is currently developing a pattern recognition algorithm which is aimed at computerized recognition of cancerous cells in blood samples.

Over the years, the NSCL has pioneered medical applications of superconducting accelerator technology. Most notably, the NSCL designed [Blo89] and constructed a gantry-mounted, superconducting K100 medical cyclotron funded by Harper Hospital in Detroit. Neutron therapy with this cyclotron is now an integral part of a variety of new cancer treatment protocols for otherwise difficult-to-treat tumors. The original design of the cyclotron has been licensed to a commercial manufacturer. More recently, the NSCL produced a conceptual design [MSU93] for a superconducting cyclotron for the treatment of cancer patients using proton beams. The cyclotron would be configured for installation at a hospital, and the NSCL is seeking funds to construct a prototype.

In addition to the activities listed above, the NSCL serves as a technical resource for other research institutions in the US and abroad. For example, the NSCL continues to provide backup expertise for the Harper Hospital's neutron therapy cyclotron. A number of special electronics modules developed at the NSCL are now licensed for fabrication by commercial companies. Transfer of NSCL know-how and technology to other research institutions is also a common service. For example, the NSCL provided the design for the Texas A&M superconducting cyclotron, and the main magnet coil for this cyclotron was fabricated at the NSCL [May84, May87]. More recently, NSCL personnel contributed to the design of the central region of the ORNL-RIB cyclotron. Today NSCL staff are collaborating with Lawrence Berkeley Laboratory on redesigning the central region of the 88-inch cyclotron to provide the single-turn extraction performance needed for the Gammasphere project.

NSCL ion source designs, data acquisition technology, and many computer programs for basic nuclear physics, beam dynamics, and magnet design are being used by researchers world wide.

NSCL Operations

During 1992-1994, the K1200 superconducting cyclotron accelerated ions over its full energy range (E/A = 20 - 200 MeV) with high reliability, presently better than 90%. Beams extracted from the K1200 are shown in Fig. C-1. A list of beams (with typical intensities) available for research is given in Table A1 of the Appendix, and the K1200 time usage over recent years is depicted in Fig. A1 of the Appendix. Noteworthy beams developed in recent years are ^{16}O at E/A = 200 MeV (the highest energy per nucleon theoretically possible from the K1200), the high-energy, medium-mass beams of ^{84}Kr at E/A = 125 MeV and ^{129}Xe at E/A = 100 MeV, and the heavy-mass ^{197}Au beams with energies up to E/A = 45 MeV (exceeding the original design goal for the NSCL facility). The extraction of the 200 MeV per nucleon beam was the culmination of a substantial R&D effort requiring technical improvements of the rf resonator sliding shorts, redesign and rebuilding of the rf power supply rectifiers, attainment of higher deflector voltages, and a vertical repositioning of the main magnet coils by less than 1 mm. The high-energy Kr, Xe, and Au beams were made possible by the outstanding performance of the superconducting ECR ion source.

Groups from the NSCL, Chalk River Laboratories, and Texas A&M University have begun to collaborate on studying techniques aimed at improving deflector voltages. Two main issues were identified: the need for improved voltage holding strength of the support insulators and for reduced cathode heating which causes enhanced field emission of electrons. Changes were made to the K1200 deflector system with encouraging results: both deflectors can now operate at voltages above 80 kV (corresponding to a voltage gradient of 133 kV/cm) with both the magnetic field and the rf turned on.

Major recent upgrades and/or construction of new experimental apparatus are:

- Acceptance upgrade of A1200 beam-analysis system (February - April 1994) by the addition of a superconducting quadrupole doublet immediately upstream of a new, heavily-shielded A1200 target box. The K1200 cyclotron was repositioned in the vertical direction to better match the horizontal plane of the NSCL beam-transport system.
- Construction and commissioning of S2 beam line and University of Rochester SuperBall, a 17 m^3 gadolinium-loaded liquid-scintillator neutron multiplicity meter (December 1993).
- Adaptation of Miniball into the SuperBall (February 1995) to allow simultaneous neutron and charged-particle detection with 4π coverage.
- Upgrades of 4π Array (1993 to present): construction of a high-rate forward-angle array, consisting of 45 close-packed fast-slow plastic phoswich detectors covering polar angles $\theta = 3°$ - $20°$; it supplements the Maryland Forward Array (installed in 1993) which covers polar angles $\theta = 1.5°$ - $2.9°$. A multinode transputer system was added to the 4π data acquisition hardware to allow real time data filtering and elimination of unwanted background.
- S800 focal-plane detector R&D: A prototype wire-chamber was developed and tested; it met the position resolution specifications, but required extensive calibration for each use. Subsequently, a prototype Cathode Readout Drift Detector for the S800 spectrograph was developed and tested. This detector also met the design value in position resolution (200 μ FWHM in the dispersion direction and 300 μ FWHM in the drift direction) for both lightly- and heavily-ionizing particles, but without the need for difficult re-calibration. Design of the full-size detector required for the S800 spectrograph is underway.
- Construction of a two-layered position-sensitive neutron time-of-flight wall for efficient measurement of two-neutron coincidences is nearing completion. Each wall consists of a 2-meter stack of 25 glass cells, each of which is 2 meters long and filled with NE 213 liquid scintillator that permits neutron/γ-ray discrimination by pulse-shape analysis. The first test with beam is scheduled for spring 1995.
- Construction of the S800 superconducting spectrograph: The project continues at the highest level of priority, and commissioning of the device is anticipated for early 1996 -- provided that no unanticipated technical difficulties are encountered.

Nuclear Science at the NSCL

The production of high-quality and innovative scientific results by NSCL staff and users is high; during 1993-94, for example, 44 papers were published in Physical Review Letters and Physics Letters. A numerical summary of invited talks presented at conferences and papers published in refereed journals since 1989 is given in Table A2 of the Appendix. It is virtually impossible to do justice to the broad spectrum of outstanding research accomplishments of the NSCL users and staff, and some omissions are unavoidable. By necessity, the following brief summary is incomplete.

Nuclear structure and astrophysics: Extended distributions of neutrons or protons ("halos") have been studied for some select nuclei near the drip lines in which the very weak binding of the last nucleons leads to extended, low-density nuclear matter distributions. These systems provide the opportunity to study quantum-mechanical few-body effects. At the NSCL, work has centered on the detailed understanding of halo structures and the extension of these studies to new (and heavier) examples which are accessible with currently available beams. These new data point to a new type of shell structure in which three-body effects play an important role. Much effort has been concentrated on the understanding of ^{11}Li which has served as a prototype halo-nucleus. The following achievements are important contributions to the elucidation of its structure:

- Longitudinal momentum distributions of projectile fragments, measured with high precision at the NSCL [Orr92], gave a new insight into the momentum and spatial distributions of the valence neutrons in ^{11}Li and other drip-line nuclei.
- Elastic scattering experiments with ^{11}Li and other A=11 nuclei [Kol92] revealed strong refractive effects (rather than suppression due to absorption) for the halo-nucleus ^{11}Li.
- The first kinematically complete experiment on the breakup of ^{11}Li [Iek93, Sac93]. The detection of both neutrons in coincidence with the ^{9}Li recoil yielded information on the soft dipole excitation mode and the unexpectedly fast time scale of the breakup process.
- The binding energy of ^{11}Li was measured with high precision [You93] resolving previous ambiguities; it is the single most important quantity in theoretical treatments of the valence neutron wave function and may provide information about the pairing interaction in dilute neutron matter.
- A major step toward the characterization of the valence neutrons in ^{11}Li was made by the observation of resonances in the ^{9}Li + n system. A particle-decay spectroscopy experiment [Kry93] and an accompanying transfer-reaction study have demonstrated the existence of a low lying s-state in ^{10}Li. The existence of this state provides important guidance to theoretical treatments of the ^{9}Li+2n three body system.
- The detailed β-delayed neutron spectrum of ^{11}Li was measured for the first time with high resolution [Mor95a].

Other achievements related to halo nuclei include:

- Longitudinal and transverse momentum distribution measurements revealed [Baz95] the single-neutron halo nature of ^{19}C -- the highest-mass halo nucleus known so far.
- A narrow longitudinal momentum distribution of the valence neutron in ^{11}Be has been measured [Kel95a], and the accuracy with which the parallel momentum distribution of the breakup products can be used to determine the momenta of halo neutron wave functions has been demonstrated.
- Unequivocal demonstration of the proton halo structure of the proton-rich and astrophysically important nucleus ^{8}B by the observation of its narrow momentum distribution [Kel95b].

Element formation in hot stellar environments via the rp process proceeds along the proton dripline. Studies of proton dripline nuclei are therefore of astrophysical interest. In addition, these nuclei may decay via new and exotic nuclear decay modes, such as ^{2}He-emission. Important results involving nuclei at or near the proton drip line include:

- Determination of the stability of key nuclei at the proton drip-line up to A=90. In particular, the particle-stability of the key branch-point nucleus ^{65}As was demonstrated, and its lifetime was directly measured [Moh91, Win93]. The observed instability of ^{69}Br shows that ^{68}Se is the probable termination point of the rp process.
- Development and use of the method of particle decay spectroscopy [Kry95] to investigate the two-proton decay of ^{12}O.

Nuclear structure studies with radioactive beams are still in their infancy, and progress is hampered by the very low beam intensities available at this time. Only recently has it been possible to perform direct reaction or (in)elastic scattering studies with resolved final states. Innovative methods at the NSCL have lead to the following achievements:

- Observation of the double exchange process ^{13}C(^{13}N,^{13}C)^{13}N at 0° via magnetic separation of the radioactive beam and analysis of the reaction products by means of dispersion matching in the same device, the A1200. The charge exchange process allowed the study of the relative strength of Fermi and Gamow-Teller transitions [Ste95].
- Coincident γ-ray measurement in the breakup of the halo-nucleus ^{6}He allowed the separation of nuclear and Coulomb breakup events, demonstrating the complexity of the halo breakup mechanism [Bal94].
- First experiments on the (p,n) charge exchange process were performed in inverse kinematics with radioactive beams [Bro95]. Such reactions will provide weak process strengths interesting for nucleosynthesis and supernovae evolution.
- Demonstration of the usefulness of the high-energy (t,^{3}He) reaction with a secondary triton beam for measurements of β^{+}-strength [Fuj95]. High resolution experiments will be possible with the new coupled cyclotron facility which will yield information important to the evolution of supernovae.

- Accurate determination of the lifetimes of ^{32}Si and ^{44}Ti via direct measurement of decay probability. Previously published lifetimes were inconsistent with each other [Che93a]. These lifetimes are used in radio-isotope dating and for tracking long-term supernova light curves, respectively.

<u>Nuclear reactions:</u> Intermediate-energy heavy-ion beams available at the NSCL allow the formation of hot nuclear systems which can expand to low density under the action of their thermal pressure, aided by an initial compression subsequently converted into a radial outward flow of nuclear matter. Thus, one may study the liquid-gas phase-transition of nuclear matter, quantum statistical properties of strongly interacting, finite many-body systems, the equation of state of nuclear matter, and modifications of nucleonic and mesonic interaction cross sections by the surrounding nuclear medium.

Major accomplishments in recent years are:

- Two-proton intensity-interferometry measurements have provided detailed tests of the Boltzmann Ühling-Uhlenbeck (BUU) transport theory. For energies below 100 MeV, the predicted space-time evolution of the reaction zone is consistent with experiment, provided that in-medium cross sections are comparable to the free ones [Gon91]. Gratifying agreement was found for longitudinal and transverse correlation functions measured for ^{36}Ar+^{45}Sc collisions selected with central cuts [Lis93]. However, recent investigations [Kun93, Han95] revealed problems in transport interpretations of peripheral collisions and, surprisingly, of higher-energy central collisions ($E/A > 100$ MeV).
- Systematic investigations of the mass-dependence of the "balance energy", the energy at which mean-field nuclear attraction is just canceled by nucleon-nucleon collision pressure, allowed detailed tests of the BUU transport theory and helped to further reduce uncertainties in the magnitude of in-medium nucleon-nucleon collision cross sections [Wes94].
- Impact-parameter filtered measurements of high-energy photon production were used to test theoretical descriptions of the very early stages of the collision process; the rate of p-n collisions producing high-energy photon bremsstrahlung now appears well understood [Rep92].

Much work has been devoted to the experimental study of multifragment-disintegrations which provide key information on the growth of density fluctuations in hot nuclear matter at low density and on the liquid-gas phase transition. Important results in this area are:

- Unambiguous observation of multifragment disintegration as the predominant decay mode of hot nuclear systems formed in central heavy-ion collisions at intermediate-energy [Bow91]. For very heavy systems (such as Xe+Au, Au+Au), the maximum amount of fragment production (~ 10 fragments observed per central Au+Au collision) occurs at $E/A \approx 100$ MeV [Tsa93, Pea94].

- Systematic investigations of charge distributions as a function of beam energy and impact parameter have been carried out to search for critical behavior [Li 93, Li94].
- Two-fragment correlation measurements, sensitive to the final-state Coulomb interaction between the emitted fragments, have revealed that fragment formation occurs on a short time scale (≤ 100 fm/c) [Bow93, Gla94].
- Statistical model calculations reproduce the large measured fragment multiplicities only if one assumes that fragment formation occurs primarily at low nuclear density (a necessary condition for a liquid-gas phase transition). Measured fragment multiplicities are much larger than predicted by the "quantum molecular dynamics" model, explicitly designed to treat density fluctuations [Bow91, Tsa93, Pea94]. Density fluctuations appear much larger than predicted theoretically.
- Clear experimental signatures in the energy spectra due to collective radial expansion of hot nuclei formed in central heavy ion collisions have been observed [Sou93, Hsi94], and the first evidence of non spherical breakup geometries has been found [Mon94].
- Measurements of the relative populations of widely separated states have been performed over a broad range of incident energy [Poc87, Kun91, Sch93]. These measurements indicate that fragment formation occurs at average temperatures of 4-6 MeV; this is thought to be due to cooling during expansion [Fri88], and it may be related to the liquid gas phase transition. A recent detailed investigation [Zhu92] of emission temperatures for central ^{36}Ar+^{197}Au collisions at E/A = 35 MeV implied that the assumption of thermal equilibrium may not be strictly valid.

  Another important accomplishment is:

- The first reaction mechanism study of N/Z equilibration during fragment formation was carried out with a radioactive beam [Yen94]. The N/Z ratio of the composite system was varied over 30% without changing the mass of target or beam. (Such experiments would greatly benefit from the higher-intensity radioactive beams of the K500⊗K1200 facility.)

Publications Resulting from Prior NSF Award

The list of publications, including invited talks and conference proceedings, for the 3-year period 1992-1994 and, under a separate heading, work submitted so far which will appear in 1995, is provided in a separate volume entitled "NSCL Publications List, 1992-95."

C-II: Proposed Facility Improvements

A number of facility improvement and upgrade projects are planned for the first two years in the new operating period:

- Deflector improvements to increase power dissipation and thus allow operation at higher beam intensities: Electrically-insulating, but thermally-conducting materials (e.g. beryllium oxide, aluminum nitride) are being investigated to cool the deflector shoes. In addition, liquid-cooled high-voltage feedthroughs are being studied (freon-type dielectric fluid).

- Improvements of the cyclotron beam chamber vacuum: leaks will be systematically eliminated, and O-rings of low vapor pressure material will be installed in the dee stem insulators.
- Improvements of the K1200 injection efficiency. These will provide the higher beam intensities needed for research with radioactive-beams. Changes include higher-current operation of the injection-line steering magnets by means of improved cooling and more robust power supplies.
- Development of the superconducting ECR ion source, especially the development of a metallic beam capability by installing a solid feed. An upgraded hexapole coil will be built to replace the existing coil, which limits operation to below 80 A. While this has not been a serious limitation at the present operating frequency of 6.4 GHz, it has prevented exploration of the performance of the source at frequencies above 10 GHz, where larger confinement magnetic fields are needed. The replacement hexapole will be built with coils of larger cross section to reduce the current density so that the higher currents required for the confinement fields can be obtained.
- The S800 project now under construction and scheduled for completion in 1995 will support only the more basic experimental requirements, and we propose to enhance the system capabilities through the incremental addition of experimental hardware. Among these additions will be a large, general purpose scattering chamber fitted with a sliding seal to allow the spectrometer angular position to be easily changed. The chamber will be sized to allow the installation of various coincidence arrays, e.g. the MSU Miniball. To more fully utilize the large S800 solid angle, a multi-hit focal plane detector is also planned.

The K500⊗K1200 facility upgrade project will require an 18-month shutdown of operations (presently envisaged to start in early 1998). The NSCL plans to delay a number of repairs and improvements of the K1200 cyclotron until this shutdown to minimize interference with user operations. Projects targeted for implementation during the shutdown are:

- Repair of vacuum leak in the nitrogen circuit of one of three cryopanels. This leak has been present since the beginning of K1200 operations.
- Additional deflector improvements for high-power operation: The ability of the deflectors to handle high power will be improved beyond that which will be implemented during the operating period preceding the 18-month shutdown.

C-III: Proposed Nuclear Structure and Astrophysics Research

The material in this section comes under the general headings of nuclear structure and astrophysics. Since much of the proposed astrophysics research is directly related to nuclear structure, it is often not possible to separate the two subjects. This section presents basic nuclear structure questions first, moves on to nuclear structure related to astrophysics, and ends with pure astrophysical questions.

The S800 spectrograph will become operational during the first year of the grant period covered in the proposal. The superior capabilities of this device, particularly when coupled to secondary beams from the A1200, will not only open new opportunities for experiments, but it will also allow more detailed and thorough investigation of subjects already being studied at the NSCL.

Giant Resonances

The study of the nuclear multipole response is essential for the understanding of nuclear structure. A great deal of progress has been made in this field over the last 15 years [Spe91]. It has been found that for a number of low-L multipole modes, a substantial fraction of the available (i.e. sum rule) strength is concentrated in a small part of the excitation spectrum; in this event a “giant resonance” is said to exist for the mode in question. Still, a number of interesting questions remain to be answered.

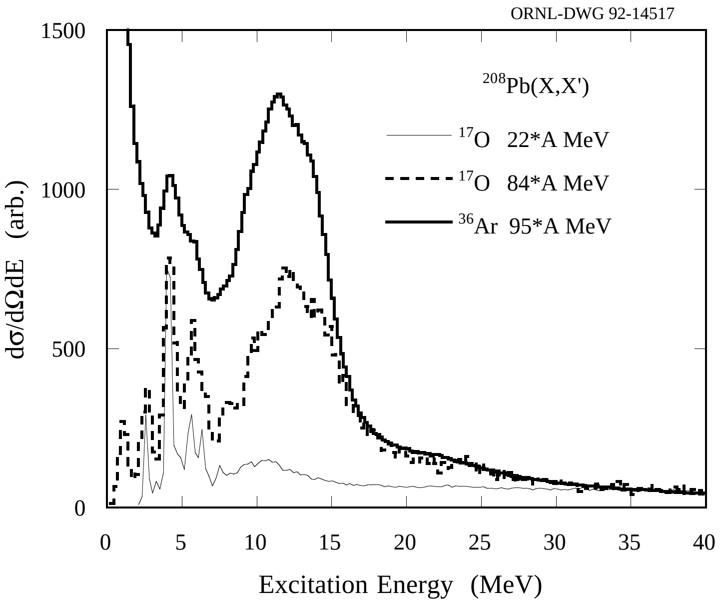

Fig. C-2: Excitation energy spectrum following the inelastic scattering of ^{17}O at 22 MeV/nucleon and 84 MeV/nucleon and of ^{36}Ar at 95 MeV/nucleon [Bee94].

The electric (ΔS=0) giant resonances can be studied particularly effectively using heavy-ion inelastic scattering because of the very large Coulomb excitation cross sections for these modes for beams of large Z at bombarding energies above ~50 MeV/nucleon. Intermediate-energy heavy-ion scattering probes both isoscalar and isovector strength because of the dominant role played by Coulomb excitation (in contrast to light hadrons or heavy ions at lower bombarding energy). The large cross sections and very large peak-to-continuum ratios provided by heavy-ion excitation are also of benefit for coincidence studies of the decay of giant resonances [Bar88, Bee89, Bee90, Suo90, Bee92] as shown in Fig. C-2. Specific decay modes can be used as filters for particular sorts of resonance strength, or as tools for determining quantum numbers associated with the excitation mode. A detailed analysis of the decay process can, in principle, reveal new information about microscopic aspects of the resonances. Resonance decay is also interesting as it provides a test, under well-understood conditions, of the multistep theories that underlie our current understanding of pre-equilibrium decay processes.

Giant Resonance Studies in Exotic Nuclei

The availability of a wide variety of exotic beams at high energy (> 80 MeV/nucleon) and high intensity, offers the exciting prospect of exploring the evolution of the characteristics of the isovector GDR in nuclear systems with very different neutron to proton ratios from those that have been investigated to date. The evolution of isovector collective modes under conditions of extreme neutron excess is a completely unexplored subject [MSU94].

For example, the halo structure in very neutron rich nuclei [Han87] could result in a completely different response of the nucleus to dipole resonance. Several experiments have been performed to search for the so called 'soft' dipole radiation [Iek93, Sac93, Shi93] which would correspond to a vibration of the halo neutrons with respect to the core. However, it is questionable whether the strong enhancement at low excitation energies observed (~1 MeV) is really due to the 'soft dipole' [Han93]. Thus it is important to measure the strength distribution for the giant dipole resonance over the entire excitation energy range. Such measurements are feasible because of the very large differential cross sections for Coulomb excitation of the GDR in ~100 MeV/nucleon scattering of the exotic beams from high Z targets (e.g. Pb). The projectile GDR-excitation cross sections scale as Z^2 of the target and also increase rapidly with bombarding energy. Experimental cross sections in this energy range are dominated by E1 excitation. The Coulomb excitation process can be treated as equivalent to a photo-absorption experiment. The effect of the rapidly changing electric field of the Pb target nuclei seen by the projectile ions can be described precisely in terms of a virtual photon field [Jac75]. The impact parameter of the target-projectile encounter can be deduced from the measured scattering angle. With this information the (essentially exponential) shape of the virtual photon spectrum can be calculated very accurately. If the products of the decay of the excited projectile are all detected, the excitation energy can be reconstructed, and consequently the GDR strength distribution can be determined. Virtual photon absorption has been used recently in the observation of the double giant resonance at GSI [Sch93, Wad94].

In another technique, a single γ–ray can be detected in the final state; the γ–ray energy accounts for all the excitation energy transferred to the projectile. The experiment can then be thought of as virtual photon elastic scattering, and can be analyzed using tools developed for analysis of elastic photon scattering data. Again, this method has been used to observe the double giant dipole resonance [Rit93]. The photon-scattering experiments require the detection of scattered particles with the S800 and the coincident detection of photons by means of a large forward-wall array of BaF_2 crystals. An array of 145 hexagonal BaF_2 crystals can be assembled from crystals belonging to ORNL, MSU and TAMU. The NSCL and ORNL are proposing a significant upgrade of the array.

Only the light secondary beams produced by the current NSCL facility have sufficient intensity and energy to be used for this sort of experiment. We are currently preparing an experiment (scheduled for spring 95) to measure the E1 strength function of ^{11}Be using virtual photon elastic scattering. Fig. C-3 shows the coincidence event rate predicted for the current array, which exhibits the structure of the GDR strength function.

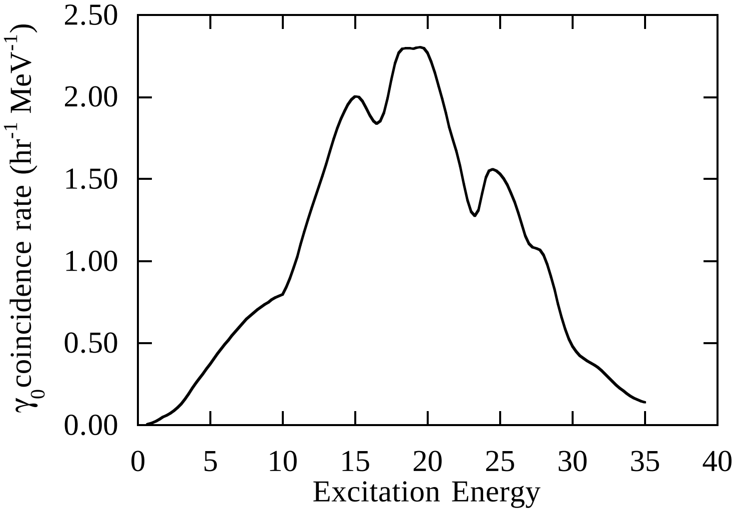

Fig. C-3: Predicted ground-state γ-decay coincidence event rate for the E1 inelastic excitation of ^{11}Be.

It is, however, the projected performance of the upgraded K500⊗K1200 facility which makes such studies extremely attractive. The proposed increase of the BaF_2 array will double the solid angle coverage for the γ-ray detection and thus will increase the range of nuclei that can be studied considerably. We hope to be able to explore the evolution of GDR strength over unprecedented ranges of isospin. For example we should be able to study Ar isotopes from mass 36 to 48 (T_z=0 to 6), Zn isotopes from mass 62 to 76, or Zr isotopes from mass 82 to 100.

Giant Resonances of Stable Nuclei

Theoretical calculations invariably predict that compact concentrations of $\Delta T=1$, $\Delta S=0$ quadrupole strength should exist in most nuclei. However, reliable, systematic data on the parameters of the strength distribution for the isovector giant quadrupole resonance (IVGQR) are notably missing from the existing body of data [Spe91]. Evidence for an IVGQR has been reported from (e,e´) experiments on medium mass and heavy nuclei. These data are subject to substantial systematic uncertainty due to very large underlying backgrounds and possible contributions from a variety of other modes not differentiated by the experiments. A few, more specific and sensitive experiments involving (n,γ) and (γ,n) reactions are available, along with one example of (HI,HI´γ). These latter experiments seem to confirm the basic results of the (e,e´) analyses, but carry little detailed information about the distribution of $\Delta T=1$, E2 strength [Spe91]. On the other hand, studies employing the ($\pi^{\pm}$,π^0) reaction, which should excite isovector states strongly, show no evidence of IVGQR strength at all.

Systematic analysis of resonance and continuum excitation by intermediate-energy heavy ions [MSU94], indicates that heavy-ion scattering in the bombarding energy range from 100 to 150 MeV/nucleon should be an excellent tool for studying the IVGQR. The IVGQR cross sections are large, and therefore experiments can be done in reasonable times even for low beam intensities. Heavy-ion scattering excites the IVGQR almost exclusively by Coulomb excitation. Coulomb excitation cross sections for high-lying strength decrease rapidly with increasing multipolarity, providing a powerful filter against the broad structures with L>2 which probably occupy the same energy region as the IVGQR. Since the cross section for target Coulomb excitation scales as Z^2 of the projectile, comparison of spectra obtained with two probes of significantly different Z can be used to isolate Coulomb-excited strength. These considerations imply that data acquired with two probes of different Z at two bombarding energies, e.g. 100 MeV/nucleon and 150 MeV/nucleon, should provide enough information to unequivocally identify the IVGQR, and to reveal details of the strength distribution. The only ambiguity in these data will be between IVGQR and IVGDR strength. This ambiguity could be resolved by ground-state γ-decay branching measurements [Bee89, Bee90]. With the S800 and the upgraded ORNL-MSU-TAMU BaF_2 array we will be able to undertake detailed γ-decay studies of the IVGQR.

Projectile Excitation Studies with Stable Beams

Initial experiments with stable beams are necessary, in order to explore the feasibility of studying the strength distribution of the giant dipole resonance in radioactive species produced as secondary beams by projectile excitations. There are a number of interesting phenomena related to giant resonances which can be investigated by projectile excitation and decay involving stable projectiles. The necessary experiments involve projectiles of mass $A \leq 60$, for which the charged-particle decay-branches are of significant magnitude. In such experiments, the projectile with energy ~100 MeV/nucleon is excited in an appropriate target (usually ^{208}Pb). The inelastic projectile excitation events are identified by determining the A and Z of the projectile residue (with the S800 spectrometer) and of all the other decay particles (with an appropriate light-particle detection array). Since we are primarily interested in regions of comparatively low primary excitation energy ($E^* <$ 40 MeV) in the projectile, the light particles emitted from the decaying projectile have comparatively low energies in the projectile rest frame, and are consequently very forward peaked in the laboratory. The excitation energy distribution in the projectile is reconstructed from the momenta of all the decay products. In order to study giant resonance structures with widths on the order of 1 MeV, the proposed high-resolution silicon array with good angular resolution is required.

Such a projectile charged-particle decay setup can be used for several experiments of interest to giant resonance research. The simplest experiments involve the reconstruction of GDR strength in rare but stable isotopes, which cannot be studied by traditional photonuclear techniques.

Cross sections for excitation of the projectile GDR in scattering on Pb can be very large; values in excess of 10 b/sr can easily be achieved for E>100 MeV/nucleon. The p and α decay branching ratios are sometimes interesting in themselves. The GDR in light (A<60) systems is split into $T_<$ and $T_>$ components ($T_<=T_0$, where T_0 is the isospin of the ground state, and $T_>=T_0+1$). The relative p and α decay branching ratios can be used to attempt an experimental isospin decomposition of the GDR.

Scarpaci et al. [Sca93, Fra94] have recently suggested that proton decay of an excited nucleus (A,Z) directly to the isoscalar GQR in the neighboring (A-1,Z-1) nucleus can be used as a signature for identifying the two phonon GQR. It should be possible to apply this idea very efficiently in the inverse (i.e. projectile excitation) reaction. Simple coupled channels calculations suggest that the two phonon GQR excitation cross sections in the ^{208}Pb(^{64}Zn,^{64}Zn*) or ^{208}Pb(^{60}Ni,^{60}Ni*) reactions at 80-100 MeV/nucleon should be an order of magnitude larger than in the reaction employed by Scarpaci et al. It should be noted that the predicted magnitude of these cross sections is, in our calculations, very small; too small to be consistent with the data. It would be of great interest, therefore, to use the S800 spectrograph to carefully investigate the decay of several nuclei in the mass range 40 to 64, excited to the excitation energy range from ~15 to 40 MeV by inelastic scattering on Pb.

Two-Phonon GDR Strength

Recently the first data on the Coulomb excitation of the two phonon GDR (DGDR) has become available [Sch93, Rit93, Wad94]. The techniques for studying the DGDR by Coulomb excitation in intermediate energy heavy-ion reactions can be employed here at the NSCL. These techniques are based on the detection of photons emitted in the deexcitation of one of the GDR phonons, in coincidence with inelastically scattered projectile ions detected and identified in a magnetic spectrometer [Bee94] and the first results, for ^{208}Pb and ^{209}Bi, are shown in Fig. C-4.

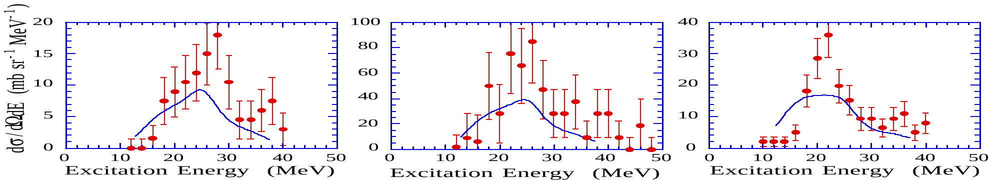

Fig. C-4: Experimental (points) and theoretical (curves) cross sections for DGDR excitation in target nuclei for, from left to right, 95 MeV/nucleon ^{36}Ar on ^{208}Pb, 80 MeV/nucleon ^{64}Zn on ^{209}Bi and 60 MeV/nucleon ^{86}Kr on ^{208}Pb. All data are from particle-γ coincidence measurements. The ^{64}Zn data (center) are preliminary.

It would be very interesting to build up a systematic set of data on strengths, widths and positions of DGDR states in a variety of nuclei. One could obtain new insight from such data on anharmonicities of GDR phonons, and on the nature and excitation-energy dependence of resonance damping. The cross section from Coulomb excitation of the DGDR in a target nucleus scales as Z^4 of the projectile, and increases rapidly with energy up to ~200 MeV/nucleon, and more slowly thereafter. The availability of high-intensity beams with $Z > 10$ at energies near 200 MeV/nucleon, would make such systematic studies of the DGDR feasible by particle-γ-ray coincidence techniques (using the S800 for particle detection, and the BaF_2-array for γ-ray detection).

Giant Dipole Resonance in Hot Nuclei

The γ-ray decay of the giant dipole resonance (GDR) built on highly excited states has yielded significant information about the shape evolution of hot nuclei [Sno86, Gaa92]. In addition, the inherent width of the GDR as a function of excitation energy and angular momentum is still controversial and has been studied intensively with fusion-evaporation reactions [Cha87, Bra89, Kas94]. Based on the initial observation of the GDR built on highly excited states with inelastic ^{17}O scattering [Tho91], we have started a program to study the excitation energy dependence of the GDR width at low (and almost constant) angular momentum. This was achieved with coincidence experiments of inelastically scattered α-particles and high energy γ-rays.

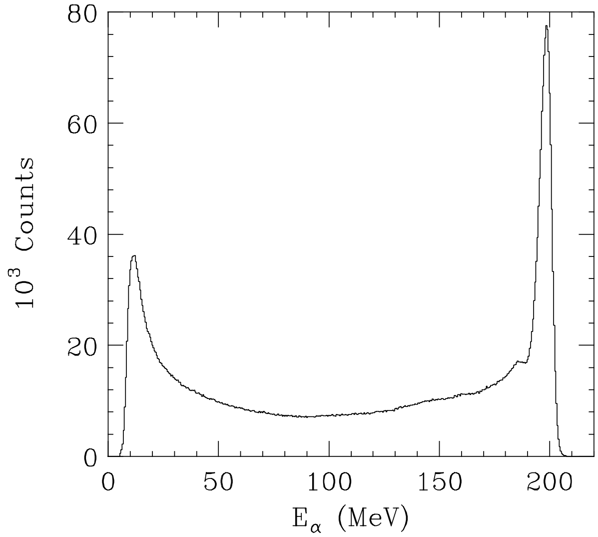

Fig. C-5: An α singles spectrum following the reaction $^{120}Sn(\alpha,\alpha')$ at 200 MeV. [Tho94]

In small angle inelastic scattering only low angular momentum states are populated, and the effects of excitation energy and angular momentum can be disentangled from each other. Thus, this method is an important complementary tool to the fusion evaporation reactions to measure the excitation energy dependence of the GDR width. In addition, by selecting excitation energy ranges from the inelastic spectrum, the whole excitation function can be measured in one experiment. During the last few years we have performed several experiments with 40 MeV/u and 50 MeV/u α beams on targets of ^{120}Sn and ^{208}Pb. The α-particles were detected with the Washington University Dwarf Ball/Wall CsI array, and the γ-rays were measured in 5 arrays of 19 BaF_2 detectors each. A singles spectrum following the reaction $^{120}Sn(\alpha,\alpha')$ at 200 MeV is shown in Fig. C-5.

In addition to the elastic scattering peak and the inelastic continuum, the spectrum shows an increase at lower α energies which is due to pre-equilibrium emission of α-particles. Because it is questionable whether these events correspond to target excitations, we had to limit our analysis to energies above this increase. However, for higher α energies we were able to demonstrate that the continuum does indeed correspond to excitation of the target [Tho94].

Figure C-6 shows the γ-ray spectrum gated on α energies of 110-120 MeV, which corresponds to 80-90 MeV excitation energies. The solid lines are results of a CASCADE calculation with the excitation energy distribution of the initial population given by the α-particle spectrum and the angular momentum distribution derived from the linear momentum transfer (~10-20$\hbar$). The dotted curve represents the Bremsstrahlung contribution which is interesting in itself, and this aspect of the data is currently being analyzed. The extracted widths for ^{120}Sn and ^{208}Pb as a function of temperature are presented in Fig. C-7. The temperature dependence of the GDR width is still uncertain. Theoretical predictions vary from a $T^{1/2}$ to a T^2 dependence [Alh90, Bro92, Cho94]. Our data are consistent with a quadratic dependence with temperature (linear with excitation energy) as depicted by the solid lines. However, this strong increase could be predominantly due to the rapid softening of the free energy surfaces in these magic nuclei which are very rigid in their ground states. A good probe to distinguish between the models would be a nucleus that is deformed in its ground state with a soft potential energy surface. We intend to study this issue in the near future.

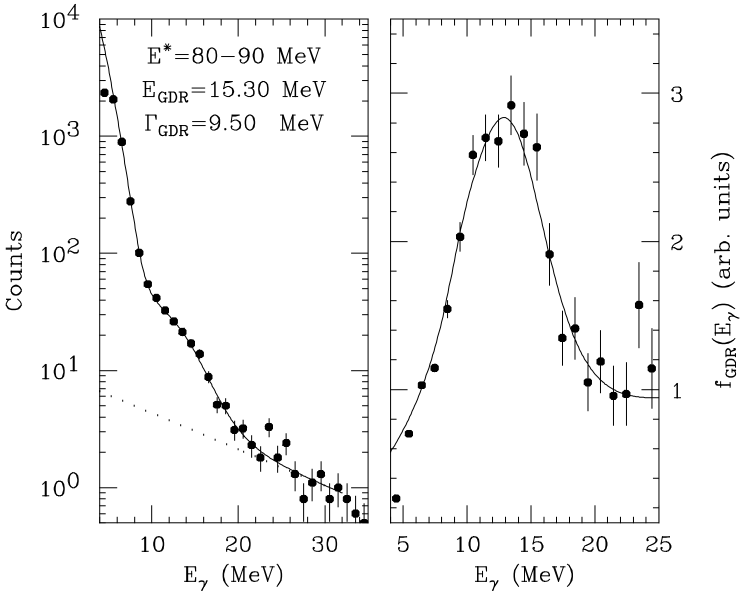

Fig. C-6: Coincidence γ-ray spectrum for α energies of 110-120 MeV on ^{120}Sn. The solid lines are a result of a CASCADE calculation with the GDR parameters given in the figure. The dotted line corresponds to Bremsstrahlung contribution. The right side shows the spectrum, after background subtraction, on a linearized scale.

The use of α–particles is limited to relatively low excitation energies, because the emission of pre-equilibrium α-particles begins to dominate the spectra at higher excitation energies. We plan to use a projectile with a low neutron binding energy (^{17}O for example) to minimize contamination of the spectra from projectile excitations. However, it is necessary to identify the ejectile isotopically, which makes the use of the S800 spectrograph essential. The loss of solid angle compared to the Dwarf Ball/Wall is partially compensated by the larger cross section at smaller angles. However, in order to study up to the higher excitation energies it will be necessary to increase the solid angle coverage of the γ-ray detection system. The upgraded ORNL-TAMU-MSU BaF_2 array will lead to a much improved ability to carry out these and related projects.

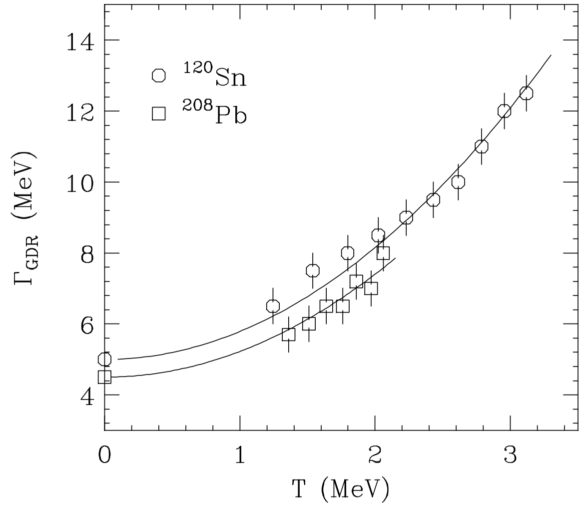

Fig. C-7: GDR width as a function of temperature for ^{120}Sn and ^{208}Pb. The solid lines are fits to the data with a quadratic temperature dependence.

Direct Reactions and Scattering with Radioactive Beams

Heavy-ion beams are being used extensively to produce nuclei far from stability in fragmentation reactions [Dét89]. A fragment separator like the A1200 allows the identification and separation of fragmentation products [She91] and provides beams above E/A ≥ 10 MeV very effectively. One of the primary new directions in nuclear spectroscopy is the study of the structure of nuclei very far from the valley of β-stability. Experimental methods to determine the masses and life times of these nuclei have been established. Essential to our understanding of the structure of nuclei is the existence and location of particle-bound states. Data on bound excited states form the basis of many microscopic and macroscopic nuclear models.

The observation of photons emitted from discrete transitions between states is one experimental signature that establishes the existence and location of particle bound states. In the particular case of radioactive heavy ion beams, this method can be realized by scattering a radioactive particle beam inelastically from a heavy target and observing the photons emitted from the projectile. Once particle bound states have been identified, particular states can then be further studied by inelastically scattering of light particles in inverse kinematics to establish spins and transition strengths, or one can use transfer reactions to populate particular states of interest.

The NSCL program to study bound excited states of exotic nuclei will employ the techniques of relativistic Coulomb excitation and inelastic scattering in inverse kinematics. The program will rely on radioactive beams provided by the K1200/A1200, a photon detector array, a high-resolution silicon detector array for the detection of protons and other light particles, and the S800 spectrograph. In the beginning, light nuclei ($Z \leq 20$) will be studied, and after the proposed K500⊗K1200 upgrade, the program will be expanded to heavier nuclei far from stability.

Relativistic Coulomb Excitation

For many years Coulomb excitation has been used for studies of low lying states in stable nuclei. In these experiments, the incident beam energy was chosen to be below the Coulomb barrier to avoid complications introduced by nuclear excitations. Stable enriched targets are bombarded with a heavy beam, and low lying states in the target are excited through exchange of a virtual photon. When the nucleus de-excites, a real photon is emitted and detected in a high resolution photon detector. An alternative way to measure the same quantities is to have the beam of the nucleus of interest impinge on and be stopped in a heavy target. In this case the emitted photon will be Doppler shifted and broadened; however at sub-Coulomb energies these effects are small.

Fabrication of targets of nuclei far from the valley of β-stability is not possible because of short lifetimes. Instead, one can use projectile fragmentation to produce beams with energies of several tens of MeV/nucleon and bombard a heavy target. In this case the projectile is excited in the Coulomb and nuclear fields of the target nucleus and de-excites from a bound state by emission of a discrete photon, thus establishing the existence and energy of the state. The feasibility of such measurements has recently been shown at GANIL [Cor94] by a group studying the excitation of ^{11,12,14}Be and ^{8}He (an excited bound state was found for ^{11}Be). It has also been found that in the energy region of several tens of MeV/nucleon the Coulomb excitation cross section can be much larger than the nuclear excitation cross section for small scattering angles [Bar88]. In cases for which the nuclear excitation cross section is negligible, it is possible to measure not only the excitation energy of a state but also the absolute cross section, which then determines the transition matrix elements. For example, the 2^+ state of the neutron-rich nucleus ^{32}Mg has been studied at RIKEN using a beam of ^{32}Mg at 50 MeV/nucleon and a ^{208}Pb target [Mot94]. In this case, a B(E2) value could be extracted since the nuclear contribution to the total cross section was small compared to the Coulomb cross section for $\theta < 4^\circ$.

The excitation energies of the first excited 2^+ and 4^+ states of even-even nuclei are important for any nuclear model and contain a great deal of basic nuclear structure information. For example, for stable nuclei a very simple scaling relation has been observed between the energies $E(2^+)$ and $E(4^+)$ [Cas93, Cas93a] for all even-even nuclei from $A \approx 80$-200. It is not clear that these correlations will hold for exotic nuclei since recent theoretical calculations indicate that when approaching the neutron drip line, the nuclear shell structure as it is presently conceived will have to be altered and magic numbers will change [Dob94]. Indeed, a sudden onset of deformation has already been observed for neutron rich $N=20$ nuclei. The semi closed-shell nucleus ^{32}Mg appears to be deformed with the energy of its 2^+_1 state below 1.0 MeV. In contrast, the nucleus ^{34}Si, only 2 protons away, looks like a doubly magic nucleus with its 2^+_1 state at 3.3 MeV [Bau89].

While the evolution of deformation and the study of the residual pn interaction is interesting from a nuclear structure point of view, the properties of certain heavier nuclei (A≈100) are relevant to the understanding of the r-process [Kra92]. A key component to the calculated abundance produced in the r-process is the deformation of the nuclei involved. The systematic of the 2^+ and 4^+ energies can be used to test the models used in these calculations.

The higher beam velocity compared to sub-barrier Coulomb excitation experiments (a typical velocity is β=0.3c) results in a larger Doppler shift and more Doppler broadening of the photo peak than that produced in sub-barrier experiments. Therefore the photon detection system requires high granularity to limit the Doppler broadening. Other considerations are the photo peak efficiency and angular coverage of the detector system. One of the only two experiments of this kind performed used three Germanium detectors [Cor94] while the other one employed an array of sixty NaI(Tl) scintillator detectors as photon detectors [Mot94]. We are currently evaluating different options for a photon detector array that will be set up in a low background environment. In a typical experiment an exotic beam with an intensity of 10^4 particles / sec and high isotopic purity will be produced in the A1200 and identified (event-by-event) by its time-of-flight from the A1200 to the experimental setup, where the beam will interact in a heavy target and be stopped in a total energy detector to discriminate against secondary reactions. The photons from the de-excitation of the projectile will be detected in an array of photon detectors. They can be clearly distinguished from photons coming from the target by their Doppler shifts and Doppler broadening.

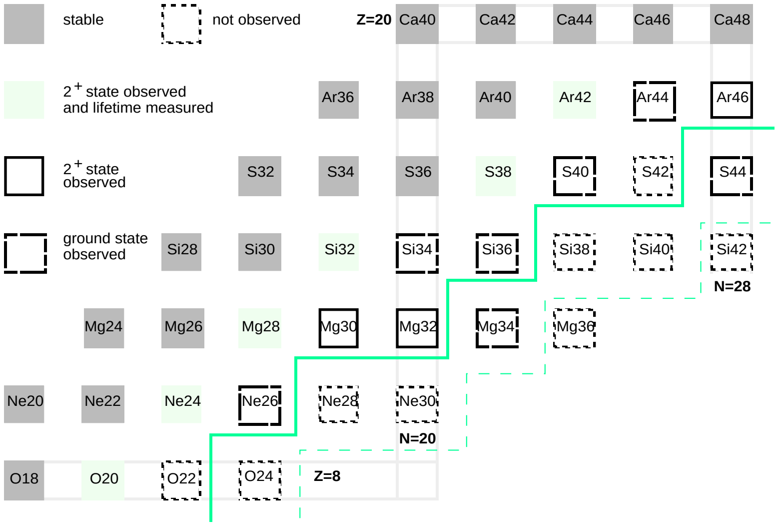

Fig. C-8: Neutron-rich even-even nuclei in the 2s-1d-1f shells. Open squares indicate that the 2^+ state has not been observed or that a transition matrix element has not been determined. The solid and dashed lines correspond to secondary beam intensities of more than 3000 particles / second for the current K1200 / A1200 and the proposed K500⊗K1200 / A1900, respectively.

As a concrete example one can study neutron-rich, beta-unstable, even-even nuclei in the 2s-1d-1f neutron shells as indicated in Fig. C-8. Seven nuclei in this region are accessible with the K1200 / A1200 at rates of more than 3000 particles / second and no excited state information is available. In three more cases the 2^+ state has been observed, but transition matrix elements have not been determined. The method of relativistic Coulomb excitation can be applied to any exotic nucleus that can be produced at a rate roughly 3000 particles / second or more – one of the recent experiments ran with a rate ten times lower [Mot94].

Direct Reactions in Inverse Kinematics

The structure of individual states has long been investigated by inelastic particle scattering. Radioactive beams produced in projectile fragmentation reactions in the A1200 with energies in the range of 30-100 MeV / A are ideally suited for these studies in inverse kinematics. For example, a (p,p') experiment in normal kinematics at E=30 MeV is equivalent to an ^{1}H(RIB,p') experiment in inverse kinematics at E / A=30 MeV. The reaction ^{1}H(^{34}Si,p') can be performed using a radioactive beam of ^{34}Si on a hydrogen target. The NSCL solid hydrogen target will be adapted for reduced thickness and used in such experiments. The recoiling protons will be detected with good angular and energy resolution in a telescope consisting of a Si-strip detector backed by a CsI crystal. In general the recoiling particles are emitted at angles close to $\theta=90^\circ$ in the laboratory frame; for the above reaction at an energy of E / A=30 MeV, a range of 25°-65° in the center of mass corresponds to 55°-70° in the laboratory. Therefore it is possible to cover a relatively large center-of-mass angular range with few detectors. While it is not necessary to detect the heavy partner, in this case ^{34}Si, it can be easily collected at forward angles in the S800 spectrometer. This reduces background and improves the resolution. In a first experiment of this kind performed at GSI, a ^{56}Ni beam (~10^4 particles / second) with 101 MeV / nucleon energy was scattered from a plastic target, and protons were detected at 79° in the laboratory in a ring of 19 silicon detectors [Kra94].

From the recoil cross sections one can deduce a transition matrix element by comparing the measured cross sections to DWBA calculations. While optical model parameters from reactions already measured in normal kinematics with stable targets can be used for studies close to the valley of stability, no optical model parameters are available far from stability. For each new region under investigation, one or two measurements of differential cross sections for elastically scattered particles will be carried out with the S800. This will permit the determination of the required optical model parameters for regions of N / Z far from stability.

Additional insight into the evolution of shell strength can be gained when one combines results from relativistic Coulomb excitation measurements and (p,p') scattering experiments for a particular state. When the first excited $J^\pi=2^+$ state (2_1^+) of an even-even nucleus is discussed as a collective quadrupole excitation, it is usually assumed to be isoscalar. However, it has been demonstrated that differences can occur between the amplitudes of the motions of protons and neutrons in 2_1^+ states (for a brief review, see [Ber83]). Such differences can be measured in a particular nucleus by comparing the matrix elements connecting the 2_1^+ state to the ground state determined by two different experimental probes. The comparison of a low energy (10-50 MeV) (p,p') result for an electromagnetic matrix element was found to be particularly sensitive to differences in the amplitudes of proton and neutron motion for stable nuclei [Mad75]. Differences in the proton and neutron motion are generally discussed in terms of the multipole matrix elements M_n and M_p for neutrons and protons, respectively. In a collective isoscalar state the ratio M_p/M_n is identical to Z/N. It has been found for stable nuclei that M_p/M_n deviates from this value for the 2_1^+ states of a number of nuclei, in particular those with a single closed shell . These deviations will be especially interesting to study when one approaches the neutron drip line where the addition of more nucleons leads to the occupation of new orbitals.

Halo Nuclei

Parallel Momentum Distributions

Nuclei with low binding energies can exhibit features that are unique in nuclear structure. For example, halos are due to quantum mechanical tunneling of the valence nucleons. For ^{11}Li, the two valence neutrons will be found outside the ^{9}Li core with a probability of more than 70%. This is a qualitatively new kind of nucleus with a large spatial separation between proton and neutron distributions. The density of the halo neutrons is very low, and this provides the opportunity to study the interactions of nucleons in low density nuclear matter. Two-body halos may also represent a special quantum three-body system in which all subpairs are unbound. Thus predictions of quantum three-body models can be tested, and searches for effects such as “super halos” or Efimov states can be made [Fed93]. Efimov states are threshold states which may exist in three-body systems under special conditions and are predicted to have rms radii of hundreds of Fermis.

The existence of a halo structure in nuclei like ^{11}Li and ^{11}Be is well established. The parallel momentum distribution method was developed at the NSCL to make a quantitative measurement of the momentum distribution of the core fragment after breakup of the halo nucleus [Orr92]. This technique for momentum wave function mapping is analogous to the well known (e,2e) reaction technique used in atomic physics [McC88] and to the (p,2p) technique in nuclear physics. In the atomic physics case, the core recoil momentum is reconstructed from the measured outgoing electrons, whereas in the case of the breakup of halo nuclei, the core momentum is large enough that it can be measured directly. Measurement of parallel momentum is less sensitive to diffractive and Coulomb effects than is measurement of transverse momentum [Ber93, Bar93]. The usefulness and accuracy of this technique was demonstrated in the case of ^{11}Be [Kel95a]. There it was shown that the FWHM of the measured momentum distribution can be related to the rms radius of the halo nucleons. The parallel momentum distributions were measured in the A1200 in the dispersion matched spectrograph mode. In this mode, the whole device is achromatic, and the secondary reaction target is placed at an intermediate image. In this way a momentum resolution of 5 MeV/c can be obtained even though the secondary beam has a spread of 100 MeV/c or more. Figure C-9 shows the measured momentum distribution transformed into the ^{11}Be rest frame and corrected for the finite acceptance of the A1200. The figure also shows a calculated momentum wave function for the $2s_{1/2}$ state of ^{11}Be and for a core $p_{3/2}$ neutron. The mean-field calculations were done with separation energies fixed to the experimental values. As expected, the data are consistent with the known s-wave nature of the ^{11}Be ground state.

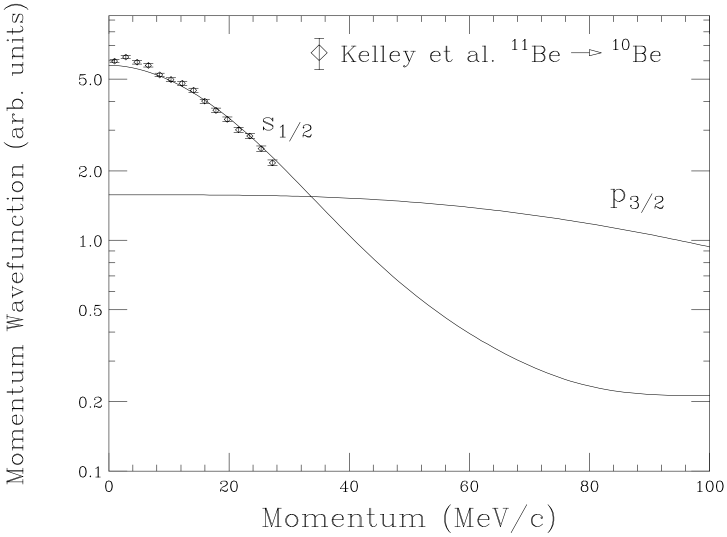

Fig. C-9: Plot of the momentum wave functions for $2s_{1/2}$ and $1p_{3/2}$ neutrons in ^{11}Be calculated in a mean-field model (solid line). The data [Kel95a] illustrate the use of the parallel momentum distributions of core fragments for testing halo wave functions.

One of the severe limitations of the present parallel momentum distribution experiments is the limited angular acceptance of the A1200, which does not allow integration over the full transverse distribution. This introduces a model dependence in the results as the measured parallel momenta (particularly the wings of the momentum distributions that sample the core parts of the halo wave functions) are modified by this acceptance. When the S800 is completed, its solid angle will be sufficient to collect all the breakup products, and this limitation will be removed. It will also allow the full momentum (transverse and parallel) to be measured for the first time with high resolution using dispersion matching of the secondary beam in the S800 analysis line.

The A1200 has been used to measure the parallel momentum distributions of the core in ^{6}He, ^{8}He, ^{11}Be, ^{11}Li, ^{14}Be, and most recently ^{19}C [Baz95]. The results show that ^{19}C is a one-neutron halo nucleus with an rms valence radius of about 5 fm, compared to the 2.5 fm rms radius of the ^{18}C core. In the same experiment distributions for the breakup of ^{18}C and ^{17}C were also measured. Figure C-10 shows the measured core momenta for these cases. In the cases of ^{18}C and ^{17}C the halo effects appear small, although the distributions may be somewhat narrower than found in more stable nuclei. The small width of the ^{19}C momentum distribution is clearly consistent with a strong s-wave component in the wave function. In almost every halo case studied so far there seems to be a significant s-wave contribution to the halo, and in fact it has been argued that this should be a general feature of halo nuclei. The stability of a nucleus is increased if the kinetic energy associated with a nucleon is reduced. This is possible for tunneling wave functions in halo nuclei, and therefore there is some additional stability associated with s-wave states, for which the halo effects can be the largest.

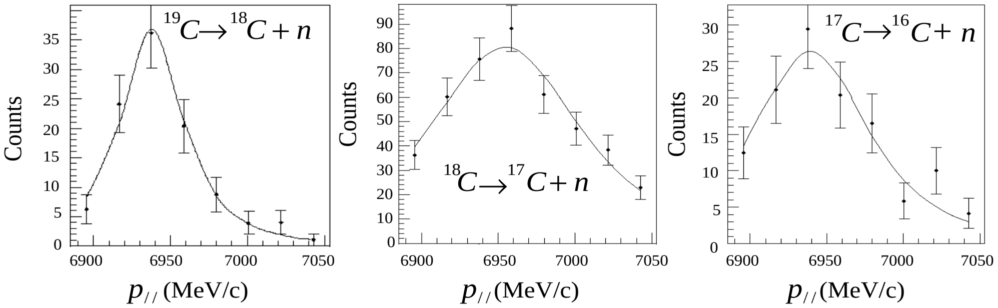

Fig. C-10: The parallel momentum distribution of C fragments from the breakup of ^{17,18,19}C.

A significant open question is the extent to which the parallel momentum measurements can sample the parts of the halo wave functions which reside in the core. Although in the case of ^{11}Li this is not a large part of the wave function, nevertheless it would contain the high momentum components of the wave function. One way to test this question is to perform high resolution experiments with a variety of target masses. Lighter targets should allow deeper penetration into the halo components. It is critical in these studies to be able to measure the high momentum components of the distributions since these are most sensitive to the central part of the wave function. One could also study the energy dependence of the distributions. At higher energy the nucleon-nucleon cross section has dropped, and the reaction should be more sensitive to smaller radius components. The S800 spectrograph will be essential for these measurements.

Core Invariance

Three-body models with two neutrons and an inert ^{9}Li core have been the most successful in describing the halo features of ^{11}Li. An important question for these models, and for the nature of the halo nuclei themselves, is the degree to which the core remains inert. Several methods can provide information about the core in halo nuclei. Three experiments have provided evidence that the core in not significantly modified. First, the charge changing cross sections for ^{11}Li and ^{9}Li are similar [Bla92a]. Second, the total reaction cross section seems to factor into a ^{9}Li reaction cross section and a two-neutron removal cross section. Finally, the quadrupole moments of ^{9}Li and ^{11}Li are almost identical [Arn92]. However these experiments do not provide detailed information on the core. Further, other halo nuclei have not been fully investigated.

We propose to use two new techniques to investigate the degree of core excitation in halo nuclei. First, if the core has significant excited state components in its wave function in the halo ground state, then in the sudden approximation for halo breakup, it should be possible to measure the core de-excitation via gamma decay. For the case of ^{11}Li breakup, one could look for the de-excitation of ^{9}Li 1/2- state at 2.6 MeV to the ground state. A similar experiment could be carried out for other halo cases, such as ^{11}Be. These experiments would use the S800 and coincident gamma-ray detectors at the target position. The use of light mass targets would reduce the γ-decay background, and the Doppler effect can be used to confirm that the γ-decay comes from the ^{9}Li in-flight.

Another, perhaps more quantitative approach, would be to use proton knockout reactions from the core to probe the core configuration. These ^{1}H(^{11}Li,2p) type reactions would be performed in inverse kinematics at high energy. The 2p and ^{9}Li final state would be measured and the internal proton momentum distributions determined under the assumption that the final state interactions with the neutrons is small. The same reactions can be studied using a ^{9}Li beam and the results compared with ^{11}Li. The proposed high-resolution silicon array would be well suited for these studies, and the S800 will be required.

Exclusive Breakup Studies

The nucleus ^{11}Li is considered to be the archetypal halo nucleus -- a light, neutron-dripline nucleus that may be viewed as a core (^{9}Li) plus two neutrons with a large spatial extent and weak binding. Similar statements can be made about ^{8}He (^{6}He core), ^{14}Be (^{12}Be core), and ^{6}He (α-particle core). In all four nuclei the pairs -- core plus neutron and neutron plus neutron -- do not bind, but the three-body system is bound. It has been suggested that the neutrons in these nuclei form a bound dineutron [Mig73, Han87]. In the one experiment performed [Iek93, Sac93] at the NSCL, ^{11}Li was dissociated by photon absorption into ^{9}Li + n + n, and ^{9}Li and both neutrons were detected. A ^{11}Li target being unattainable, two ingenious developments were used -- the NSCL radioactive beam facility and the method of equivalent photons [Bau86, Ber88]. The projectile was ^{11}Li, and the electric field of a Pb target nucleus was the photon source. Each event was transformed back into the ^{11}Li rest frame, where various histograms were constructed.

In the so-called soft dipole model [Han87, Kob89, Ike92], ^{11}Li is excited by E1 photon absorption into an electric dipole resonance similar to the giant dipole resonance. In the soft dipole resonance the restoring force on the oscillating protons is provided by only the two halo neutrons. The deduced electric dipole strength function had a maximum at E_x at 1.0 MeV and a width $\Gamma = 0.8$ MeV. If this peak corresponds to a resonant state, its period is 1250 fm/c and its lifetime 250 fm/c, only 1/5 of an oscillation. Such a short lifetime does not support the picture of a core oscillating back and forth in the halo.

In the NSCL experiment a method to measure lifetime based on Coulomb barrier was discovered. The data in Fig. C-11 show that the ^{9}Li velocity is systematically higher than the average neutron velocity. A computer simulation of un-accelerated events was made to check for a possible instrumental bias, and the histogram in the figure was obtained. It is symmetrical and centered on zero. One possible interpretation of the velocity difference is that the lifetime of the excited ^{11}Li is so short that break-up occurs while the ^{11}Li is still high on the Coulomb hill. The ^{9}Li then receives a Coulomb acceleration, and the neutrons do not. The measured average value of V_9-V_{2n} can be used to deduce a lifetime (t), and a value of t ~60 fm/c is obtained. From the width of the "resonance" we deduced a t of 250 fm/c. This discrepancy casts doubt on the existence of a resonant state. The peak in the dipole excitation function looked like a resonance, but an excitation function must rise from zero at threshold and, because of a sum rule, eventually come down again. The Coulomb acceleration method of lifetime determination is independent of whether or not there is a soft-dipole resonance, and, of course, 60 fm/c is only 5% of the 1250 fm/c oscillation period for a soft-dipole resonance at $E_x \leq 1$ MeV. Thus the evidence points to a direct break-up of ^{11}Li rather than a soft-dipole resonance.

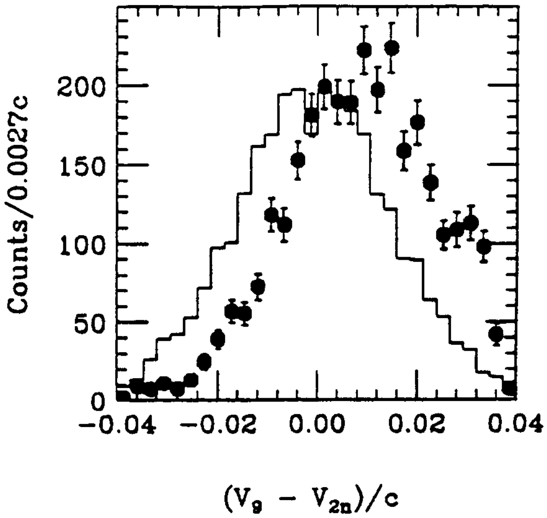

Fig. C-11: The spectrum for the velocity difference $V_9 - V_{2n}$, where V_{2n} is the average velocity of the two detected neutrons. The histogram is the result of a Monte-Carlo simulation assuming no Coulomb-acceleration effects.

In a direct transition to continuum states, the equivalent photon method is a very good way to look at the ground-state structure of ^{11}Li. There are two requirements: 1) the momentum of the absorbed photon should not significantly perturb the motion of the ^{9}Li core or of either neutron, it should be a gentle perturbation, and 2) the photon absorption process should take place so quickly that the positions of the three constituents are not significantly changed, it should be a sudden absorption. If these requirements are met, no theory is required to see the n-n ground-state correlation in the final state. A look at Fig. C-12 shows that the first requirement is met, because a typical ^{9}Li momentum is about 30 MeV/c, and a typical neutron momentum is about 18 MeV/c, whereas the peak in the strength function requires $p_\gamma \leq 1$ MeV/c. At our beam velocity, 0.25c, photon absorption occurs over a time of ~ 100 fm/c, whereas the orbital period of a halo neutron is ~ 1,000 fm/c; the second requirement is therefore satisfied. One can, therefore, expect that a dineutron in the ground state would show itself in the final state. With that expectation, one can look for evidence for a dineutron in the data.

If the Coulomb dissociation is indeed both gentle and sudden, a dineutron structure in the ground state results in a two-body breakup in the first instance. The kinematics of the breakup are reflected in the momentum spectrum of the ^{9}Li, the solid histogram of Fig. C-12a. The data are not fitted by this model, but they are fitted by the two other models shown--a three-body phase-space model and the three-body hyperspherical-harmonic direct-breakup model [Chu93]. In the hyperspherical-harmonic model the angular effects of the $l = 1$ photon absorption are included. The same three models are compared with the data on the momentum distribution of a single neutron in Fig. C-12b. Again, the three-body models agree with the data, but the dineutron model predicts a shift beyond the measured spectrum.

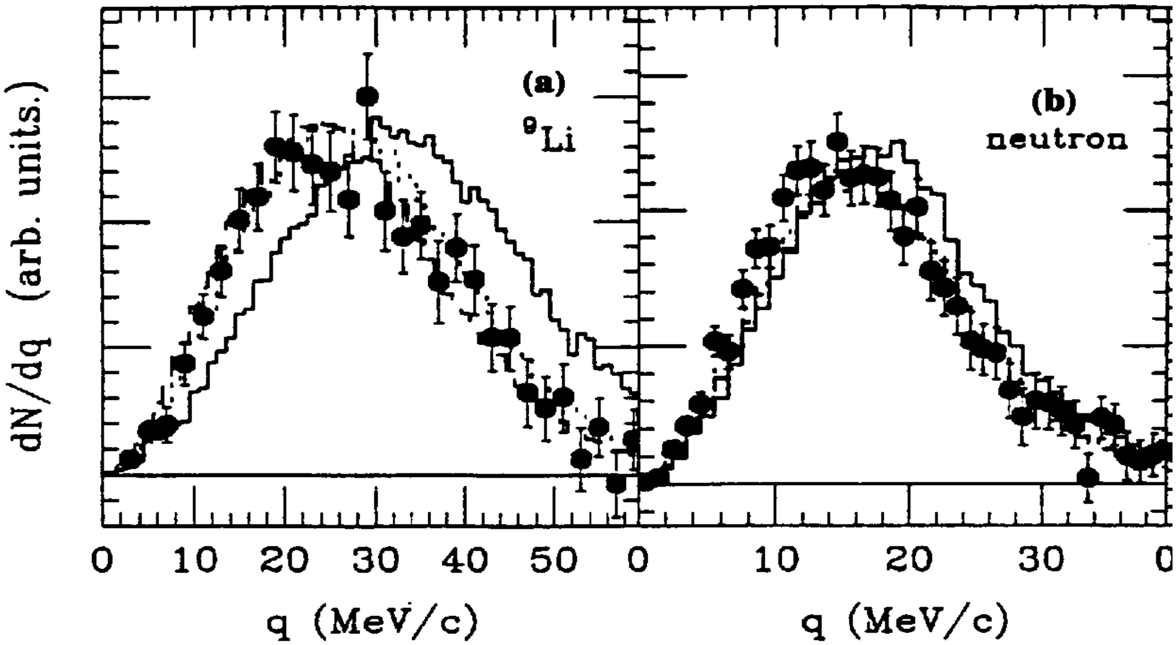

Fig. C-12: Momentum spectra of ^{9}Li fragments and of single neutrons. The points are from our experiment. The histograms are Monte-Carlo simulations of three decay models; dashed--standard 3-body phase space, dotted--3-body hyperspherical-harmonic, solid--2-body decay into ^{9}Li and a dineutron.

The dineutron model makes a prediction that the angle θ between the two neutrons is zero. The detector response smoothes the prediction but still leaves a strong peak at $\cos\theta = 1$. In Fig. C-13 that peak goes off scale beyond 2,000--more than ten times the value in the data. Again, the two other models both agree with the data.

In a two-neutron experiment the efficiency was about 0.01, and the ^{11}Li intensity was below 6 x 10^2/s (although it has improved somewhat since then). To compensate for difficulties presented by the low beam currents in radioactive beam experiments, a pair of neutron walls is being constructed, each consisting of 25 long glass cells filled with NE213 liquid scintillator with photo tubes at the ends. The walls will contain 500 liters of scintillator, ten times the quantity in the array used previously. In a two-neutron experiment the efficiency is increased by a factor of 100. The increased lateral extent will enable the study of photonuclear excitations up to around 10 MeV excitation energy. With the Coupled-Cyclotron upgrade, beam intensities of light neutron dripline nuclei such as ^{11}Li will increase by a factor of 1,000. One of the best ways to take advantage of this increase is to increase the flight path and, therefore, the energy resolution. With two neutrons in the final state the factor of improvement without loss of counting rate would be ~ $(1{,}000)^{0.25} = 5.6$. Photonuclear excitation functions could be studied with 100-keV resolution. Also, two-neutron correlation functions could be measured down to momentum transfers of 1 MeV/c.

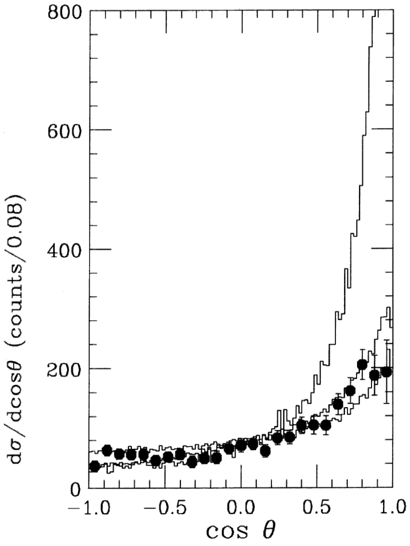

Fig. C-13: Angle distribution of the two neutrons when ^{11}Li decays. into ^{9}Li + n + n. The angle between the neutrons is θ. The points are from our experiment. The histograms are Monte-Carlo simulations of three decay models; dashed--standard 3-body phase space, dotted--3-body hyperspherical-harmonic (Ref. 14), solid--2-body. The last one rises above 2,000 at cos θ = 1.

Dripline nuclei

Particle Decay Spectroscopy

The measurement of properties of exotic nuclei is not limited to β- decaying nuclei but can be expanded beyond the drip-lines to particle unstable nuclei. These nuclei are extremely difficult to study, mainly because they decay immediately in the target by emitting a proton or neutron and thus cannot be detected with standard techniques. We have developed methods to study the structure of neutron and proton unstable light nuclei (A<13) by using sequential particle spectroscopy [Dea87] and transfer reactions with exotic beams [Kry93, Kry95]. The initial unstable nucleus is formed in a high energy heavy-ion fragmentation reaction, and thus the decay products as well as the neutrons are forward focused. Sequential particle spectroscopy is based on a collinear coincidence measurement of the decay product of the unstable nucleus and the neutron. This method has been successfully applied to ^{10}Li [Kry93], and most recently attempts to measure up to ^{16}B have been carried out. However, it will not be possible to extend this method to heavier systems along the drip-line because the production cross sections decrease rapidly. An alternative method is to use transfer reactions with secondary beams. Initial experiments both at the neutron and proton rich side have been successful. However, up to now only very little is known about the transfer / stripping cross sections of these exotic nuclei. We plan to measure these cross sections for nuclei along the dripline in order to understand the production mechanism and to determine the most promising reactions to populate nuclei beyond the dripline. These cross section measurements are ideally suited for the initial experiments with the S800 spectrograph.

Neutron Rich Nuclei

The measurement of light nuclei beyond the neutron dripline have yielded important structure information for the understanding of the neutron halo nuclei [Esb92]. The method of sequential particle decay spectroscopy demonstrated the s-wave nature of the ground state of ^{10}Li which was found to be very close to the threshold [Kry93] and had not been observed by multiple particle transfer reactions [Wil75, Boh93].

The top part of Fig. C-14 shows a relative velocity spectrum of ^{10}Li which exhibits only a single peak with a resonance energy of 50 keV and a width of 100 keV. This is consistent with the results of a pion absorption measurement [Ame90]. Recently evidence for this low lying state has also been observed in a multi-particle transfer reaction [You94]. For comparison, the known decay of ^{7}He to ^{6}He with a resonance energy of 450 keV and a width of 160 keV [Ajz88] is shown in the bottom part of Fig. C-14. The data were recorded simultaneously with the ^{10}Li data and used as a calibration reaction.

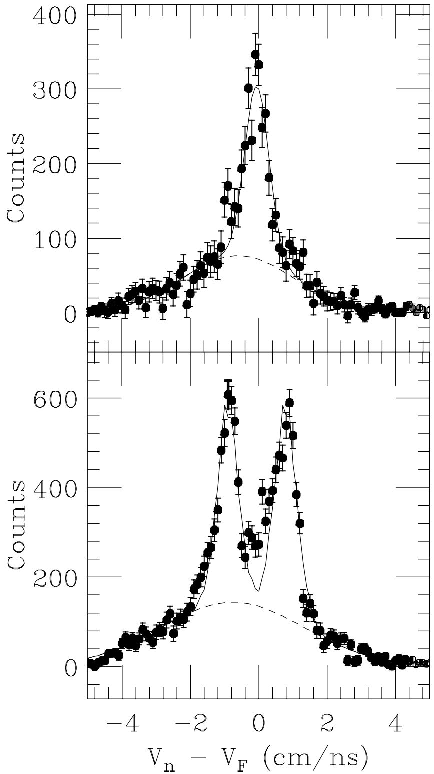

Fig. C-14: Relative velocity spectra from the decay of ^{10}Li (top) and ^{7}He (bottom) into neutron n and fragment F. The solid lines correspond to fits with decay parameters given in the text.

In our most recent experiment we extended the method of sequential particle decay spectroscopy to measure the decay of ^{13}Be, and perhaps enough data will be available for ^{16}B. The case of ^{13}Be is important for the understanding of the two neutron halo nucleus ^{14}Be. First evidence for such a low-lying state in ^{16}B has been reported [Boh95].

The exploration of the drip-line towards heavier nuclei has to be performed with transfer reactions using exotic beams. For example, ^{16}B can be produced by a one-proton stripping reaction from a beam of ^{17}C. The unstable ^{16}B will decay immediately in the target, and the invariant mass of ^{16}B can be calculated from a coincidence measurement of ^{15}B and a neutron. We will determine the energy of the neutrons from a time-of-flight measurement with the newly developed neutron wall. If the fragment detector was positioned at zero degrees, projectiles interacting with the detector would produce a large neutron flux, thus adding a large background in the neutron wall. Thus we plan to use a large-gap dipole which was formerly in the Bevalac beam line to bend the fragments away from zero degrees into a position-sensitive detector telescope. With the secondary beam intensities of the coupled-cyclotron upgrade this method can be applied up to Z=16 [MSU94].

Proton Rich Nuclei

Masses of particle-unstable nuclei and the study of exotic decay modes like the two-proton decay yield crucial information for the extrapolation of mass models. So far only a few ground-state proton emitters have been observed [Rob90], and the search for long-lived ground state two proton emitters has been unsuccessful. However, the search does not necessarily have to be limited to long-lived systems. We already performed two successful experiments measuring nuclei beyond the proton dripline in very light systems for which the Coulomb barrier is small, and thus the lifetimes very short. So far we have studied the two-proton decay of ^{12}O [Kry95] and measured the mass of ^{11}N [Azh95]. For both cases we used single neutron stripping reactions from secondary ^{13}O and ^{12}N, respectively. The decay products were measured in coincidence with two (one) protons. The mass/decay energy can then be calculated by a complete kinematical reconstruction.

Figure C-15 shows the invariant mass spectrum of ^{12}O. The extracted resonance energy (1.77 MeV) and width (578 keV) are in agreement with previous measurements. The decay character of ^{12}O can then be determined from the relative energy (top) and opening angle (bottom) spectra of the two protons as shown in Fig. C-16. While it is not possible to clearly distinguish a possible di-proton emission (left) from a sequential emission (right) from the difference energy of the protons, the observed isotropic emission of the protons sets an upper limit of the di-proton decay probability of ^{12}O to < 7%. This experiment seems to show that ^{12}O decays by a sequential emission through ^{11}N. However, with the currently accepted value for the ground state of ^{11}N, this sequential emission is not consistent with the large observed decay width of ^{12}O. Currently, the possibility of a direct simultaneous uncorrelated decay is being considered, and three-body calculations are being performed.

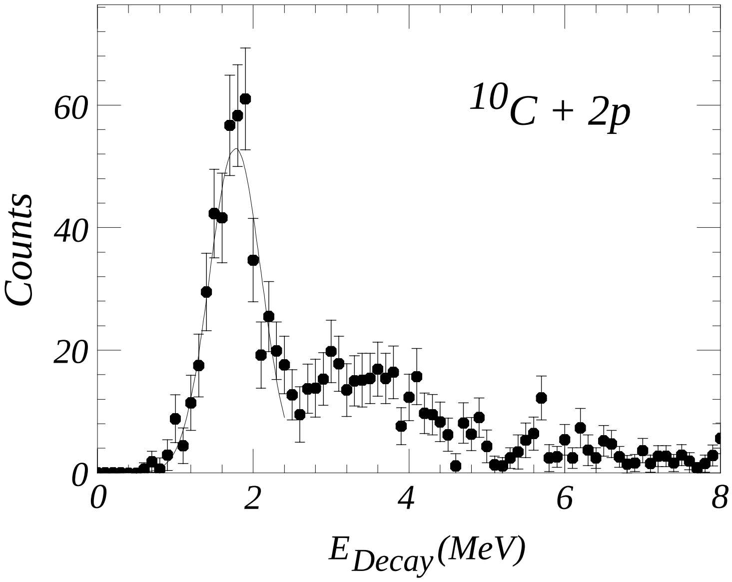

Fig. C-15: Relative energy of the 2p + ^{10}C coincidence events. The solid line corresponds to a calculation with the decay parameters given in the text.

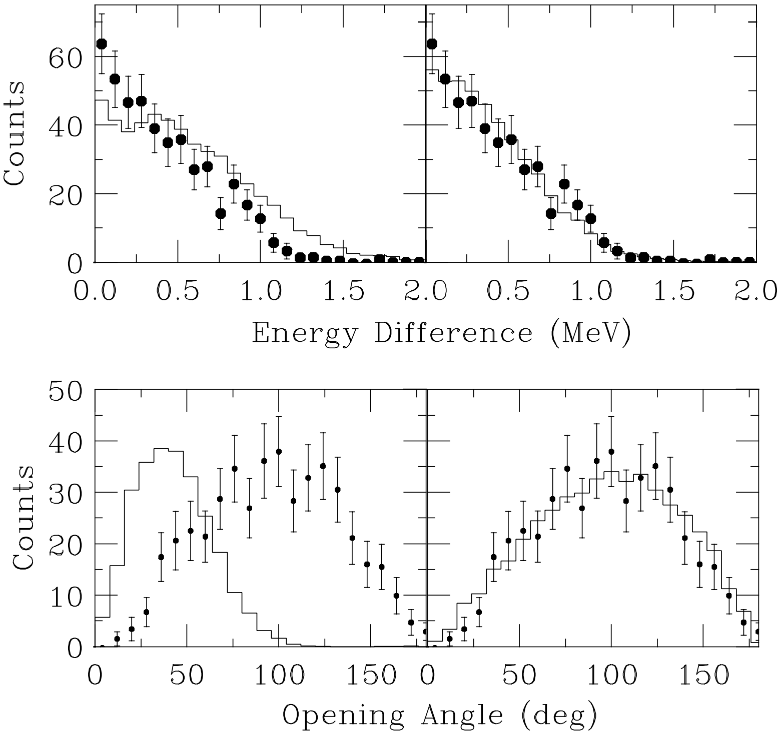

Fig. C-16: Energy difference (top) and opening angle (bottom) spectra for the decay of ^{12}O into 2p and ^{10}C. The calculations on the left were performed assuming a di-proton decay and the calculations on the right correspond to sequential proton emission via an intermediate state of ^{11}N.

Another possible explanation lies in the uncertainties of the position and width of the ^{11}N ground state. The mass of ^{11}N has never been measured and was only deduced from the isobaric mass multiplet equation [Ben74]. Thus, the mass measurement of ^{11}N was performed to resolve this open question, and the analysis is currently in progress.

In order to extend these measurements further along the dripline towards heavier nuclei and to search for other possible diproton emitters, the S800 spectrograph is essential to separate the fragments isotopically. In addition to the S800, the proposed high resolution forward array is needed to yield the necessary energy and position resolution for the proton detection. ^{16}Ne and ^{19}Mg are possible candidates which could have significant diproton emission. Again, in order to understand the decay structure of these nuclei the intermediate systems ^{15}F and ^{18}Na have to be measured. The mass of the ground state of ^{15}F is poorly known, and that of ^{18}Na is not known at all.

Stability and Lifetime Measurements

The ability of the NSCL to provide unusual primary beams for fragmentation studies and the versatility of the A1200 fragment separator continue to provide the basis for studies of a wide variety of drip-line nuclei. We have concentrated our studies of the production and decay of the most exotic nuclei in two regions: the most neutron rich light elements and the heaviest nuclei with N=Z. These nuclei present the strongest tests of our understanding of nuclear structure because they represent the limits of nuclear stability. They are also important in explosive astrophysical situations in which nuclei are processed along the limits of stability, with the outcome dependent on the details of nuclear stability.

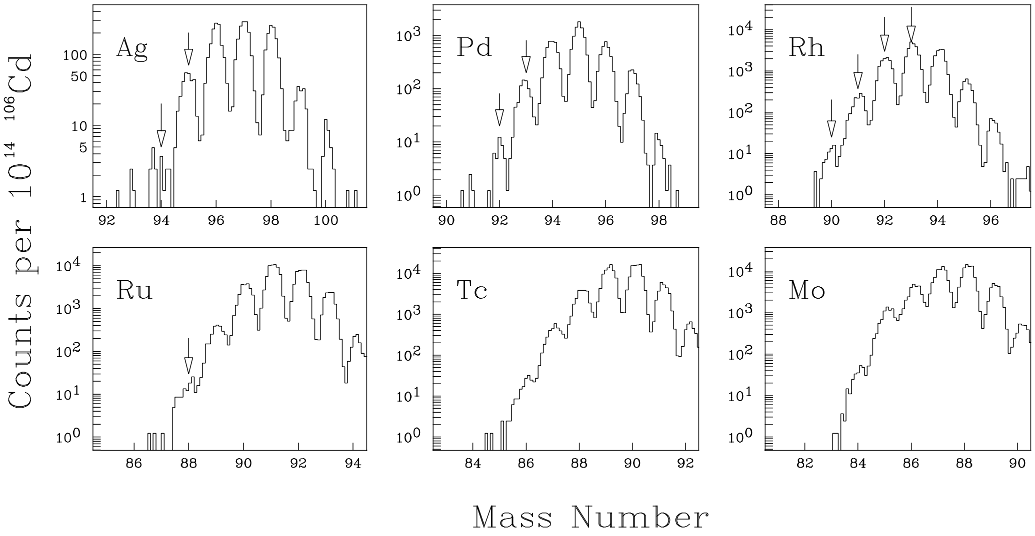

Fig. C-17: Mass spectra of elements produced by the fragmentation of a ^{106}Cd beam. Isotopes observed for the first time are indicated by arrows.

The heaviest N=Z nuclei are thought to play important roles in the astrophysical rp-process, determining its extent, energy generation and abundances of various nuclei. Most recently, the residues from the fragmentation of ^{106}Cd were measured in a survey of the production of proton drip-line nuclei in the region [Hen94] of ^{95}Ag, following on the important studies started with ^{78}Kr [Moh91] and ^{92}Mo [Yen92]. The mass spectra in Fig. C-17 from the ^{106}Cd fragmentation provided the first identification of nine new nuclei produced: ^{88}Ru, ^{90,91,92,93}Rh, ^{92,93}Pd, and ^{94,95}Ag. The large number of new rhodium isotopes indicates the power of the projectile fragmentation technique as it avoids chemical specificity. The stability of ^{95}Ag is of special astrophysical interest, since this isotope has recently been singled out as being particularly important in the nucleosynthesis of ^{92}Mo and ^{94}Mo [Hen94a]. These two molybdenum nuclei are unique among the "p-process" nuclides (nuclei which are blocked from production by the usual neutron capture processes) in that their isotopic abundances are relatively large, and their synthesis has remained a puzzle. Hencheck et al. [Hen94a] have shown that synthesis of the neutron deficient molybdenum isotopes could proceed via a series of rapid proton captures on preexisting material. However, the success of this model requires that ^{95}Ag be bound to ensure that ^{92}Mo and ^{94}Mo be produced in the observed ratio, thus the present work supports such a synthesis model. These survey measurements have provided the information necessary to perform the decay studies and the mass measurements discussed below. Detailed survey work of this type will become important again when beams from the coupled cyclotron become available.

Based on the various predictions of the proton drip-line ^{65}As, ^{69}Br, and ^{73}Rb have been identified as potential termination points [Cha92]. Following the identification of ^{65}As in the fragmentation of ^{78}Kr, second generation experiments to measure the β-decay half-lives for a number of very proton-rich nuclei in the A=60-70 mass region were carried out. [Win93, Win93a] A special detector system was developed to identify the implanted ions and the beta-particles from their radioactive decay. The ions were identified event-by-event, and the K1200 cyclotron rf was rapidly dephased so as to stop the beam whenever an interesting nucleus arrived. The results for ^{65}As indicate that the primary decay mode is positron emission, with a half-life of 0.19(11) s. Thus, proton capture in the rp-process to produce ^{66}Se should be possible. The observed half-life was used to put a lower limit of $S(p) \geq -250$ keV on the proton separation energy (in case the ground state is proton unbound). Repeated attempts to observe ^{69}Br and ^{73}Rb indicate that these nuclei are unbound, so the location of the proton drip line in this region is still an open question.

Mass Measurements

Direct Measurements: One of the most important features of drip-line nuclei is their mass. Gillibert et al. have shown [Gil86, Gil87] that projectile fragments can be tuned from a production target through a long beam line into a high resolution magnetic spectrograph to determine the relative masses of a broad range of nuclei. These fragments can extend out to the limits of stability as this technique only places a weak constraint on the lifetimes of the products, $T_{1/2} > 200$ ns [Orr91]. We have proposed a program to use the new S800 spectrometer to measure the masses of the most exotic nuclei with a direct time-of-flight technique. In a recent collaboration with the SPEG group in France, an E/A= 73 MeV ^{78}Kr beam was used to produce a number of neutron deficient fragments at GANIL.

Using on-line estimates of the counting rates and the calibrations, we expect an uncertainty of 500 to 800 keV in the measured masses of ^{65}As and other nuclei with similar values of A/Z that can be observed at the level of ~100 counts. Closer to stability we expect the uncertainty to approach ~250 keV. We will measure a broad range of nuclei with the A1200/S800 system, first in the region below mass 100 and then in regions of higher mass.

Q-value measurements: The S800 spectrograph, when coupled to the stable, rare isotope beams from the K1200 cyclotron, makes an ideal system for measurements of the mass, energy levels, and stability of nuclei near the proton and neutron drip lines via two-body final-state reactions. However, two body reactions leading to these nuclei have very negative Q-values and small cross sections. The large solid angle and high resolution of the S800 and the high energy and intensity of the beams available make a large range of experiments possible. Fig. C-18 shows the kind of results expected for mass measurements in the S800. In this case the low solid angle A1200 was in its spectrograph mode to measure the mass of ^{11}Li to within 28 keV [You93].

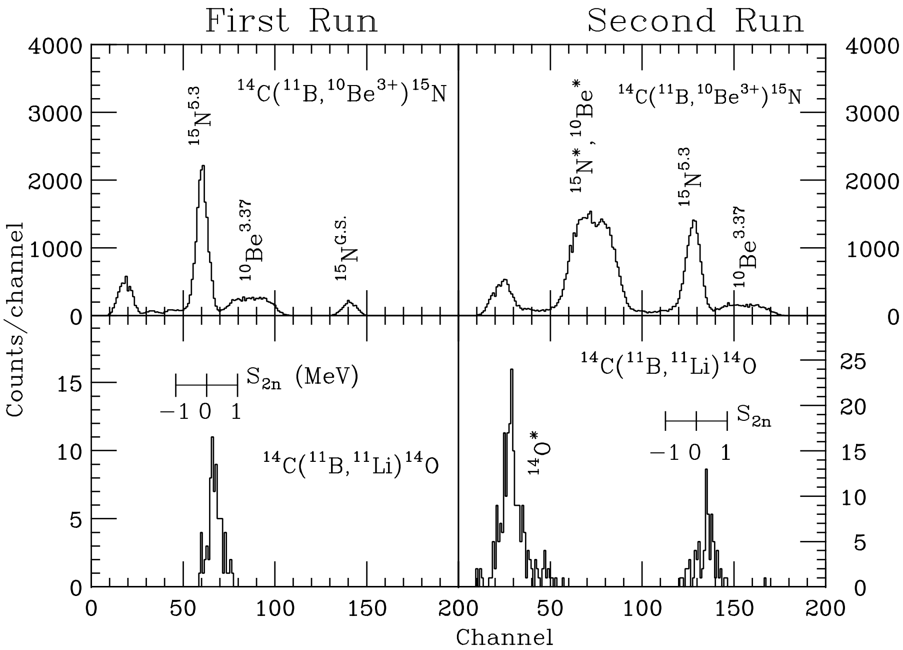

Fig C-18: Spectra from the precise measurement of the mass of ^{11}Li [You93]. The upper windows show the calibration spectra taken simultaneously with the primary reaction shown in the lower windows.

Recent experiments at the NSCL [You93] and the HMI [Ost94] have shown that two body nuclear reactions give a distinct viewpoint on the structure and masses of light nuclei near the limits of stability. For example, narrow excited states of very neutron-rich unstable nuclei can be observed even though they are unbound to proton or neutron decay by many MeV. Mass measurements with two body reactions can be made with much greater precision than those with other available methods, and unlike the case for direct mass measurements, ground state masses of unstable nuclei are accessible.

The first series of experiments would attempt to solve some of the remaining problems concerning masses and energy levels of halo nuclei. For example, the controversy concerning the existence and location of an excited state of ^{11}Li can be studied via the ^{14}C(^{11}B, ^{14}O)^{11}Li reaction at $E/A \approx 40$ MeV. This will yield a new and better mass for ^{11}Li and because the energy resolution should be less than 100 keV substantially reduce the possibility that present ground state mass measurements include a bound excited state. The so-called soft dipole state just above the breakup threshold can be well characterized in this experiment. In addition, a new high resolution look at ^{10}Li can be made with the ^{9}Be(^{9}Be, ^{7}B)^{10}Li and other similar reactions. A ^{10}Be target is available at MSU for these studies also. Precise measurements of the masses of ^{19}C and ^{18}C are very badly needed in order to interpret the recently discovered halo nature of ^{19}C. This could be achieved with, for example, the ^{18}O(^{18}O,^{19}C)^{17}Ne or the ^{14}C(^{18}O,^{19}C)^{13}O reaction.

On the proton rich side, many unknown or poorly known masses can be studied. For example the ^{46}Ti(^{6}Li,^{8}He)^{44}V reaction can be used to find the mass and energy levels of ^{44}V, a practically uncharacterized nucleus. There is a whole series of targets in this mass range for which this type of reaction, for example the ^{24}Mg(^{6}Li,^{8}He)^{22}Al or the (^{7}Li,^{8}He) reaction leads to new or poorly known nuclei.

β-decay Studies of Drip Line nuclei

In a recent review, Mueller and Sherrill [Mue93] pointed out that the location of the astrophysical rapid neutron-capture nucleosynthesis (r-process) path depends strongly on the properties of neutron-rich nuclei far off stability, especially those at or near neutron shell closures. Since the neutron capture rate will decrease drastically for these nuclei, the process has to wait for β−decays before heavier species can be synthesized. For a comprehensive understanding of the resulting abundance peaks it is important to measure decay properties like the half-life and delayed neutron emission probability of selected key nuclei around closed shells.

Measurements of the β-delayed neutron decay of very neutron-rich boron, carbon, and nitrogen isotopes have been performed at the NSCL. Harkewicz et al. [Har91] began these studies with the development of a large area neutron spectrometer and measured the β-decay branching ratios of ^{15}B. In collaboration with a group from Notre Dame, Scheller et al. have measured the β-delayed neutron decays of ^{18}N [Sch94] and ^{17,18}C [Sch95]. In the ^{18}N study, transitions to nine neutron unbound states in ^{18}O were found, with a total branching ratio of 2.2±0.4 %. The ^{17,18}C study confirmed the earlier lifetime measurements of these nuclei (193±5 ms and 92±2 ms, respectively), significantly reducing the uncertainties. In addition, several discrete β-delayed neutron groups were observed for the first time, yielding total branching ratios of 10.8± 2.2 % and 21.4±4.4 %, respectively. A unique identification of states in the daughter nuclei ^{17,18}N was not possible, however, because neutron transitions to excited states in the secondary nuclei ^{16,17}N are energetically allowed, indicating the need for further studies including neutron-γ coincidence measurements.

A study of the neutron spectrum following the decay of ^{11}Li is nearing completion. This nucleus also has a complicated decay spectrum and comparison to shell model predictions should shed light on the nature of the ^{11}Li ground state. The A1200 and the future A1900 are very well suited for the production of low mass neutron drip line nuclei. These nuclei are expected to be β−delayed neutron emitters, and therefore neutron spectroscopy will be an important tool for determining their properties. The possibility of studying multiple neutron emission following β-decay is another intriguing possibility for these exotic nuclei.

Astrophysics

Introduction

Studies of nuclear properties important for astrophysics have been an important part of the NSCL program for many years. Cross sections for spallation reactions of protons on CNONe, needed to understand the formation of isotopes of Li, Be and B in the cosmic rays, were measured using time of flight particle identification [Aus81] and were the forerunner of later measurements at Maryland and the IUCF. A major effort was also devoted to an understanding of the triple-reaction ($3\alpha \rightarrow {}^{12}C$) that synthesizes ^{12}C in helium burning stars; these studies first revealed a factor of 3 error in the 3α rate [Aus71], and later played a major role in reducing the uncertainty in this rate to about 15% [Rol88]. Less programmatic work was aimed at an understanding of nucleosynthesis on the high mass side of the "Fe" peak (discovery of ^{64}Ge [Rob72]); at an understanding of the solar neutrino problem (measurement of the rate of the $^{4}He(^{3}He,\gamma)^{7}Be$ reaction [Rob83]); and putting limits on the universal mass density from the abundance of ^{7}Li [Aus77]. More recently, there have been a series of experiments, described elsewhere in this document, aimed at delineating the path and limits of the rp process that burns hydrogen in hot stellar environments.

With the availability of the S800 spectrograph, and later, the proposed coupled cyclotron upgrade, the range of accessible studies in nuclear astrophysics will expand greatly. This section describes much of the work along these lines proposed for the next few years; some work with large overlap with nuclear structure studies is described in other parts of this document. Many of the proposed experiments will yield information needed for an understanding of the supernova process and of nucleosynthesis during evolution to and through a supernova explosion. However, we discuss first three other experimental programs aimed at (1) improving our understanding of production of high energy neutrinos in the sun via the $^{7}Be(p,\gamma)^{8}B \rightarrow {}^{8}Be+e^{+}+\nu_{e}$ process, (2) a better determination of the rate for the $^{12}C(\alpha,\gamma)^{16}O$ reaction that produces ^{16}O in helium burning stars, and (3) understanding the production of $^{6,7}Li$ in the early galaxy.

Determination of the Rate for the $^{7}Be(p,\gamma)^{8}B$ Reaction

Neutrinos produced in the decay of ^{8}B dominate the predicted event rates in two of the solar neutrino detectors (^{37}Cl--75%, and Kamioka--100%) and contribute at a lower level to the ^{71}Ga detector [Bow93a]. Unfortunately, the measurements of the cross section for the $^{7}Be(p,\gamma)$ reaction do not agree. Mainly, the disagreements are in normalization, but the excitation functions are not always well described by calculations that include both s and d wave contributions [Fil83].

A study of the breakup $^{8}B+\gamma\rightarrow^{7}Be+p$ mediated by the flux of virtual photons accompanying a collision with a high Z target, could in principle provide the required information via detailed balance. A recent experiment [Mot94a] has shown that this is possible, at least for center of mass energies above 600 keV. However, these results have been controversial because of uncertainties on the contribution of E2 amplitudes; the virtual photon flux is rich in E2 photons (and deficient in M1 photons). It may be possible to separate E2 and E1 contributions experimentally [Gai95], but it is not yet clear whether this separation is significantly affected by contributions from nuclear excitation at larger angles.

We have undertaken a program that should provide a better understanding of the mechanisms involved in the breakup of ^{8}B and a better estimate of the breakup cross section. This program will proceed in several experimental stages. In the first experiment the breakup products will be detected in a telescope consisting principally of a two-sided Si strip detector followed by a segmented CSI stop detector to provide high rate multi-hit capability. We expect to obtain a reconstruction accuracy sufficient for c.m. energies above 200-300 keV and to gain an understanding of the problems involved in such experiments. Measurements at several energies in the 40-100 MeV/nucleon range and on two targets (e.g. Ag and U) should help provide experimental separation of nuclear and E2 effects. When the wide-gap magnet presently under construction is complete, a second experiment with better energy and angular resolution will allow an extension of the measurements to lower excitation energies. Finally, measurements of total reaction and breakup cross sections, on a variety of targets at four energies, will provide further systematic information on E2 and nuclear effects.

Measurements of breakup momentum distributions may provide additional useful information. Recent NSCL measurements [Kel95] of the parallel and transverse momentum distribution of ^{7}Be resulting from the breakup of 40 MeV/nucleon ^{8}B, yield a narrow momentum distribution (75±5 MeV/c FWHM) for Be, Nb and Au targets. This indicates the ^{8}B has a halo structure. There is a similar result in the breakup on ^{12}C at 1471 MeV/nucleon at GSI [Sch95a]. These results may place further constraints on the ^{8}B wave function at large distances and hence on the reaction rate [Rii92].

The Rate of the $^{12}C(\alpha, \gamma)^{16}O$ Reaction

The $^{12}C(\alpha, \gamma)^{16}O$ reaction is of great importance in several areas of astrophysics. Its rate, given by the S factor near 300 keV, $S_{\alpha 12}$(300 keV), determines the relative abundances of the isotopes of life, ^{12}C and ^{16}O, produced in helium burning stars. In turn the $^{12}C/^{16}O$ ratio influences the future evolution of stars. For example, if little ^{12}C is produced, a massive star may skip the ^{12}C burning phase, shortening the star's lifetime and producing a larger core of iron-like elements. This in turn influences the nature of the core collapse process in the ensuing supernova. It has been shown [Wea93] that the abundances of nuclides with $A\leq40$ are better produced if the rate of the $^{12}C(\alpha, \gamma)$ reaction is 1.7±0.5 times larger than the recommended value [Cau88]. Unfortunately, in spite of heroic experimental and theoretical efforts over many years, $S_{\alpha 12}$ is still poorly known.

Cross sections for ^{12}C(α, γ)^{16}O are difficult to measure, and the results are not in good agreement at the lower energies [Rol89]. Recent measurements of β-delayed α emission from ^{16}N [Buc93, Zha93, Azu94] fix the E1 part of the rate, and hence S_{E1}, fairly well provided one accepts that the two 1^- levels (at 7.12 MeV and 9.6 MeV) interfere constructively in ^{12}C(α, γ)[Azu94, Bar94]. However, the E2 strength remains poorly known, and it would be highly desirable to have a still more accurate result for S_{E1}. We propose a two pronged attack on this problem, involving measurements of α-transfer cross sections and of Coulomb breakup.

Because the virtual photon spectrum is so rich in E2 photons, the Coulomb breakup cross section for ^{16}O is entirely dominated by E2 processes. Coulomb breakup studies may then provide a useful complement to the ^{16}N($\beta\alpha$) which is sensitive to E1. However, the experiment is technically difficult, and in addition, it seems that nuclear processes will be important [Ber94]. Systematic studies will then be necessary if there is to be a chance of extracting useful information. However, the importance of this reaction warrants a serious effort, and the S800 is a particularly powerful tool for these studies since both products (α and ^{12}C) will have similar rigidity. A second approach is to determine the α widths (θ_α^2) of the 7.12 MeV, 1^- state and the 6.92 MeV 2^+ state of ^{16}O. The values of θ_α^2 for these bound states essentially determine the values of S_{E1} and S_{E2}, respectively, at astrophysical energies. They are the principal results of fits to the ^{12}C(α, γ) and ^{16}N($\beta\alpha$) data that have been used to determine $S_{\alpha12}$(300 keV).

Pioneering measurements of these widths were carried out by Becchetti, et al. [Bec78, Bec89] partly at the NSCL, but their use in determinations of $S_{\alpha12}$ has not been broadly accepted by the astrophysics community. We propose to determine θ_α^2 with the ^{16}O(^{7}Li, t)^{12}C(1^-, 2^+) reaction at a variety of energies from 10 to perhaps 50 MeV/nucleon. A measurement of any energy dependence of these ratios may permit a more reliable extraction of the widths, or at the least, of their ratio to the known α width of the 9.6 MeV 1^- level. Fixing these ratios should greatly reduce the ambiguities in fits to the other relevant data.

The Production of ^{6,7}Li in the Early Galaxy

Because ^{6}Li is not made in the Big Bang but is observed in very old stars in the galactic halo, it is assumed to arise from reactions in the galactic cosmic rays. At the present time, the interstellar medium is enriched in CNO, and their spallation by GCR protons (p + CNO$\rightarrow^{6,7}$Li) dominates the cosmic ray production of ^{6,7}Li. However, in the early galaxy CNO were rare, and ^{6,7}Li presumably resulted from $\alpha+\alpha\rightarrow^{6,7}$Li reactions. A number of measurements have been carried out at lower energies with the MSU K-50 cyclotron and at Maryland and the NSCL. However, there are no measurements of the ^{6}Li cross section at energies above 200 MeV and for ^{7}Li only poorly defined upper limits exist from unpublished measurements done at Orsay many years ago. As a result, it is impossible to predict the amount of ^{6}Li produced by cosmic rays in the early galaxy. Consequently, one cannot determine whether models properly describe the combined effects of big-bang production, cosmic ray production, and stellar processing.

Measurements using the standard technique, in which the ^{4}He target gas is contained in a cell and the interaction region is defined by slits, are difficult at high energies, since the defining slits are very thick, and backgrounds from the widow are hard to eliminate when the desired cross sections are small and decreasing with energy as in the present case. A University of Colorado-NSCL collaboration is measuring these cross sections from about 160 MeV to 600 MeV using a new technique. The entire 92" diameter scattering chamber is filled with helium, and the interaction region is defined by position sensitive detectors. Early results are promising.

Nuclear Physics and the Supernova Process

Nuclear processes influence the evolution of massive stars through a sequence of quasistatic burning stages, resulting in the formation of a core of iron-like elements, the subsequent collapse and rebound of that core, and formation of a shock wave that in some manner ejects the overlying material. This section concerns mainly the later stages, including the supernova explosion.

As a star evolves through its oxygen and silicon burning stages, the abundances of the elements produced in the pre-supernova star begin to depend on the strengths for electron capture, $B(GT_+)$ when the electron Fermi energy becomes high enough to induce transitions to higher lying states. Later, $B(GT_+)$ affects the nature of the ensuing core collapse and of its subsequent bounce and expansion. The effects involved are the following. The pre-collapse core of iron-like isotopes is supported largely by the pressure of degenerate electrons, so that the amount of electron capture, and hence the neutronization of the core, affects the size it attains prior to collapse. As the collapse proceeds, the amount of neutronization affects the division of the core into an inner homologous (i.e., uniformly collapsing) core and an outer core. Thus, EC directly affects the difficulty of generating a supernova explosion following collapse and bounce; much of the bounce shock energy is spent in dissociating the outer iron core.

It follows that a detailed understanding of B(GT) is necessary for an accurate description of the supernova process and nucleosynthesis in supernovae. It is also necessary to understand the nuclear equation of state of hot neutron rich matter since it affects the strength of the core bounce. Finally, excitation of spin-dipole states by inelastic neutrino scattering may mediate the production of key light elements; their excitation depends on experimentally unknown strengths.

Gamow -Teller Strengths for Medium Weight Nuclei

Many nuclei participate in the electron capture (EC) and β-decay processes in stars, and the most important of them are radioactive. As a result, it will be necessary to rely on model calculations for most of the information on B(GT) required by stellar evolution codes. However, the calculations involve severely truncated model spaces, and it will be necessary to calibrate them with some care before they can provide reliable results. Data from (n,p) studies are available for several nuclei, but because of their difficulty these experiments have relatively poor energy resolution, usually 1 MeV or worse. Hence, while they provide a critical check of the gross features of EC strength, they are unable to check the more detailed spectroscopy. No data are available for radioactive nuclei.

There are a number of options for studies of EC strength on stable nuclei. Perhaps the most promising approach is the (t, ^{3}He) reaction using secondary tritium beams. In a test experiment at E_t = 380 MeV [Jan95] a resolution of about 800 keV was obtained using the A1200 in a dispersion-matched mode; a spectrum is shown in Fig. C-19. The S800 spectrograph should yield a resolution in the 100 keV range. We will study this reaction for several important nuclei in the Fe region.

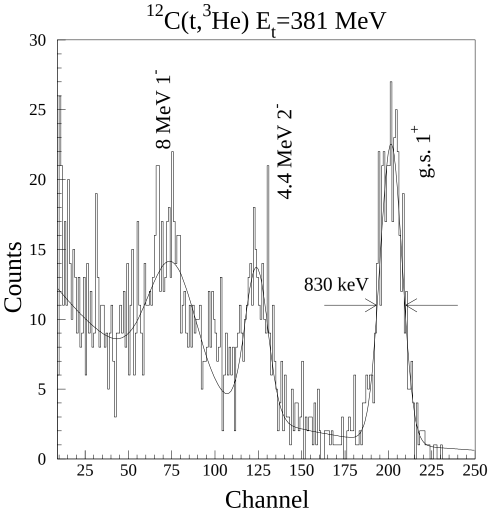

Fig. C-19: Spectrum from ^{12}C(t, ^{3}He) reaction at 381 MeV. The A1200 was used to separate the triton beam and as a momentum matching spectrograph to analyze the ^{3}He's.

Another possibility is the (^{12}C,^{12}N) reaction. We have shown [Ana91] that this reaction yields reliable results at 70 MeV/nucleon, with a resolution of about 240 keV, and RIKEN results at 135 MeV/nucleon are still cleaner albeit with poorer resolution. However, the resolution obtainable is probably poorer and the reaction mechanism more complicated than for (t, ^{3}He). Still another option is the (^{7}Li, ^{7}Be*(431 keV)γ) reaction[Nak91]; coincidences with the outgoing 431 keV gamma ray allow one to sort out the Fermi and Gamow-Teller strengths, at least for lighter nuclei. However the resulting experimental complication may not be warranted for stable nuclei.

The situation for radioactive nuclei is more complex. It will be possible to obtain beta decay strength by studying (p, n) reactions in inverse kinematics. Resolutions of 100-200 keV should be possible with this technique, the principal challenge lying in the need to detect the low energy neutrons characteristic of the forward c.m.-angle process. It may turn out to be simpler to study the inverse kinematics (^{6}Li, ^{6}He) reaction; however, this option has not yet been examined in detail.

It is still more difficult to obtain EC strength for radioactive nuclei, although this is the most important need. One approach is the (^{7}Li, ^{7}Be*(431 keV)γ) reaction described above, but in reverse kinematics. Another is to observe the equivalent $T_>$ strength in (p,n), (^{3}He,t) or (^{6}Li,^{6}He) reactions. This strength is suppressed by isospin geometrical factors, compared to the dominant $T_<$ strength. However, it has been shown [Ant95] that $T_>$ excitations can be observed in (p,n) reactions on iron-region isotopes (^{60,62}Ni), even with relatively poor (500 keV) resolution. The resolution of 100-200 keV obtainable in inverse (p,n) reactions will make this approach possible for most of the important nuclei, although a comparison with (p,p') may be necessary in some cases to confirm the $T_>$ identification.

Our planned approach to these measurements is as follows. Studies of the (t,^{3}He) reaction will be possible for a variety of nuclei when the S800 spectrograph is complete, and we will begin an experimental program at that time, concentrating on the iron region. However, the higher intensities available with the coupled facility will improve the quality of these measurements. At the same time we will begin to examine the feasibility of measuring EC strengths for radioactive nuclei. Until the coupled cyclotron facility is available, most of this work will involve prototype experiments using stable beams in inverse kinematics. However, a few favorable cases, for example, ^{60}Co the most important electron capturing nucleus for supernova evolution [Auf94], may be possible with the present facility.

Spin-Dipole Strength and Neutrino Nucleosynthesis

Woosley and Haxton[Woo88] have proposed that certain rare nuclei, e.g. ^{7}Li, ^{11}B and ^{19}F are synthesized during a supernova explosion by inelastic neutral current neutrino scattering on abundant nuclei. For example, of 0^-, 1^-, and 2^- spin-dipole states excited in ^{20}Ne are unbound and can decay by proton or neutron emission to ^{19}F and ^{19}Ne. Following further processing in the explosion, a certain amount of ^{19}F remains. This process is intriguing, since it may explain the abundances of nuclides difficult to form in other astrophysical sites.

It has been necessary to base these calculations on theoretically calculated strengths. However, the ^{6}Li*(3.56 MeV, 0^+, T = 1)γ) reaction may provide a way to measure the requisite matrix elements. This reaction is unique, in that it is sensitive only to isovector spin-transfer processes in the inelastic channel. It does, however, require a high resolution spectrograph and a high granularity gamma-ray array around the target. A test experiment using the ORNL, TAM, NSCL BaF_2 array will be carried out in May of this year.

Giant Monopole Resonance for Neutron Rich Nuclei.

At the completion of quasistatic burning processes in a heavy star, the "Fe" core collapses, reaches nuclear density and then rebounds, forming a shock wave that in some way expels the overlying material in a supernova explosion. The strength of this bounce and hence of the shock depends on the equation of state for neutron rich hot matter. Studies of the inelastic alpha scattering from a broad range of isotopes of a given element, for example from $^{54-68}$Ni, should allow one to control for Coulomb effects and obtain a more accurate measure of the symmetry term in the equation of state. It will be necessary to use radioactive beams in inverse kinematics to obtain sufficiently neutron rich systems.

The coupled facility will be required for these studies. A helium-filled TPC, as a combined target and detector, may provide the best approach to this problem. During the next few years we will carry out prototype experiments with stable beams, in an attempt to determine the best approach to this problem.

C-IV: Proposed Nuclear Reactions Research

Reaction Studies with the 4π Array

The Disappearance of Flow

One of the most basic relations in nuclear physics is the equation of state of nuclear matter (EOS). Recent work has established that the incompressibility, K, of nuclear matter at normal nuclear density and zero temperature is 210 MeV [Gup93]. Another basic concept in nuclear physics is that of a liquid/gas phase transition (LGPT) in nuclear matter. Several experiments are underway to demonstrate that the LGPT can be studied experimentally. A related phenomenon may be the onset of multifragmentation.

We have carried out a study of the EOS by measuring the incident energy at which the attractive nuclear mean field is balanced by the repulsive nucleon-nucleon interactions [Wes93]. This energy is termed the balance energy, E_{bal}, and is extracted by observing the disappearance of transverse collective flow as a function of incident energy. Flow measurements were made for 55 to 155 MeV/nucleon C+C, 55 to 140 MeV/nucleon Ne+Al, 35 to 115 MeV/nucleon Ar+Sc, and 35 to 75 MeV/nucleon Kr+Nb. In Fig. C-20, the extraction of the balance energy for Ar+Sc is depicted.

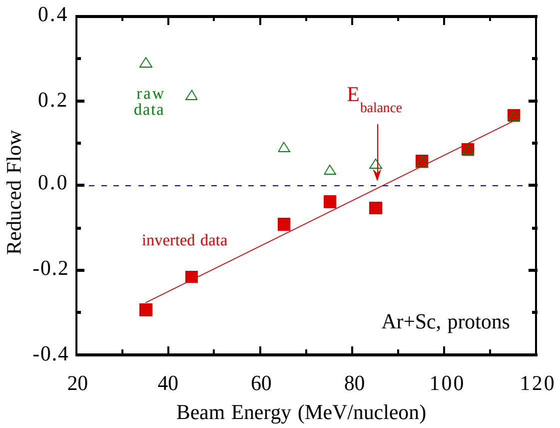

Fig. C-20: Extraction of the balance energy for protons from Ar+Sc reactions.

To facilitate the measurement of E_{bal}, we assigned a negative value to the flow at the lowest incident energies where BUU predicts that the flow should be negative and then made a linear fit to all the measured values. We extracted E_{bal} in a similar way for a wide range of systems as shown in Fig. C-20. A previous result for Ar+V is also shown. Relating these results to the EOS was done through the transport model BUU which incorporates aspects of the EOS through the nuclear mean field and includes the effects of nucleon-nucleon scattering. We found that BUU underpredicted the measured balance energies independent of the parameters of the EOS.

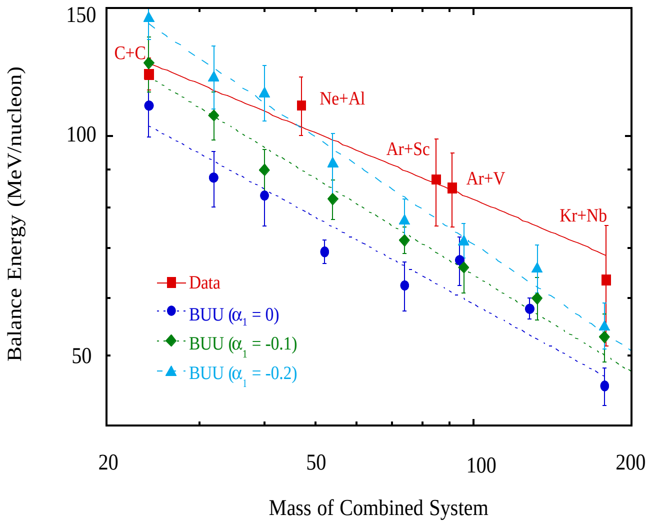

Fig. C-21: The mass dependence of the disappearance of flow compared with BUU calculations.

Better agreement was obtained under the assumption of a density dependent reduction of σ_{nn},, the free nucleon-nucleon cross section in the nuclear medium, on the order of 20%. In Fig. C-21, the BUU results for a soft EOS (K = 200 MeV) are shown for free σ_{nn} ($\alpha_1 = 0$), a 10% density dependent reduction in σ_{nn} ($\alpha_1 = -0.1$), and a 20% density dependent reduction in σ_{nn} ($\alpha_1 = -0.2$). The BUU predictions including the 20% reduction in σ_{nn} reproduce qualitatively the magnitude and mass dependence of the measured balance energies.

Disappearance of Fusion/Fission

At low incident energies the probability that an incident nucleus will fuse with a target nucleus is high [Vio89]. One decay channel that is available for this phenomenon is fission of the resulting compound system. The fission fragment opening angle, θ_{ff}, will reflect the momentum transfer of the reaction. We have completed a study of the system ^{40}Ar+^{232}Th in which we studied fission fragment correlations in well characterized events from 15 to 115 MeV/nucleon [Ye95, Gua95]. The cross section for various θ_{ff} are shown in Fig. C-22 for a minimum bias trigger. Clearly visible are low momentum transfer peaks characterized by large values of θ_{ff}. Also visible at the lower incident energies is a large momentum transfer peak at angles around 110˚. The low momentum transfer peaks correspond to peripheral collisions while the high momentum transfer peaks can be related to central collisions.

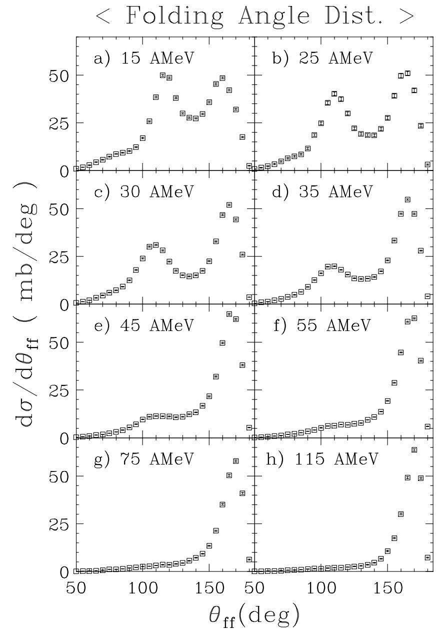

Fig. C-22: Cross sections for fission fragment opening angles for Ar+Th reactions.

As the beam energy is raised, the disappearance the central collision peak signals a change in reaction mechanism. This disappearance had been observed previously [Con85, Sch94a]. We have shown that these reactions reflect the onset of multifragmentation by studying the global shape of the momentum distributions of these events characterized by the sphericity of the event. In Fig. C-23 the sphericity is plotted as a function of charged particle multiplicity and incident energy for central collisions of Ar+Th. This method of display explicitly treats the well-known effects of the finite particle number on sphericity observable.

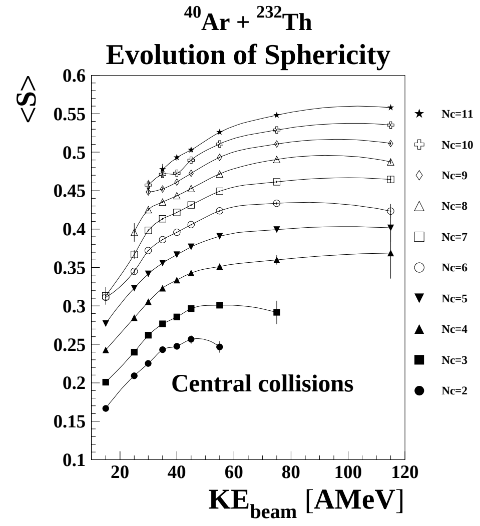

Fig. C-23: The evolution of sphericity with incident energy and charged particle multiplicity.

One can clearly see that the sphericity increases with incident energy and reaches a plateau for each value of the charged particle multiplicity. This plateau value is near the maximum possible sphericity for each multiplicity. The fact that the sphericity is smaller at low incident energies reflects the fact that the events are elongated in momentum space indicative of two body sequential emission. The larger and relatively constant values at the higher incident energies implies a multifragment emission mechanism which is intrinsically spherical.

Onset of Multifragmentation

To get more information about the onset of fragmentation, we have carried out an extensive set of measurements and analyses which incorporate three projectile/target systems, Ar+Sc, Kr+Nb, and Xe+La at a variety of incident energies ranging from 35 to 115 MeV/nucleon [Llo95]. We have applied six different methods to look for signatures of the onset of multifragmentation as shown in Fig. C-24.

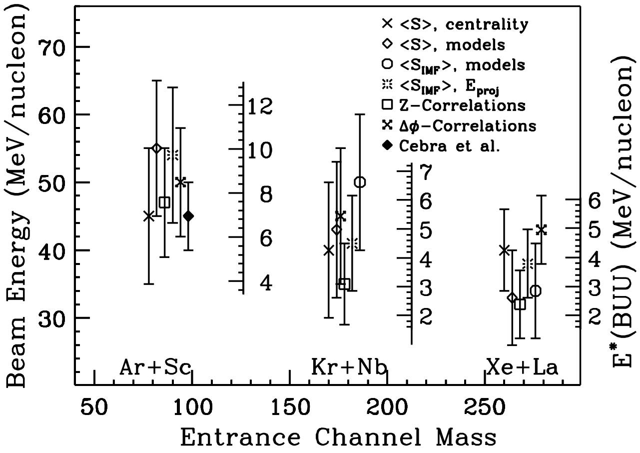

Fig. C-24: Energies extracted for the transition from sequential binary decay to multifragmentation. The predicted excitation energies are extracted using BUU.

All the methods share the ability to distinguish between two body sequential binary decay and many body multifragmentation. The first method involves a systematic study of event shapes in terms of the average sphericity <S> and its correlation with many centrality variables. The second technique compared measured <S> values with hybrid models that used BUU to calculate the input parameters or sequential binary decay models and for multifragmentation models. The third approach followed a similar path but used only intermediate mass fragments (IMFs) in the shape analysis. A fourth method studied the values of the sphericities for IMFs as a function of incident energy. A fifth method used Z correlations for the three heaviest measured fragments. A sixth method incorporated azimuthal correlations of IMFs. A previous result using event shapes for Ar+V is also shown [Ceb90].

The transition from sequential binary decay to multifragmentation implies that the time scale for emission of fragments will dramatically decrease at the transition energy. In Fig. C-25 the time scales extracted from fragment-fragment correlations are compared to the extrapolated region of excitation energy over which we observe a transition as a function of entrance channel mass. These extracted time scales are substantially shorter at energies above the transition than below the transition.

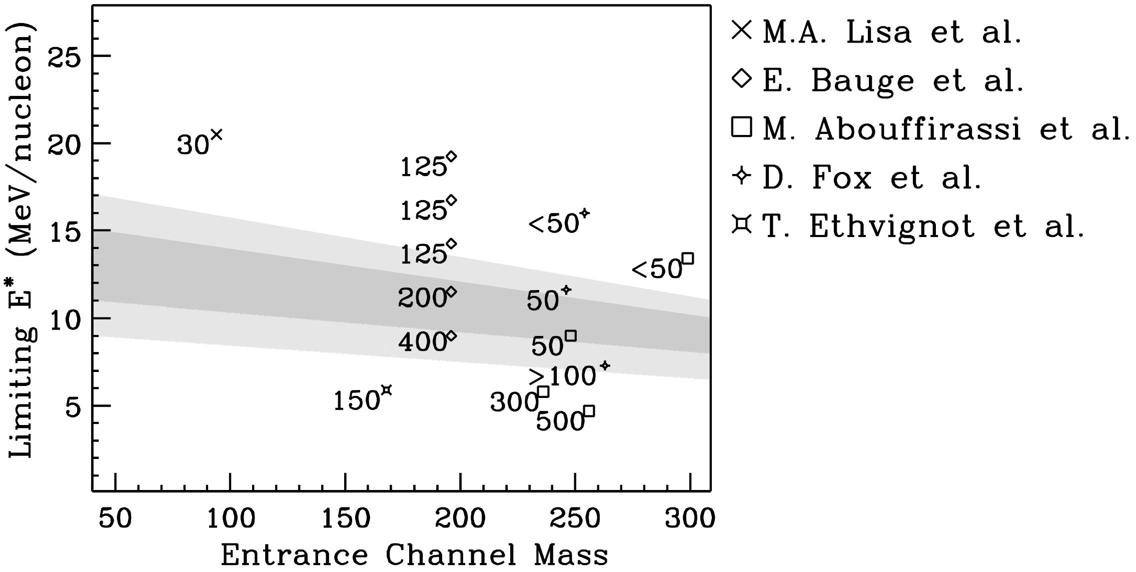

Fig. C-25: Shaded area represents the limiting excitation energies corresponding to the transition from sequential binary to multifragmentation as a function of entrance channel mass extracted from analysis of six different observables. The numbers represent previously measured time-scales for particle emission in fm/c by five previous groups (see references in [Llo95]) plotted as a function of system mass and excitation energy. In Fig. C-24 there is clear evidence for a transition from sequential binary decay to multifragmentation. The energy at which the transition occurs goes down with increasing mass of the system.

The Impact Parameter Dependence of the Disappearance of Flow

Having established the systematics for the mass dependence of flow, we have begun a series of experiments to find observables that may be more sensitive to the EOS. The first of these experiments is the study of the impact parameter dependence of the disappearance of flow. One expects that the balance energy will increase with increasing impact parameter because the effects of the repulsive nucleon-nucleon scattering will be reduced relative to the attractive mean field at large impact parameters [Ber87]. This effect is observed as shown in Fig. C-26 [Pak95]. In this figure, extracted flow values are given for four bins using 10% bins in cross section based on the reduced transverse kinetic energy. The increase in the balance energy with increasing impact parameter is clear.

Transport model calculations can incorporate soft and stiff descriptions of the EOS as well as momentum dependence. In Fig. C-27, QMD calculations for a hard equation of state with and without momentum dependence are shown [Sof95].

Clearly more work is needed to make a definitive comparison between experiment and theory, but the present trends favor the calculations which incorporate momentum dependence.

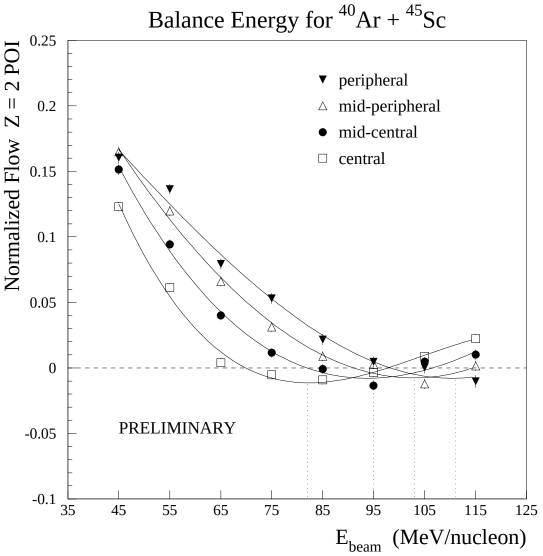

Fig. C-26: Preliminary results for the impact parameter dependence of the disappearance of flow in Ar+Sc reactions. In this plot the low energy flow has not been set to negative values.

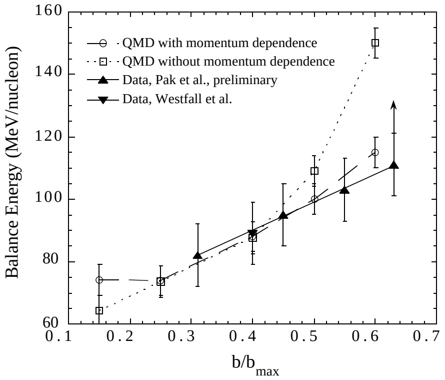

Fig. C-27: Preliminary values of the extracted flow as a function of impact parameter compared with the QMD model [Sof95] incorporating a hard equation of state with and without momentum dependence.

Subthreshold Pion Production

Another direction that we are exploring is subthreshold pion production in well characterized events. Observables such as pion flow and pion squeeze-out may provide insight into the mechanism of pion production at these energies which must proceed through some kind of collective phenomenon [Aie88, Nol84]. In Fig. C-28 the particle identification spectrum for pions is shown. Pions are identified by observing the τ=2.2 μs decay of the muon to a positron.

We have carried out a series of measurements for 150, 110, and 90 MeV/nucleon Ne+Al in which we instrumented all 170 detectors of the 4π Array to detect the delayed coincidence from the μ^+ decay. We plan to extract variables such as collective flow which has been observed to be anticorrelated with nucleon flow at higher energies [Gos89].

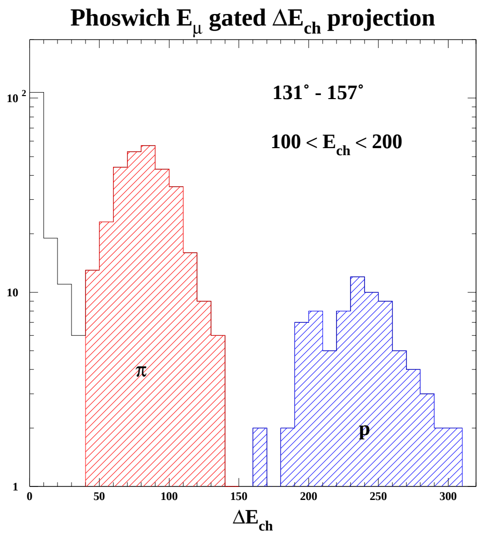

Fig. C-28: article identification spectrum for pions from 150 MeV/nucleon Ne+Al reaction gated on the decay of $\mu^+ \rightarrow e^+$.

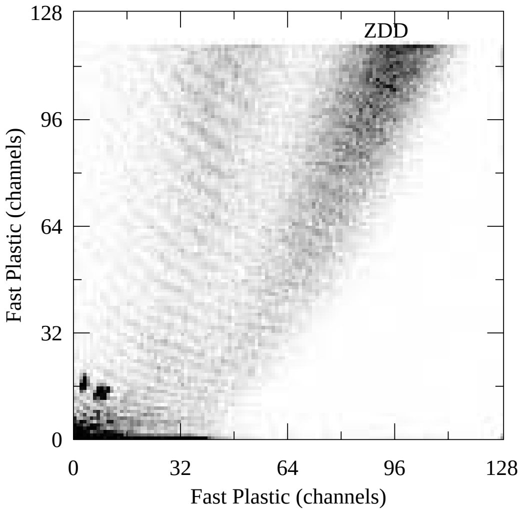

Fig. C-29: ΔE-E spectrum from two incident energies of Kr+Nb for angles between 0.5° and 1.5°.

Search for Non-Compact Geometries

The formation of nuclear matter in non-compact geometries (toroids, bubbles, etc.) has been predicted using transport models [Bau92a, Mor92]. One signature of the formation of such a system is enhanced emission of IMFs. These IMFs would be emitted from a system moving at the center of mass velocity and would be observed at forward angles. The acceptance of the MSU 4π Array was augmented to improve its ability to observe these types of reactions by adding a detector capable of measuring IMFs at angles from 0.5° to 1.5°, the Zero Degree Detector (ZDD). Combined with the High Rate Array, and the Maryland Forward Array, the 4π Array now has excellent sensitivity to these types of phenomena. In Fig. C-29, a ΔE-E plot is shown for one of the eight detectors in the ZDD. The excellent Z resolution and dynamic range are visible.

Future Directions

Isospin Dependence of the Disappearance of Flow: We have demonstrated that the balance energy in nucleus-nucleus collisions depends on the nucleon-nucleon cross sections. We have also shown that the impact parameter dependence of the disappearance of flow can provide details concerning the reaction mechanisms. We propose to combine these studies with the exciting prospects of high intensity exotic beams provided by the proposed coupled cyclotron facility to study systematically the isospin dependence of the EOS by measuring collective flow and the disappearance of collective flow as a function of isospin. In our energy regime, the n-p cross section is about three times the n-n and p-p cross sections. Thus one expects that effects of mean field and nucleon-nucleon cross sections can be isolated and studied.

An example of this type of experiment is the comparison of flow in the reactions ^{40}Sc+^{58}Ni and ^{40}Cl+^{58}Fe. These combinations would allow the variation of N/Z by about 30% while preserving the mass number of the system which will change the nucleon-nucleon cross sections significantly without varying the mean field very much. As our previous disappearance of flow studies demonstrated, detailed excitation functions are the key to the extraction of the precise results needed for these studies.

The large acceptance of the 4π Array allows the use of the relatively low intensity secondary beams (compared to stable beams). Typical beam intensities for flow measurements with stable beams are on the order of 10^7 particles/second. We have carried out reaction studies with secondary beams in the 4π Array using additional small solid angle silicon detector telescopes. These intensities ranged from 10^4 to 10^6 particles/second. The flow observable lends itself better to low statistics measurements than do our previous studies of isotope ratios because isotope resolution will not be required.

Flow and Multifragmentation in Asymmetric Systems: Recent work by Danielewicz [Gup93] has shown that ambiguities in the parametrization of the EOS can be resolved by comparing predictions from transport models with flow measurements from both symmetric and asymmetric systems. We propose to study the disappearance of collective flow in asymmetric systems to help untangle the effects of momentum dependence and incompressibility in transport models. We have demonstrated the mass dependence of the disappearance of flow for symmetric systems, but unfortunately it was difficult to make definitive statements about the EOS from those results. Thus we propose to study the disappearance of flow in asymmetric systems as a function of mass of the system, Proposed asymmetric systems would include Ne+Ni, Ag, Au, Ar+Ni, Ag, Au, and Kr+Ni, Ag, Au.

Our recent results for Ar+Th reactions show a surprisingly low multiplicity of IMFs even at relatively high incident energies (115 MeV/nucleon) compared with the symmetric system Xe+La at comparable excitation energies. We propose to measure the onset of multifragmentation as a function of size of the system and relative size of the projectile and target nuclei. The geometry of the 4π Array is particularly well suited to normal kinematics with heavy targets and light beams. The observables we plan to use include event shapes, azimuthal correlations, and Z correlations. The systems we propose to study are C+Ni, Ag, Au, Ne+Ni, Ag, Au, and Kr+Ni, Ag, Au over the full range of the NSCL energies.

<u>The Disappearance of Flow for Heavy Systems</u>: Systematic data for collective flow have been obtained for Au+Au reactions at incident energies between 150 and 1150 MeV/nucleon [Par95]. The detailed study of flow in Au+Au reactions at and below 150 MeV/nucleon can address the question of the apparent contradiction hydrodynamic-like scaling of these flow values and the observation of the disappearance of flow in lighter systems. These heavy beams will require an upgrade of 4π Array in the form of increased granularity of the five most forward hexagonal modules. This upgrade will improve the double hit problems currently being encountered for heavy systems at high energies. Also, beams of Au nuclei at energies up to 150 MeV/nucleon will require coupled cyclotron operation. The 4π Array is ideally suited for these studies with high energy heavy beams because of its main detectors are capable of stopping protons up to 210 MeV while identifying IMFs down to 1 MeV/nucleon. The high speed data acquisition system of the 4π Array allows detailed excitation functions to be obtained in a reasonable amount of running time.

We propose to measure collective flow in Au+Au reactions from 20 to 150 MeV/nucleon in 5 MeV/nucleon steps. In our previous measurements of excitation functions, we have quickly changed the beam energy in small steps by using energy degraders. These closely spaced measurements will allow an accurate determination of the balance energy for Au+Au. In addition, other effects that have recently been shown to be important, such as radial flow and squeeze-out, can be studied in a very systematic and detailed manner in this crucial energy regime.

Light Particle and Fragment Flow In Heavy Ion Reactions

The dynamics of heavy ion reactions have an interesting evolution with incident energy. At low incident energies (< 50 MeV per nucleon), the attractive mean field dominates; particles are emitted mainly in the reaction plane and preferentially to negative scattering angles. As the incident energy is increased beyond $E/A \approx 200$ MeV, the central collision zone become significantly compressed, the attractive nuclear mean field weakens and becomes repulsive. Pressure develops in the compressed central region due to collisional heating and the repulsive mean field, which leads to a directed flow of particles in the reaction plane to positive scattering angles. Participant particles from the compressed central region also preferentially escape in directions above and below the reaction plane (the squeeze-out effect) where their motion is unhindered by spectator matter. Measurements of the many forms of collective flow provide constraints upon transport model calculations, the high density and momentum dependencies of the nuclear mean field and the medium modifications to the elementary cross sections [Dan95]. Analysis directions that promise the isolation of these quantities with significantly increased precision are being pursued, while new flow observables are being quantified.

Azimuthal Correlations

The evolution of collective motion has been explored over a wide incident energy range in experiments at the NSCL and at GSI and Saturne using the Miniball/Wall multifragment detection array. The variation of the dynamics with incident energy can be easily observed via azimuthal correlations or azimuthal distributions [Lac93, Tsa90, Wil90]. Fig. C-30 shows the azimuthal α-particle correlations for ^{84}Kr + ^{197}Au collisions at E/A = 35 - 400 MeV as a function of energy and impact parameter, deduced from the associated charged particle multiplicity [Pea94]. Here $\Delta\phi_{\alpha\alpha}$ denotes the relative azimuthal angle between one α-particle measured at center of mass rapidity $0.2 \leq (y/y_{beam})_{c.m.}$ and another α-particle measured at center of mass rapidity $(y/y_{beam})_{c.m.} \leq -0.02$. (Here y is the rapidity of the measured particle and y_{beam} is the rapidity of the beam; both are evaluated in the center of mass frame.) At low incident energies, maxima are observed at both $\Delta\phi_{\alpha\alpha} \approx 0°$ and $\Delta\phi_{\alpha\alpha} \approx 180°$ consistent with a rotation-like attractive deflection by the nuclear mean field [Tsa91, Tsa93a, Wil90]. With increasing incident energy this rotation-like deflection disappears and is replaced by a peaking at $\Delta\phi_{\alpha\alpha} \approx 180°$ due to a collective sideward directed flow [Dos86, Par95].

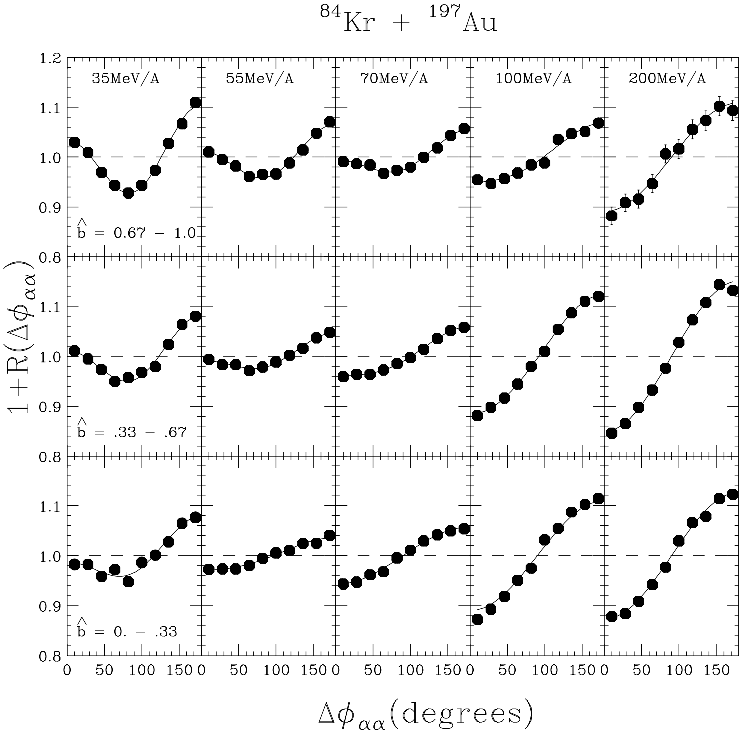

Fig. C-30: α-particle azimuthal correlations for ^{84}Kr + ^{197}Au collisions for E/A=35 - 400 MeV as a function of energy for peripheral (upper panels), mid-central (middle panels) and central (lower panels) collisions.

Energy Dependence of Flow for Asymmetric Heavy Ion Systems.

Flow is generally defined by the rapidity dependence of the mean transverse momentum per nucleon $<p_x/A>$, i.e. $F = d(<p_x/A>)/dy$ at mid rapidity ($y_{cm}=0$) [Par95]. Most current analysis techniques for extracting collective flow observables require the determination of the reaction plane, and there is a consequent sensitivity of these analyses to the dispersion of the experimentally deduced reaction planes relative to actual reaction plane defined by the total angular momentum [Sul92, Dan85]. To avoid the complications associated with this reaction plane, “tensor product” techniques have been introduced [Dan88]. In these techniques, mean values for the flow and the squeeze out ratios are derived from averages over the tensor products of the momenta for two and three particles detected in the same event. Thus the reaction plane is not needed, and the uncertainties of the reaction plane determination do not enter. Corrections for other effects such as nonuniformity of the experimental apparatus, momentum conservation constraints and final state interactions can be included.

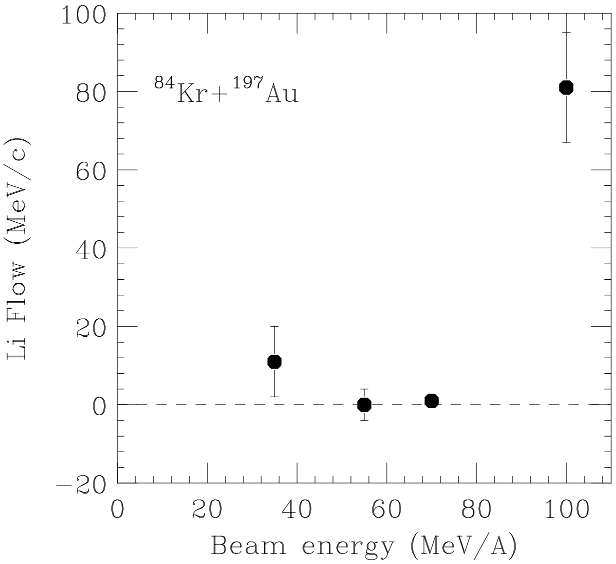

Fig. C-31: Li flow extracted with the “tensor product” techniques as a function of incident energy for central collisions.

Figure C-31 shows the Li flow extracted with “tensor product” techniques as a function of the incident energy for central collisions. These measured values describe the transverse momentum distribution in a coordinate system defined by the beam axis and the total angular momentum and do not require any correction for reaction plane dispersion; the current technique therefore allows a particularly accurate determination of the small collective flow at NSCL energies around E_{bal} where the directed flow vanishes. The measurements indicate a small, but nonzero, flow at E/A = 35 MeV, from E/A = 55 to 70 MeV the flow vanishes, and for E/A ≥ 100 MeV the flow becomes large due to a repulsive compression. The onset of flow around the balance energy is sensitive to the interplay between the attractive mean field and the nucleon nucleon scattering [Wes93]. Calculations predict that comparisons of the directed flow at high energies for this mass asymmetric system to that for mass-symmetric Au+Au allow a separation of effects due to the compressibility of the repulsive mean field from that due to the momentum dependence [Pan93]. Further applications of tensor product flow determination techniques to measurements obtained at the NSCL are envisioned to provide quantitative measurements of flow at energies below and above E_{bal}.

Mass Dependence of Transverse Collective Flow

In general, the momentum and energy distributions of emitted particles contain both thermal and collective components. Thermal energies are generally independent of the particle's mass while the collective energy is proportional to the mass of the emitted particle [Stö86]. Thus intermediate mass fragments (IMF's; $3 \leq Z_{IMF} \leq 20$) provide a more sensitive measure of flow and carry much of flow information [Ono94, Ono95]. Fragment flow is dependent upon the origin and formation mechanism for the fragment. Thus the determination of fragment flow is important for the understanding of the fragment formation mechanism as well as for the determination of flow and ultimately, transport properties like the medium modified cross sections and the compressibility of nuclear matter.

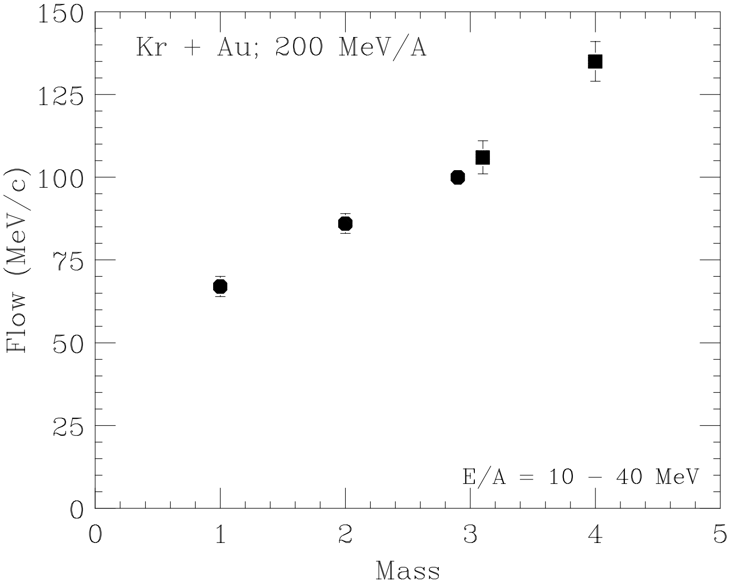

Fig. C-32: Mass dependence of fragment flow for ^{84}Kr + ^{197}Au collisions at E/A=200 MeV.

Figure C-32 shows measured values for the fragment flow as a function of particle mass for Kr+Au collisions at E/A=200 MeV. The observed increase in flow with mass for hydrogen and helium isotopes is consistent with expectations based upon coalescence relationships and previous measurements [Dos87, Ogi89, Par95, Sul90, Tsa86]. Limited fragment flow data for fragments with charge Z ≥ 3 exist [Dos86]; the extension of these data to higher mass and a broad range of incident energies and systems is planned and will provide considerable new information about the dynamics of fragment formation and collective flow.

Onset of Radial Flow

At E/A ≥ 100 MeV, dynamical models [Pei89] predict that the fragment multiplicities will be strongly influenced by a rapid expansion from supranormal densities achieved early in the nuclear collision, and experimental evidence now suggests a significant collective "radial" expansion [Hsi94, Jeo94]. Radial flow effects should be manifested in the fragment energy spectra. Figure C-33 shows the laboratory energy spectra for Boron fragments from near central collisions $\hat{b} < 0.33$. The energy spectra display exponential slopes that become steeper with scattering angle. Such spectra have been well described at lower incident energies and for mass asymmetric systems [Pha92] by a superposition of three isotropically emitting thermal sources corresponding to the decay of a participant region formed by the overlap of the projectile and target as well as the decay of remnant projectile- and target-like spectator nuclei.

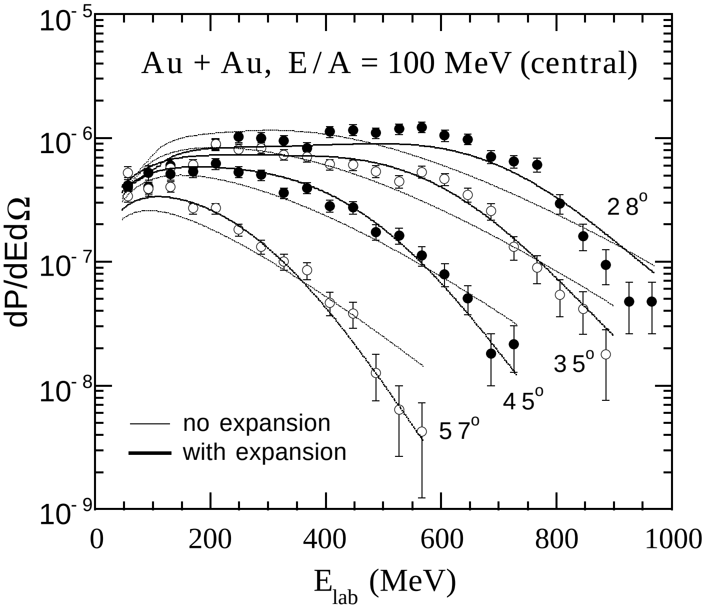

Fig. C-33: Energy Spectra for boron fragments emitted in Au+Au collisions at E/A=100 MeV. The thick and thin lines are fits with three Maxwellian sources with and without collective radial expansion of the central-rapidity source, respectively.

The thin lines in Fig. C-33 indicate best fits to the energy spectra under the assumption of three relativistic Maxwellian distributions. The shapes of the measured spectra are only poorly reproduced. By allowing for a self-similar radial expansion of the (spherical) participant source, the data can be described much better (thick lines). Figure C-34 shows the mass dependence of radial collective expansion velocity. Measurements at E/A = 35 MeV [Dag95] are consistent with a Coulomb expansion, and a negligible radial collective expansion velocity, from a breakup density of less that half that of normal nuclear matter. Further investigations of the onset of radial expansion at 35 MeV < E/A < 100 MeV are needed to clarify the role of expansion in multifragmentation processes. The K500⊗K1200 upgrade will be essential for the extension of the measurements to the heaviest systems.

Squeeze-Out

Significant anisotropies may exist in the azimuthal distributions at mid-rapidity for non-zero impact parameters due to shadowing by surrounding spectator matter. Such azimuthal anisotropies have been modeled by constructing a coalescence invariant ellipsoidal flow energy tensor for each event [Gut90], and diagonalizing the flow tensor to obtain the 3 eigenvalues, λ_1, λ_2, λ_3, and the flow angle θ_{flow}. The reaction plane for the event is defined by the plane containing the major axis of the event ellipsoid, λ_3, and the beam axis. Squeeze out ratios $R_\lambda = \lambda_2/\lambda_1$, defined as the ratio of the out-of-plane eigenvalue to the in-plane eigenvalue of the flow energy tensor, provide the requisite information about the emission anisotropies. Here again, however, this method relies upon the construction of a reaction plane for the event and therefore will suffer from problems associated with the dispersion of the experimentally extracted reaction plane.

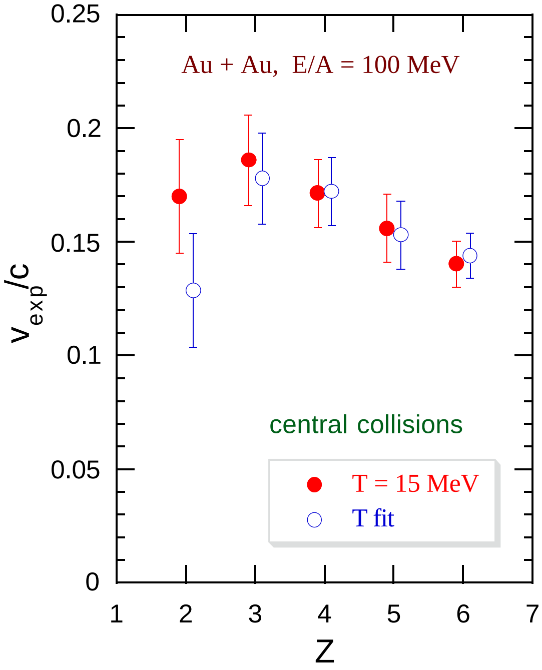

Fig. C-34: Radial collective expansion velocities extracted for fragments for Au+Au collisions at E/A = 100 MeV [Hsi94].

Such problems with the dispersion of the experimentally determined reaction plane may be avoided by the implementation of an appropriate "tensor product" method which relies upon the extraction of mean values for the 3 eigenvalues, λ_1, λ_2, λ_3, and the flow angle θ_{flow} from mean values of appropriately constructed tensor products of the momenta for two and three particles detected in the same event. Details of the procedure may be found in [Dan88].

The impact parameter dependence of squeeze out ratios for Au+Au collisions at E/A=100 MeV are plotted in Fig. C-35. Values for R_λ extracted by the technique in which reaction planes are constructed event-by-event are shown as the open points, and corresponding values obtained by the tensor product technique are shown by the solid points. Values for Rλ extracted by the tensor product technique which avoid reaction plane dispersion better reflect the true event shapes. This occurs because the technique in which the reaction planes are reconstructed eventwise suffers from a poor determination of the reaction plane whenever the transverse flow is small. Poor reaction plane determination will make Rλartificially close to unity because the two transverse coordinates cannot be accurately differentiated. Values for Rλ exceeding unity are observed for central collisions, consistent with a collective out-of-plane expansion and in-plane shadowing by spectator matter. Values for Rλ less than unity are observed at larger impact parameter collisions (b>0.67) indicating an enhanced emission of particles in the reaction plane.

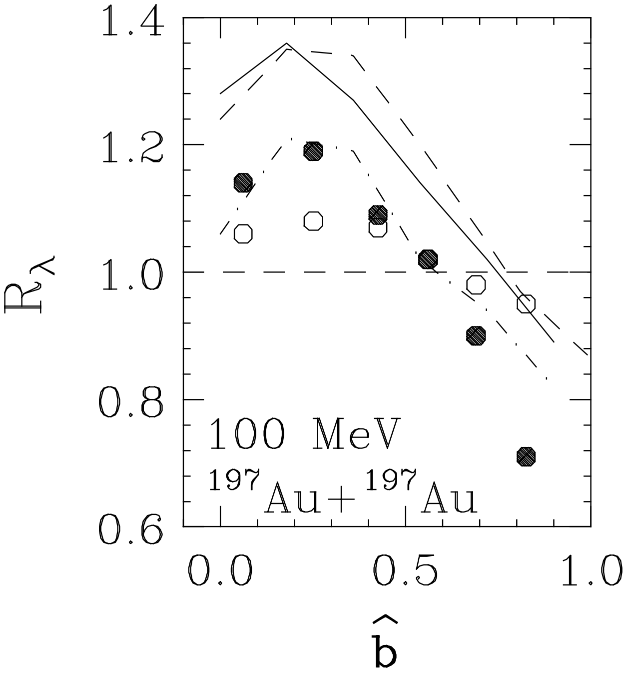

Fig. C-35: Squeeze out Ratios obtained for Au+Au collisions at E/A=100 MeV. Open points show values Rλ extracted with respect to experimentally determined reaction planes and solid points show values extracted with the "tensor product" technique. The solid and dashed lines show the results of filtered BUU calculation with the stiff and soft EOS and the free nucleon-nucleon cross section. The dashed-dotted lines show the result of BUU calculations with the stiff EOS and a nucleon-nucleon cross that has been reduced by 20%.

Values of Rλ calculated with the BUU transport model are also shown obtained with the tensor product technique. All calculations are filtered through the experimental apparatus. At all three energies, the BUU calculations reproduce the data qualitatively. These comparisons indicate that the data at E/A=100 MeV are sensitive to medium modifications of the nucleon-nucleon scattering cross section.

The observation in Fig. C-35 of the onset of squeeze-out phenomena at energies of about E/A=100 MeV is generally expected for a broad range of colliding systems. Utilizing the sensitivity offered by the tensor product method, further constraints upon the medium-modified nucleon-nucleon cross section will be obtained via measurements at lower energies E/A < 100 MeV with the lighter beams accessible with the present K1200 cyclotron and with the heavier beams with the proposed coupled cyclotron facility.

Multifragment Disintegrations: Liquid and Gaseous Phases

Two phase transitions are predicted for bulk nuclear matter: the liquid-gas phase transition at $T \approx 10$ MeV and $\rho < \rho_0$ and a deconfinement transition to quark and gluonic degrees of freedom at $T > 150$ MeV and densities $\rho > \rho_0$. Conditions relevant to the deconfinement transition may be achieved at the Relativistic Heavy Ion Collider (RHIC) during nucleus-nucleus collisions at incident energies of order 100 GeV per nucleon. Temperatures and densities relevant to the liquid-gas phase transition may be achieved in nucleus-nucleus collisions using beams from the K1200 cyclotron at a broad range of incident energies.

Signatures of bulk phase transitions are expected to be sharpest for the largest nuclear systems. Systems with more than 400 nucleons may be formed via nucleus-nucleus collisions at the NSCL. If such systems expand due to thermal pressure or through dynamical compression-rarefaction cycles to sufficiently low densities where bulk nuclear matter is thermodynamically unstable, multifragment disintegrations may result from the rapid growth of density fluctuations. Given sufficient time, these multifragment decay configurations may approach those characteristic of mixed liquid-gas phase equilibrium. Whether this occurs or whether these systems proceed through alternative rapid, dynamically-driven decays or much slower, sequential, statistical decays depends upon details of the reaction dynamics and the time evolution of the nuclear density. Clarification of these issues, the determination of appropriate systems for extracting phase transition information and the extraction of the relevant parameters of the phase transition are essential goals of the reactions program at the NSCL.

Incident Energy and Impact Parameter Dependence of IMF Multiplicities and Charge Distributions

Two detailed excitation functions have been recently measured to determine the impact parameter and incident energy dependence of multifragment decays. Figure C-36 shows the incident energy dependence of the mean intermediate mass fragment ($3 \leq Z_{IMF} \leq 20$) multiplicity $<N_{IMF}>$ for central ^{84}Kr + ^{197}Au collisions measured, at the NSCL for E/A = 35, 55, and 70 MeV and at the Laboratoire National Saturne for E/A = 100, 200 and 400 MeV, using the Miniball/Wall multifragment detection array [Pea94]. The "reduced impact parameter" $\hat{b} = b/b_{max}$ was determined from the measured charged particle multiplicity N_C, assuming a monotonically decreasing dependence of N_C upon impact parameter [Pea94]. The measured onset and decline of the mean IMF multiplicity [Pea94] with incident energy is qualitatively consistent with the expectations of statistical models [Fri90, Bon85, Bon85a, Bar86] of an initial growth of fragment production with increasing excitation energy deposition, followed by a later decline when the system becomes too hot and vaporizes. Both the data for ^{84}Kr + ^{197}Au and corresponding data in Fig. C-37, measured at GSI for ^{197}Au + ^{197}Au collisions with the Miniball and the GSI Aladin spectrometer [Tsa93], indicate that the maximum IMF multiplicities occur in central collisions between heavy nuclei at E/A≈100 MeV. The growth of density fluctuations in very heavy systems is thus optimally investigated at energies E/A < 200 MeV; at higher energies, multifragmentation is predominantly confined to peripheral collisions for which the process has been shown [Ala95] to depend little on incident energy.

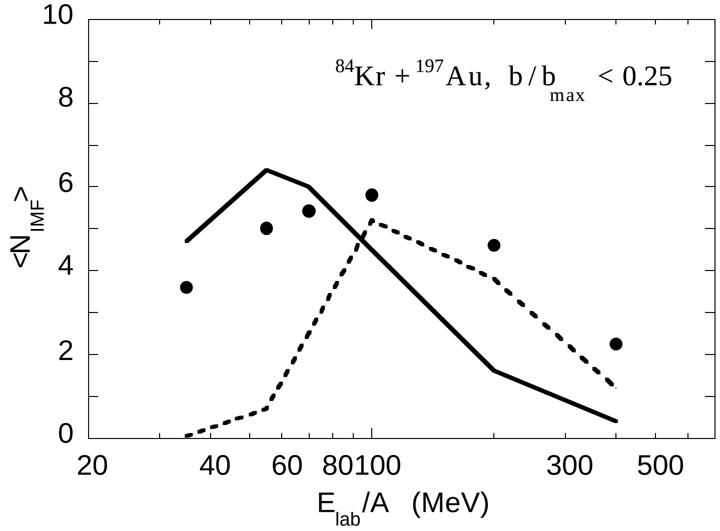

Fig. C-36: The measured incident energy dependence of the mean fragment multiplicity for Kr+Au collisions is shown by the solid points. The dashed and solid curves depict the QMD and QMD-SMM calculations, filtered through the experimental acceptance. [Pea94]

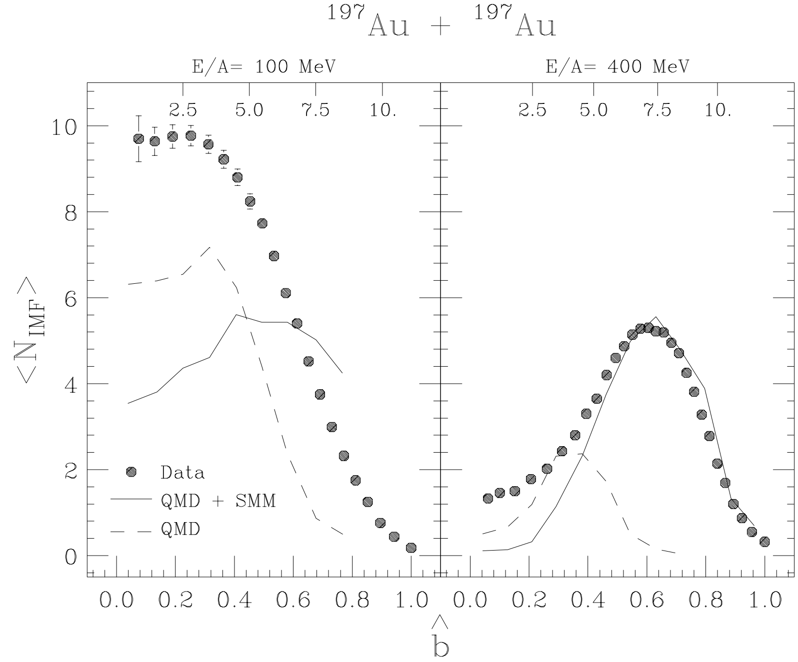

Fig. C-37: The measured impact parameter dependence of the mean fragment multiplicity for Au+Au collisions is shown by the solid points. The dashed and solid curves depict the QMD and QMD-SMM calculations, filtered through the experimental acceptance [Tsa93].

The dashed curves in Figs. C-36 and C-37 represent IMF multiplicities predicted by the Quantum Molecular Dynamics (QMD) model of [Pei92]. These calculations fail to reproduce the large IMF multiplicities observed at lower incident energies in central collisions and at higher incident energies at larger impact parameter collisions. This failure has been attributed to an inadequate treatment of the statistical fluctuations that lead to the decay of highly excited reaction residues which are produced within the model for central Kr+Au collisions at E/A ≤ 70 MeV and for peripheral Au+Au collisions, but are predicted by the QMD model to decay primarily by nucleon and not by fragment emission -- in contrast to expectation from statistical models [Fri90, Bon85, Bon85a, Bar86, Bot87]. The suppression of statistical fragment emission in QMD calculations is not fully understood, but it may be related to the classical heat capacities and the neglect of quantum fluctuations by the model.

The solid curves in Figs. C-36 and C-37 represent multiplicities predicted by hybrid-model calculations wherein the decay of the hot reaction residues from the QMD model is treated by the Statistical Multifragmentation Model (SMM) of [Bot87] which contains a cracking phase transition at low density. At high incident energies, E/A ≥ 100 MeV, this hybrid model more closely approximates the IMF multiplicity at larger impact parameters but underpredicts the IMF multiplicity at small impact parameters. For such collisions, IMF's are either produced by the QMD model in insufficient quantities or are too highly excited to survive the SMM statistical decay in numbers consistent with the experimental observations.

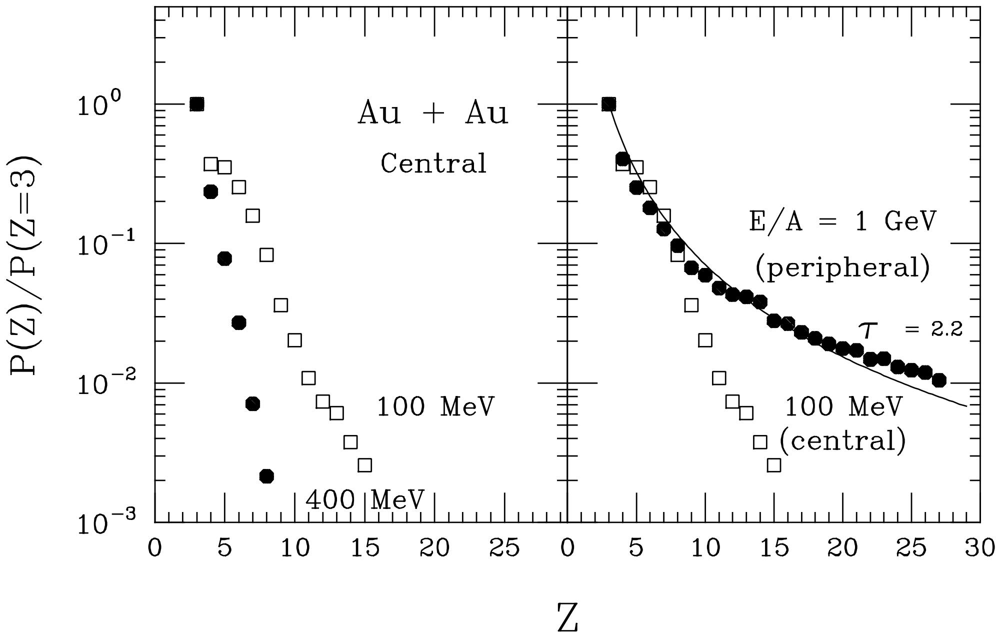

Fig. C-38: (Left Panel) Charge distributions observed in central Au+Au collisions. The data are from refs. [Tsa93, Kuh93]. (Right Panel) Comparison of charge distributions for central Au+Au collisions at E/A=100 MeV to peripheral Au+Au collisions at E/A=1000 MeV. All distributions are normalized to 1 at Z=3 [Kun95].

Fragment charge distributions for central Au+Au collisions at E/A= 100 and 400 MeV are compared in the left panel of Fig. C-38; the right panel compares those for central Au+Au collisions at E/A=100 MeV and peripheral Au+Au collisions at E/A=1000 MeV. Collective expansion may reduce the phase space density at freeze out [Kun95], and this results in steeper charge distributions for central collisions at E/A=100 MeV (for which expansion plays an important role) as compared to those resulting from the decay of projectile fragments produced in peripheral collisions at E/A=1000 MeV (for which expansion has been shown to be less important), see right panel Fig. C-38. Whether the dilution of the phase space density due to rapid collective expansion is a dominant physical effect which causes the energy-dependence of the charge distributions shown in the left panel is under present scrutiny. The extension of these investigations of charge distributions to lower incident energies is of particular interest in such heavy systems. Landay-Vlasov calculations predict that the large Coulomb field of this system causes an instability that leads to a bubble-like breakup configuration [Bor93]. As discussed below, a bubble-like decay configuration will lead to an enhanced production of IMF's relative to that expected for a more compact spherical object. Further exploration of such heavy systems at E/A< 100 MeV is clearly a priority in the upcoming years because of the pivotal role they play in the extrapolation of multifragmentation observables to the limit of infinite neutral matter for which the liquid-gas phase transition is accurately defined.

Exotic Decay Configurations

Recent transport model calculations indicate that non-compact bubble or ring-shaped decay configurations may occur at higher incident energies, even for non highly charged systems [Mor92, Bau92a, Bau92a]. The occurrence of such non-compact decay configurations depends upon impact parameter and the initial compression. Calculations suggest that measurements of the detailed conditions leading to ring or bubble shaped decay configurations may provide constraints on the nuclear incompressibility. While direct experimental evidence for such non-compact decay configurations is virtually nonexistent for central collisions, experimental searches for signatures of such effects are underway at the NSCL and will be a strong focus of continued research. Many-body trajectory calculations predict [Gla94], for example, a measurable difference between parallel ($|\hat{v}_{rel}\cdot\hat{z}|\geq 0.75$ and transverse ($|\hat{v}_{rel}\cdot\hat{z}|\leq 0.25$) two-fragment correlation functions (v_{rel} is the two fragment relative velocity and $\hat{z}$ is the beam direction).

Non-compact decay configurations may have a profound impact on the applicability of scaling laws which have been used to explore critical phenomena in nuclear systems. To assess sensitivities to the breakup geometry for finite systems, percolation models are attractive since they exhibit phase transitions in infinite systems, can be generalized to finite systems, describe the power-law behavior of many measured fragment mass distributions [Bau85, Cam86], and have been instrumental in to the development of techniques to extract critical exponents [Ell94]. The results of bond-percolation calculations [Pha93] for the decay of spherical nuclear systems are compared in Fig. C-39, to fragment multiplicities measured [Bow91] for ^{129}Xe + ^{197}Au collisions. Thick and thin curves represent results of filtered and unfiltered calculations [Pha93], respectively. In these calculations, the critical bond-breaking parameter, p=0.7, was employed which provides an upper bound for the admixture of IMF’s among the emitted charged particles. The calculations fail to reproduce the large fragment admixtures measured for the ^{129}Xe + ^{197}Au system if the decaying system is assumed to have a spherical shape. For non-compact decay configurations, on the other hand, the model can produce larger fragment admixtures [Pha93], compatible with those observed. As an illustration, Fig. C-39 shows the enhancement in fragment production which can be obtained within a percolation ansatz from the breakup of bubbles as compared to that of spheres [Pha93]. Percolation calculations for finite systems indicate a strong dependence of extracted "critical" parameters on the geometrical configuration of the system at breakup. Compilations of power law exponents τ characterizing mass distributions of the shape $\sigma(A) \propto A^{-\tau}$ observed for different entrance channels [Li93], impact parameters [Ogi91], or incident energies [Cam86, Li93, Ogi91] may contain different geometrical configurations which render a minimum in τ difficult to interpret. For infinite systems, critical exponents govern the scaling laws near critical points. The percolation calculations indicate that the application of scaling laws to finite systems of potentially complex breakup geometries could be much less straight forward than originally surmised.

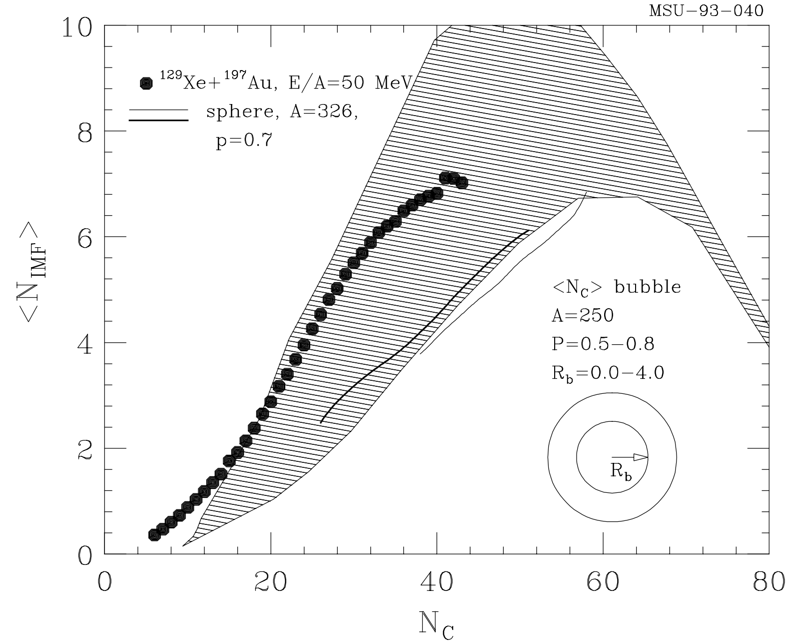

Fig. C-39: Relation between average IMF and charged particle multiplicities. Solid points represent values measured for ^{129}Xe + ^{197}Au at E/A=50 MeV. Thin (thick) solid line shows the raw (efficiency corrected) percolation calculation for a solid sphere using the near-critical bond-breaking parameter p = 0.7. The hatched area shows the range of average IMF and average charged particle multiplicities predicted by percolation calculations for bubble-shaped breakup configurations [Pha93].

Most transport model calculations predict the formation of elongated neck-like structures in peripheral collisions when the relative velocity between projectile and target approaches the nuclear-matter sound-velocity [Col93]. Similar to the expectations for the breakup of toroidal or bubble-like systems formed in central collisions, the breakup of elongated cylindrical systems should lead to enhanced emission of medium-size fragments relative to that expected from the breakup of spherical distributions. First experimental explorations of such breakups have been conducted for the ^{129}Xe + ^{nat}Cu system at E/A=50 MeV [Mon94]. Figure C-40 shows a two-dimensional projection of the velocity of beryllium nuclei onto the reaction plane determined by the beam axis and the velocity of a projectile-like residue, for events in which only one intermediate mass fragment (IMF) is detected in addition to the projectile-like fragment. The velocities of beryllium nuclei are plotted as the large contour plot in the center of the frame. The measured velocity distribution of the projectile-like residue and the deduced velocity of the target-like residue are also shown as contour plots localize near the labels "PLF" and "TLF" in the figure. A clear enhancement is observed for beryllium velocities in between those of the projectile- and target-like residues. Figure C-41 shows differential multiplicities of IMF's originating from the neck and from isotropically decaying projectile-residues, observed for collisions of reduced impact parameter $\hat{b}\approx0.6$. IMFs from the neck are relatively more abundant, and they have a somewhat broader charge distributions as may be qualitatively expected for the cylindrical geometry of such decay configurations. Neck fragmentation may prove to be an excellent first testing ground for theories designed to describe the growth of fluctuations of the mean field. Future investigations will explore how the neck evolves into the fireball with increasing incident energy. Investigations of the impact parameter dependence of neck formation and decay will address questions regarding the disintegration of the neck into multiple IMF's. The precision of the impact parameter selection in such investigations will be greatly improved with the Rochester University Superball as an impact parameter filter.

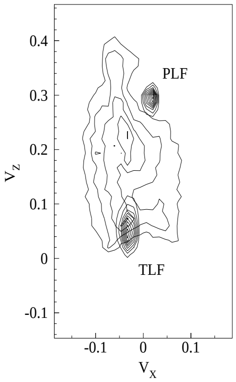

Fig. C-40: Two dimensional projection of the velocity of beryllium nuclei onto the reaction plane determined by the beam axis and the velocity of a projectile-like residue. This distribution is somewhat modified, though not strongly, by the experimental detection efficiency.

Emission Temperatures

Statistical treatments of fragment emission processes require the knowledge of the local excitation energy density (or temperature) at the time of emission. The extraction of these emission temperatures from the kinetic energy spectra of emitted light particles or intermediate mass fragments is complicated by distortions of the energy spectra by Coulomb distortions, by collective expansion, flow or rotation effects, and by fluctuations of the total fragment momentum due to the Fermi and thermal motion of its A_f constituent nucleons. Information about the excitation energy density of regions of fragment formation can be extracted alternatively from the relative populations of states [Gla94, Sch93a, Zhu92] or from ratios constructed of the yields of different fragment isotopes [Poc95]. In many cases, temperatures extracted from excited state populations are strongly affected by sequential feeding from higher lying states [Zhu92, Che88], but for certain widely separated states in some light nuclei (e.g. ^{4}He, ^{5}Li, and ^{8}Be) uncertainties due to feeding from higher lying states are of minor importance [Che88].

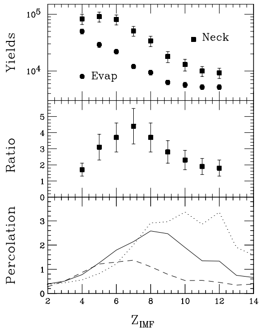

Fig. C-41: Upper panel: A comparison of the extracted multiplicities of IMF's emitted from the neck (solid squares) and from the isotropically decaying projectile-like residue (solid points). Middle Panel: The ratio of multiplicities from the neck divided by the corresponding multiplicity for statistical emission from the projectile-like residue. Lower Panel: The corresponding ratio of multiplicities predicted by percolation calculations assuming a dumbbell geometry consisting of target- and projectile-like residues joined by a neck of variable width [Mon94].

Figure C-42 summarizes [Sch93a] emission temperatures determined from the relative populations of widely separated states in ^{4}He, ^{5}Li, and ^{8}Be for a number of reactions with incident energies ranging from $E/A \approx 30$ - 200 MeV. Temperatures have also been extracted [Poc95] from the isotopic yields of Lithium and Helium nuclei according to the semi-empirical relation

$$T_{\mathrm{HeLi}} = 16 / \ln\left(2.18 \cdot \frac{Y_{^6\mathrm{Li}} / Y_{^7\mathrm{Li}}}{Y_{^3\mathrm{He}} / Y_{^4\mathrm{He}}} \right) \quad .$$

The extracted temperatures from both techniques are of the order of 3 - 6 MeV, significantly smaller than "kinetic" temperature parameters which characterize the slopes of the kinetic energy spectra of emitted particles, and they exhibit [Kun91, Sch93a] a small, but significant rise with incident energy (see Fig. C-42) or deduced excitation energy [Poc95]. These features have been reproduced in statistical models in which low density phase transitions play a role [Fri90, Bon85, Bon85a, Bar86] and via non-equilibrium transport model calculations in which the connection to phase transitions is less evident

[Xu93]. A sensitivity to the low density nuclear equation of state is observed in a number of calculations [Fri90, Xu93].

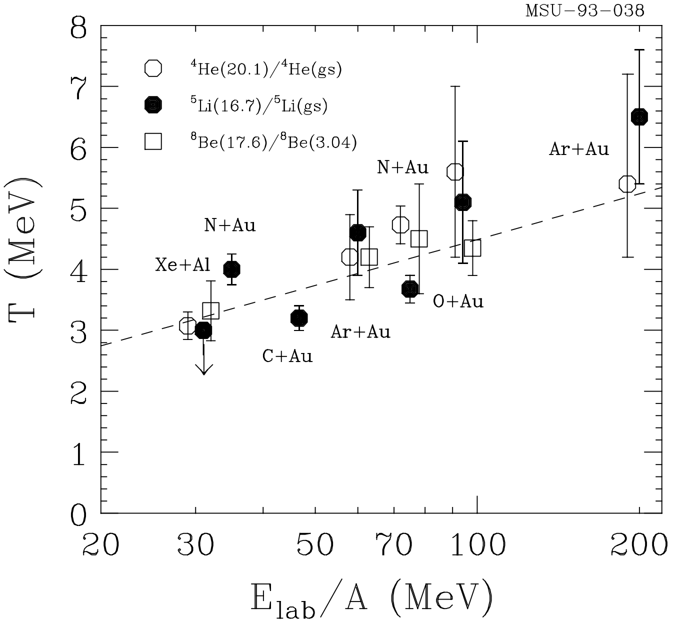

Fig. C-42: Emission temperatures extracted from the relative populations of widely separated states in ^{4}He, ^{5}Li, and ^{8}Be. From ref. [Sch93a].

The experimental results summarized in Fig. C-42 were obtained without impact parameter selection and for systems of different size. Therefore, the extracted temperatures represent averages over very different classes of events. Recent measurements with impact parameter selection [Zhu92] reveal that populations of excited states are more consistent with local thermal equilibrium for central collisions than for peripheral collisions. Additional measurements are needed to cross-calibrate the two techniques employed in Fig. C-42 and ref. [Poc95] and to map out the relationship between excitation energy and temperature for heavy systems of fixed mass and small impact parameter. We plan to determine the densities and temperatures for a variety of multifragmentation decays and thereby map out the variation of the fragment charge and multiplicity distributions as a function of the freeze out density and temperature. For this research, a more efficient particle hodoscope than the one presently available at the NSCL is needed. Such a hodoscope is being proposed for general lab work particularly for direct reactions with radioactive beams.

Intensity Interferometry

Information about the space time-evolution of the reaction zone can be obtained via intensity interferometry, i.e. measurements of two-particle correlation functions at small relative momenta [Koo77, Boa90, Bau92]. Basic features of the correlation functions for different particle pairs depend on details of the final state interaction between the two particles and, for the case of identical particles, on quantum statistics.

Tests of Transport Theory via 2p-Correlation Functions

In recent years, we have performed detailed measurements of two-proton correlation functions [Gon91, Gon91a, Lis93, Lis93a] to test the space-time evolution of the reaction zone as predicted by microscopic transport models based upon the BUU transport equation. The two-proton correlation function exhibits a minimum at relative momentum $q = \frac{1}{2}|p_1 - p_2| \approx 0$, due both to antisymmetrization and the repulsive two-proton Coulomb interaction. For small sources, it exhibits a pronounced maximum at $q \approx 20$ MeV/c, due to the attractive S-wave nuclear interaction. This maximum decreases for increasing source dimensions and/or emission time-scales.

Figure C-43 gives an example of two-proton correlation functions, measured without impact parameter selection for ^{14}N + ^{27}Al at E/A = 75 MeV [Gon91]. The observed pronounced momentum-dependence qualitatively indicates that high-energy protons are emitted on a faster time-scale and/or from a smaller source than low-energy protons. This momentum dependence is reproduced by microscopic BUU transport calculations, appropriately averaged over impact parameter, see solid curves. The calculations were found to exhibit little sensitivity to the equation of state, but they are sensitive to the in-medium nucleon-nucleon cross section [Gon91].

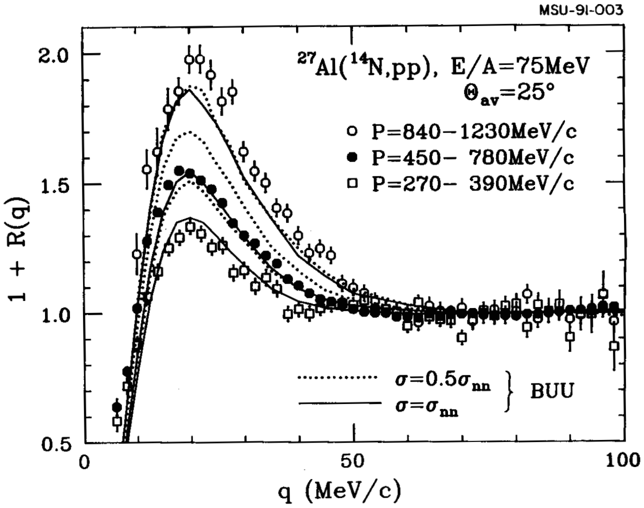

Fig. C-43: Inclusive two-proton correlation functions, measured for the reaction ^{14}N + ^{27}Al at E/A = 75 MeV with different cuts on the total momentum $P = |p_1 + p_2|$. Dotted and solid curves depict BUU predictions using in-medium cross sections $\sigma = 0.5\,\sigma_{nn}$ and $\sigma = \sigma_{nn}$, respectively [Gon91].

Model predictions of correlation functions depend strongly on impact parameter because the space-time evolution of the reaction zone is different for central and peripheral collisions. Results from the first [Lis93] study of two-proton correlation functions with simultaneous cuts on the event centrality and on the total momentum of the proton pair are shown in Fig. C-44. The figure shows the total momentum dependence of the average height of the correlation function in the peak region $<1+R>_{15\text{-}25\ \mathrm{MeV/c}}$. Data and model predictions are represented by full and open symbols, respectively. For central collisions (top panel), the agreement between experimental and theoretical correlations is quite good, suggesting that the BUU transport theory provides a reasonable description of the final phase space density distribution of nucleons emitted in these collisions. For peripheral collisions (bottom panel), on the other hand, the BUU transport theory underpredicts the total momentum dependence of the correlation function, pointing to areas in which future experimental and theoretical work is needed.

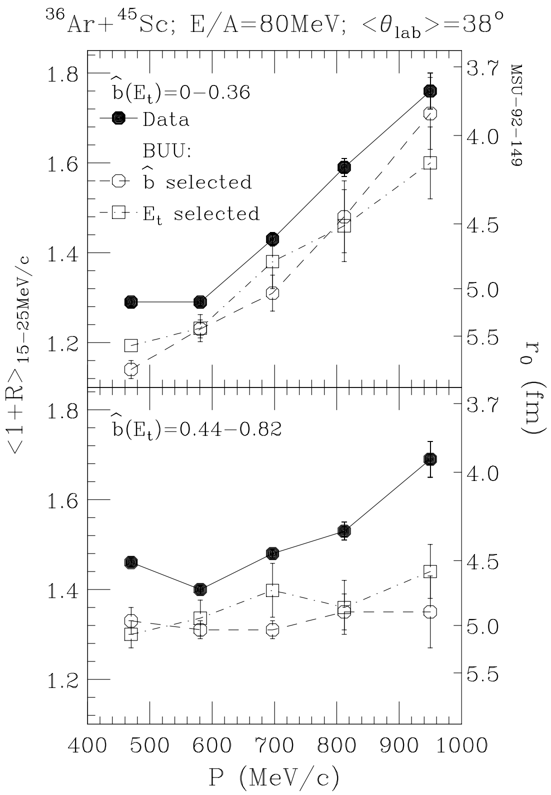

Fig. C-44: Total momentum dependence of the average height of the two-proton correlation function, $\langle 1+R(q)\rangle_{15\text{-}25\ \mathrm{MeV/c}}$, for central (top panel) and peripheral (bottom panel) collisions. For reference, the right-hand axis gives the Gaussian radius of a zero-lifetime spherical source that produces a correlation function with the same peak value. Solid and open points represent data and transport model predictions, respectively. [Lis93].

Suppressed correlation functions, observed at lower total momenta, P, in Figs. C-43 and C-44, signify either that the emission of less energetic protons occurs over a longer time or from a more extended emission volume. Correlation function techniques may help distinguish these scenarios from each other, as long-lived sources generate non-spherical phase-space distributions which display different dependencies of the two-proton correlation function on the direction of the relative momentum $\vec{q}$ than those characteristic of prompt emission from an extended spherical source [Gon91a, Pra87]. Such directional dependencies are difficult to detect and require a clear characterization of emitting system. They have recently been observed for central collisions of ^{36}Ar + ^{45}Sc at E/A=80 MeV [Lis93a]. The data were consistent with emission from a spherical Gaussian source of radius and lifetime parameters r_o = 4.7 fm and τ = 25 fm/c, but also with BUU predictions which indicated a more complex (ring-shaped) source geometry [Han94]. Independent confirmation of such more complicated source geometries requires data of much improved statistical accuracy than currently available [Han95].

For reactions below E/A ≈ 80 MeV, BUU transport calculations appear to describe the space-time evolution of the emitting system rather well -- at least for central collisions. However, difficulties are observed at higher incident energies [Kun93, Han95], E/A ≈ 200, where the BUU simulations greatly overpredict the magnitudes of the correlation functions at $q \approx 20$ MeV/c. The origin of this discrepancy is presently unknown; it could be due to the expansion and subsequent multifragment disintegration of the system and/or due to non-negligible contributions from longer-lived particle-unbound states. Since the experiment at 200 MeV had been performed without impact-parameter selection, we have begun measuring impact-parameter selected correlation functions at energies above 100 MeV to pinpoint at which energy the discrepancies between experiment and theory become appreciable and whether the model also fails for central collisions. Experiments for Ar+Sc at E/A = 110 and 160 MeV are currently being analyzed, and the future direction of two-proton correlation program will depend on the outcome of this analysis. It has, however, become clear that a more efficient hodoscope will be necessary for the needed high-statistics measurements which allow both impact-parameter selection as well as directional cuts on $\dot{q}$ of sufficient sensitivity to elucidate the tri-axial shape of the phase space distributions of emitted protons. We plan to build the needed high-efficiency hodoscope and resolve this important issue during the next five years.

Determination of Compound Nucleus Lifetimes via 2n-Correlation Functions

Much effort has been devoted to gain information about the intrinsic fission time scales for compound nuclei which are now known to be much longer than expected from statistical theory, see e.g. [Hin92, Ike94] and references therein. Fission time-scales are generally derived by the utilization of neutron and charged-particle emission as a "clock", i.e. by measuring the relative yields of pre and post-scission neutrons or charged particles. This assumes the accuracy of the light-particle emission rates predicted by the statistical theory of compound nuclear decay. However, the predicted light-particle evaporation times of $\tau < 10^{-20}$ s have not been tested by experiment and are, hence, not calibrated.

Proton and neutron evaporation time scales in the interesting range near 10^3 fm/c can be determined from 2p and 2n correlation measurements. Indeed, longitudinal and transverse two-proton correlation functions measured for ^{129}Xe + ^{27}Al collisions at E/A = 31 MeV could be described in terms of emission from a spherical source lifetime $\tau = 1400 \pm 300$ fm/c [Lis94]. Unfortunately, Coulomb distortions in the field of the heavy fusion residue may not be negligible for the evaporation of low-energy protons, and the Koonin-Pratt approximation may become inaccurate [Gon92]. While technically more challenging than two-proton intensity interferometry, two-neutron intensity interferometry [Cro93, Iek93] is free from Coulomb distortions while retaining sensitivity to the two-neutron interaction and to antisymmetrization. We plan to perform high-quality two-neutron correlation-function measurements for different directional cuts on $\dot{q}$ in order to calibrate the evaporation-time scales predicted for compound nucleus decay and to provide an experimental test of the importance of final-state Coulomb distortions in two-proton intensity interferometry both for evaporation and preequilibrium processes. The Neutron Wall now under construction at the NSCL, will be uniquely suited for these experiments.

Two-Fragment Correlation Functions

In view of the difficulties [Bow91, Tsa93] that dynamic models have in reproducing the multifragmentation process, considerable theoretical effort has been spent to develop statistical treatments of fragment formation and to link these treatments with transport theory via hybrid approaches [Bow92, Bla92]. Current statistical models alternatively employ two extreme assumptions about the time scale for fragment emission. In models of sequential decay (see, for example, refs. [Fri83, Cha88, Fri90]) a sequence of "binary" mass splits is assumed with complete loss of memory between successive emissions. Since the decay of hot nuclei is too rapid to allow re-equilibration between successive binary splits, other models [Bon85, Bon85a, Gro86] utilize the alternate extreme assumption of prompt multifragment disintegration of an expanded system.

Experimental information about the space-time characteristics (i.e. source size and lifetime) can be extracted from two-fragment correlation measurements [Kim91, Kim92, Bow93]. As an example, Fig. C-45 shows show two-fragment correlation functions measured and calculated [Gla94] for central ^{36}Ar + ^{197}Au collisions at E/A = 50 MeV. Correlation functions without directional cuts (solid points and thin curves) exhibit the known space-time ambiguity (smaller source radii can be traded off against larger emission times). The calculations predict that this space-time ambiguity can be reduced by employing directional cuts (thick curves), but unfortunately the data are of insufficient quality to fully resolve this ambiguity. Calculations further predict that more detailed information about the geometrical configuration [Gla93] and the relative sequence of emission of different fragments can be obtained from high-statistics two-fragment correlation measurements performed with improved resolution and for tight cuts on impact parameter and the direction of $\vec{v}_{red}$. For example, two-fragment correlation experiments may be used [Gla93] to test the predicted [Bau92a, Mor92] formation of ring-shaped breakup configurations. We plan to perform such measurements in the near future. Especially for non-central collisions, the combined capability of the Miniball/Miniwall arrays and the SuperBall neutron multiplicity meter should provide event characterization with the high selectivity needed for a clean definition of the collision geometry.

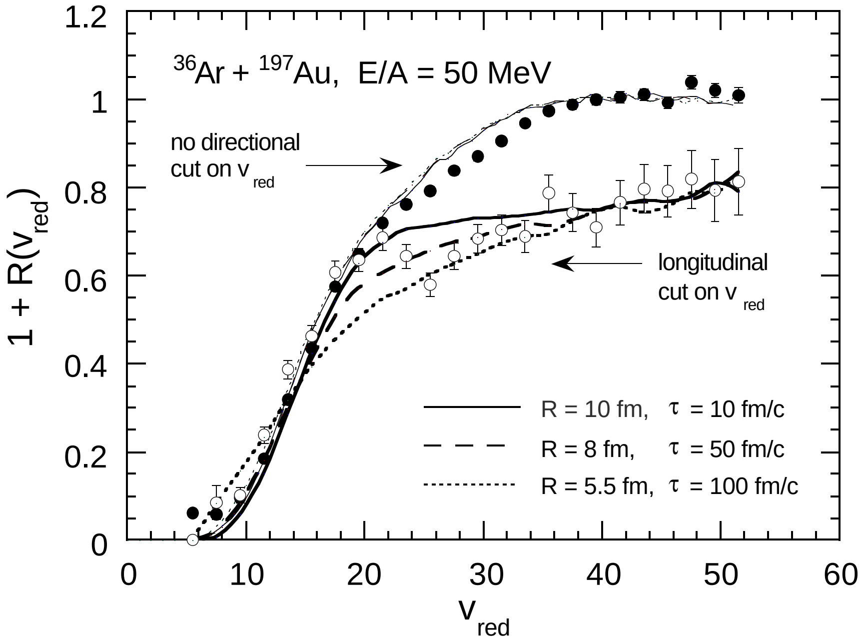

Fig. C-45: Two-fragment correlation functions for central Ar+Au collisions at E/A = 50 MeV without (solid points and thin curves) and with (open points and thick curves) directional cuts.

C-V: Proposed Accelerator and Instrumentation R&D

Beam Dynamics and Diagnostics

High Intensity Beam Dynamics

The desire to achieve beams of increasingly higher intensity and quality has required correspondingly greater detailed consideration of the beam diagnostics and the underlying beam dynamics. This, for example, will be particularly true for the K500⊗K1200 Project where the high intensity beam quality must be conserved at each stage of the acceleration chain. Therefore, during the next funding period, we will develop and implement diagnostic capabilities for high intensity, high quality beams. In particular, it is anticipated that the space charge forces will be an important consideration both for transport to as well as acceleration in the cyclotrons. We will build upon our beam diagnostic developments discussed below to produce beam parameter measurement systems appropriate for use with high intensity beams.

Internal Beam Dynamics Studies with a TV Probe

Building upon our successful use of scintillators and a frame grabber to tune and study external beams [Mar89], we have developed a beam probe which allows direct inspection of the beam inside the K1200 cyclotron [Mar91]. A small TV camera mounted in close proximity to a ZnS covered aluminum plate is used to obtain a detailed view of the radial and vertical current density with a position resolution of about 0.05 mm. Total beam currents below one electrical pA are easily analyzed. This new probe has been in use for more than a year and has given a very satisfactory performance. It allows us to measure beam parameters that were unavailable before and to automate some labor-intensive K1200 beam tuning procedures.

The first observation made with the probe demonstrated that the internal K1200 beam was oscillating about the median plane by as much as 2 mm. Since the beam size is about 1 mm, the oscillation significantly increased the effective beam size. In order to reduce the vertical oscillations, an asymmetric current supply was added to the top and bottom trim coil 0 which together with the adjustment of the inflector vertical position removed the vertical oscillation. This effect was not previously diagnosed since the original current probe did not have adequate resolution to detect this error.

As discussed in the March 1992 operating grant proposal, we have developed an automatic beam centering system and have studied the beam dynamics of resonance crossing with the TV probe. If the beam is radially centered, the width of the beam trace seen on the probe should be equal to the radius gain per turn and approximately constant in a small region of radii. If the beam is off-center, the beam width will appear to fluctuate when moving the probe radially. A computer program was developed which uses the TV probe information to center the beam automatically. The program searches in the phase and amplitude of the first harmonic bump used to center the beam until the beam width observed in a radius range is constant. The program has control of the probe and the harmonic coils. The process takes approximately 12 minutes with convergence in most cases and has the intelligence to ignore spurious effects such as beam interruption due to rf sparks. The program is now routinely used during beam tuning.

The TV probe has provided and will continue to provide a strong diagnostic tool for improving the K1200 beam quality. Since it provides significantly more detailed information on current density as a function of radial (r) and vertical (z) position than the previously available diagnostic (differential probe), it has allowed the study of the beam quality and halo formation during the acceleration process. One of the most interesting phenomena evaluated was the crossing of the $\nu_r=2\nu_z$ resonance. The beams in the K1200 cyclotron cross the $\nu_r=1$ resonance between 0.65 m and the extraction radius of 1.00 m, depending on the ion energy and Q/A. Beam losses are minimized by crossing the resonance with a centered beam. This is normally possible unless the resonance crossing occurs just before extraction. The computer simulations of the TV probe observations have been successful in reproducing the observed phenomena and validating our simulation model of the K1200 [Mar93].

The simplification offered by inserting the camera close to the scintillating plate, compared to using an optical system with its associated optical loses, motivated the design of the K1200 TV probe. We have recently commissioned a new TV probe for the K500 cyclotron using a rigid borescope to transfer the scintillator image to a standard TV camera outside the cyclotron. In the future, we will be developing further diagnostics of this type with improved resolution and more importantly, with higher beam intensity capabilities for both cyclotrons.

Internal Beam Timing Measurements

In the March 1992 operating grant proposal we discussed the development of an internal timing probe for the K1200 cyclotron. This project has been successfully accomplished. A silicon detector with the active area extended to its edges by cutting the guard rings has been used to measure the internal beam phase width. This device has been installed in a probe drive that allows the measurements to be performed between a radius of 32 inches and the extraction radius. In conjunction with the phase slits installed at a radius of 7 inches we have been able to reduce the circulating beam phase to 4 degrees. This beam phase helps to meet the requirements of the experiments which employ time of flight measurements.

Future efforts in this context will seek to develop probes which allow similar measurements but with the full intensity, space charge affected beam. Initial investigations have pointed toward non-interceptive schemes which will be developed during the next funding period.

Cyclotron Codes

The K1200 operation has very successfully used calculated settings for the trim and main coils as well as calculated positions for the extraction elements (for which there are approximately 27 different drives). This agreement with calculation permits beam changes in a short time and very efficient scheduling of the facility. The main code utilized for the calculation evolved from many separate computer programs developed during the last thirty years at our Laboratory. This particular code was written specifically for the K1200 cyclotron. We now plan to modify the code to accept a more general description of any cyclotron and to provide a more flexible and useful graphical interface. This code will then be made available to the community in general, and will also provide an important tool for the K500⊗K1200 Project.

Collaborations with Other Institutions

We have continued collaborations with other institutions such as Orsay, Texas A&M, ORNL, Chalk River and LBL. We recently collaborated with the ORNL in support of a design for a new central region associated with their planning of a radioactive beam facility upgrade. As discussed in the section on medical accelerators, we have had a collaboration with IBA (Ion Beam Applications) a Belgium company. We have made available to them some of our orbit codes to continue the design of their 235 MeV proton cyclotron to be installed at Mass General Hospital since the complicated magnetic structure of their cyclotron design required more accurate codes than they had available.

In general, these collaborations have been fruitful, and we foresee similar collaborations for the future.

Separated-Sector Cyclotron Studies

In the process of evaluating alternative possibilities to increase the capabilities of our facility, a separated sector cyclotron was studied. The design specifications were for a device which would accelerate beam from the K1200 cyclotron to an energy of 500 MeV/u for fully stripped light ions and a final energy of 100 MeV/u for the heavier ions (Au-U).

There has been a proliferation of superconducting cyclotrons during the last decade [Blo86, Sch89, May89, Ale92, Sch92]. All of these accelerators are of the compact type with the circular superconducting coils wound around the whole beam chamber. Only the coil package is at liquid helium temperature. By increasing the coil magnetic field, the flutter is decreased because of the smaller difference between the magnetic field in the hills and valley, which causes a decrease of the vertical focusing. The separated sector cyclotron offers an attractive alternative when higher energies are required. The coils are wrapped around each sector and the magnetic field difference between hills and valleys is very large, increasing the flutter and providing stronger vertical focusing. An additional advantage is the large space in the valleys which allows rf cavities with higher voltages and thereby increased turn separation. Injection from another cyclotron and extraction are also simplified.

Room temperature separated sector cyclotrons have been built at many laboratories (PSI, IUCF, GANIL, RIKEN, etc.), but no superconducting coils have been used as the sector coils. The Munich group [Tri84] worked for some time building a sector magnet for a superconducting separated sector cyclotron. More recently the GANIL group [Ber92, Baz90, Vec] studied in detail the design of a separated sector cyclotron with characteristics very similar to our study design goals. We have borrowed extensively from their studies.

The evaluation concentrated on a six-sector cyclotron with an injection radius of 2.5 m and extraction radius of approximately 5 m. One of the difficulties associated with designing a variable energy cyclotron capable of accelerating ions over a broad range of charge to mass (Q/A), is the large dynamic range of magnetic fields necessary to maintain isochronicity. Due to the magnitude of the adjustment required, superconducting trim coils are necessary, and to accommodate the trim coil package, a large median plane gap between pole tips is necessary. Figure C-46 shows as dashed curves the range of isochronous fields necessary to achieve the high energy limit for the Q/A values considered. As shown in Fig. C-46, the field level and the gradient vary substantially.

It is possible to achieve a large radial gradient in the magnetic field by increasing the fraction of azimuth occupied by the hills and spiraling the sectors. However, this requires that the coil be wound with a negative curvature which causes a significant manufacturing difficulty due to the large forces caused by the high magnetic fields produced with the superconducting coils.

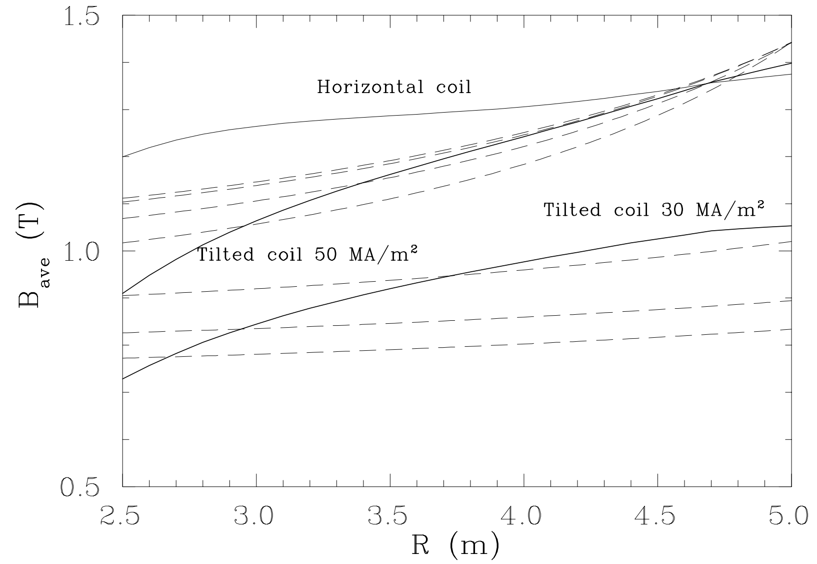

Fig. C-46: Average field for several different isochronous fields (dashed lines) ranging from Q/A=0.5 and E/A=496 MeV/A to Q/A=0.35 and E/A=98 MeV/u. The solid line on top shows the average field obtained in the TOSCA model with horizontal coils parallel to the median plane. The thicker solid lines show the average field for the tilted coil model at two different excitations.

Traditionally the main sector coils have been placed parallel to the median plane, with the primary contribution to the magnetic field coming from the iron. However, in order to reduce the magnitude of the trim coil adjustment required to maintain isochronicity, the effect of tilting the sector coil was explored. Using the computer code TOSCA [Vec], the magnetic field was calculated for several different configurations of the sector coil with a small tilt (approximately 10 degrees) with respect to the median plane. See Fig. C-47. This tilt moves the inner section of the coil away from the median plane, decreasing its field and increasing the gradient in the total resulting field. When the coil current is reduced, the iron contribution becomes more important and the effect of the tilt decreases, matching the required smaller gradient at lower excitations. Figure C-46 shows the average fields for a horizontal coil with a current density of 50 MA/m^2 (solid line on top) and for one of the tilted coil models at two different excitations. The tilted coil produces a magnetic field better matched to the large gradient needed for the high energy fields. This implies that a smaller correction field would be necessary from the trim coils. Further refinements such as sloping the iron pole tip were also considered.

The proposed configuration for a separated sector magnet with tilted coils, provides a field with a radial gradient much closer to that required for a high energy cyclotron (Q/A=0.5, E/A=500 MeV/u). The disadvantage of this configuration arises from the mechanical requirements associated with the large forces on the coil, which forces the pole tips to be at liquid helium temperatures or requires more complicated mechanical structures.

Work was stopped on this design concept when the decision was made to pursue the more cost effective K500⊗K1200 Project. As prudent planning requires consideration of the Laboratory direction some years in advance, it is anticipated that near the end of this funding cycle preliminary discussions will begin to focus on a next possible step, and an accelerator of this type could easily be a candidate for an upgrade in this regard. Therefore, we intend to further develop a design concept for a separated sector cyclotron during this funding period.

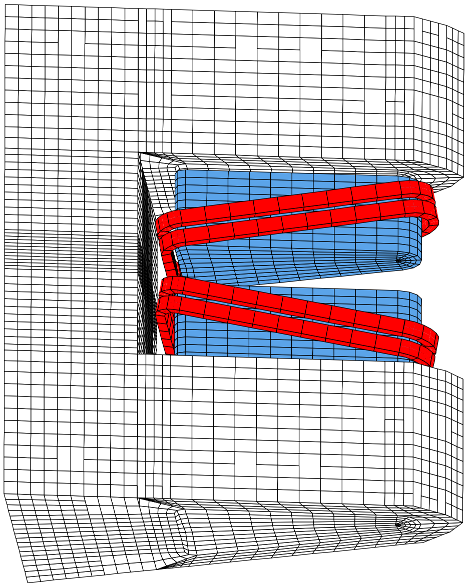

Fig. C-47: TOSCA model for the tilted coil sector magnet.

High-Field Magnets

The MSU cyclotron group is seeking to extend the range of magnetic fields now used in cyclotrons to take further advantage of the scaling laws which reduce overall cyclotron weight and cost as the field is increased. A thesis study completed in 1994 involved the construction of a superconducting magnet which at a magnetic field of 8 tesla would provide acceleration of particles of Q/A=1/4 to an energy of 6 MeV/nucleon, i.e., the energy of interest for a large component of gamma ray physics. This magnet weighs only 4.5 tons, produces fields up to 8.3 tesla, and will have a beam radius of 16 cm for 6 MeV, Q/A=1/4. A follow-on student thesis is now based on outfitting this magnet as a working cyclotron to demonstrate cyclotron performance in an historically new magnetic field level with correlated compactness.

One of the MSU medical colleges has inquired whether a more compact, less costly device for extracting magnetic metal fragments from tissue might now be achievable. An effort is being made to explore this issue.

Medical Accelerators

Historically the Laboratory has had a strong tradition of responding to requests from the medical community for assistance in developing novel devices to address medical accelerator problems. The largest such project involved the design and construction of a superconducting cyclotron for cancer therapy in a joint program with Detroit's Harper

Hospital. This cyclotron is now in routine use in the hospital, treating a full schedule of cancer patients, and the results are quite promising in the short range (but not yet of sufficient duration to provide information as to five-year-survival, the customary statistic used in medicine to assess effectiveness of new cancer therapy modalities). The original design of the cyclotron has been licensed to a commercial manufacturer, who is currently negotiating construction and installation of a copy at several medical centers. Laboratory support of the Harper Hospital project continues on a cost-reimbursed, low-level basis through the process of providing technical backup for the hospital staff in maintenance situations requiring special skills and/or special equipment. With this backup, reliability of the superconducting cyclotron has effectively matched that of the electron linear accelerators, the traditional workhorse radiation therapy devices at both Harper and worldwide.

In addition to the Harper project, the Laboratory has undertaken design studies of cyclotrons appropriate for proton therapy for Princess Margaret Hospital of Toronto (the largest radiation therapy center in North America) and for a Michigan consortium consisting of Harper, the University of Michigan Hospital in Ann Arbor, and Sparrow Hospital of Lansing. Both of these studies involved very restricted sites, a situation which is typical of large metropolitan hospitals, and one where the compactness advantage of the superconducting cyclotron is particularly compelling. Unfortunately, in spite of this, neither of these projects was approved for construction funding. A third such collaboration with Missouri Baptist Hospital of St. Louis is in a phase of preliminary discussions.

A proton therapy center is now under construction at Massachusetts General Hospital (MGH), in a project sponsored jointly by the National Cancer Institute and by private gifts. To date the NSCL has had only low-level participation in the MGH program primarily because of the MGH project management decision to proceed via a bidding solicitation based on guaranteed performance at fixed price with performance bond guarantees. As a matter of policy, the University does not enter into an arrangement of this type since it has the obvious characteristics of a private for-profit enterprise and is inconsistent with the purpose and goals of a research University. We are now, however, moving to undertake a careful exploration of an interesting new cyclotron design concept which has arisen out of the MGH project.

A Belgium company, Ion Beam Applications, Inc. (IBA), was selected by MGH to provide an appropriate cyclotron and beam transport system. IBA is building a room temperature cyclotron with the novel feature of a very much smaller magnet gap in the extraction region than has previously been attempted in cyclotrons (1 cm vs. 10 cm). With this feature, they expect to be able to furnish the cyclotron at a cost comparable to that of a superconducting cyclotron. Such a major shift from a mature, well-developed technology to a novel new approach does, however, almost always involve unforeseen elements of technical risk; a key element in the successful assimilation of such important new concepts is then to come to grips with the initially unforeseen problems at the earliest possible time.

Both from the perspective of supporting the MGH project, and from the more general perspective of the on-going MSU/NSCL tradition of pressing cyclotron concepts to the point of fullest refinement, it is of compelling interest to explore the novel IBA magnet gap design in a thorough way. (The IBA design, for example, immediately raises the issue of whether cyclotrons as a generic class have been wastefully over-designed by the traditional choice of magnet gap.) Our group is particularly well-qualified to address this issue because of our extensive experience in both theoretical and practical aspects of cyclotron construction. Thus the greatest technical risk inherent in such a small gap cyclotron arises from the very much larger non-linearities in the magnetic field in the extraction region; these could distort the beam to a degree that would severely impact its effective utilization in either a therapy system or in a physics research application. Numerical evaluation of non-linear effects has always been severely limited by noise components in the representations of the fields (the higher order derivatives needed for evaluation of the non-linear terms must remain physically reasonable rather than diverging as they inevitably do in the presence of dominant noise components). A recent NSCL PhD thesis [Jeo95] accomplished a major advance in this process by adapting noise suppression techniques from communication theory to the evaluation of derivatives in cyclotron field maps; the thesis convincingly established this technique as a highly effective process for achieving near order-of-magnitude improvement in the accuracy with which derivatives can be evaluated in situations of extreme non-linearity. Using these techniques we are then proceeding with evaluations of cyclotrons with much smaller magnet gaps both as a general study and with as much specificity relative to the MGH project as can be achieved within the framework of the field data available from the commercial vendor.

ECR Development

The NSCL has been a leader in ECR development, and the Laboratory's Superconducting ECR (SCECR) has produced some of the highest intensity high-charge-state ion beams in the world. The dramatic performance enhancements of K500⊗K1200 Project are made possible by the performance of the ECR ion sources, and we intend to continue to lead in the development of improved ECR ion source performance. A very important feature of the ECR system has been the ability to produce rare isotope beams from very small samples. This capability is very important for the production of secondary beams.

To enhance the present SCECR performance further, the superconducting sextupole coils will be replaced with an improved design which supports higher field operation. As an element of the K500⊗K1200 Project, we will increase the performance of the Room Temperature ECR (RTECR) by replacing the present permanent magnet sextupole material (SmCo) with the higher energy product NdFeB. This will provide a significant and cost effective enhancement of the RTECR performance by allowing operation of the RTECR in a mode similar to that of the high-performance SCECR. See Fig. C-48. However, further performance increases for the RTECR are limited because the solenoidal coils will only allow the SCECR-magnetic field mode at the lower rf frequencies, and the fixed sextupole field will not provide the flexibility inherent in the SCECR.

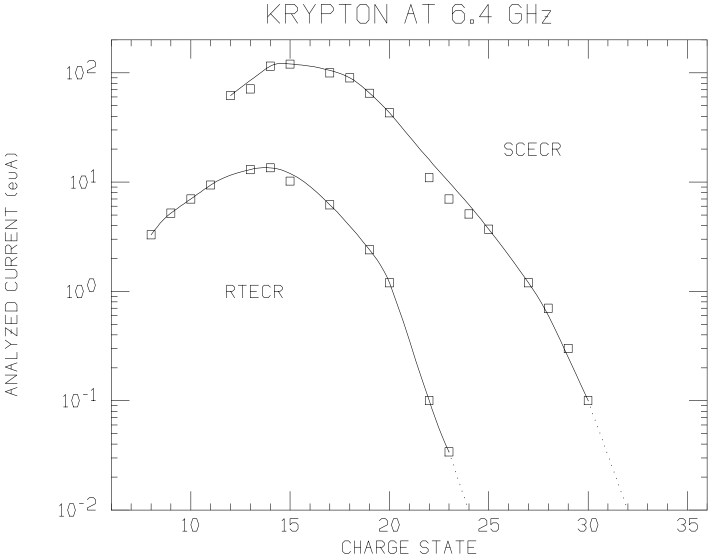

Fig. C-48: Comparison of the present SCECR and RTECR performance

The SCECR provides the most fertile test bed on which to continue significant ECR research and development. However, because of the increasingly high demand for beam time at the Laboratory, it is not as a practical matter feasible to use the present SCECR in this regard. Therefore, at the end of the proposal period, we plan to begin to construct a new SCECR of an advanced type to achieve further intensity of emittance improvements in keeping with the historical thrust of the NSCL ECR program.

Radiation Damage in Permanent Magnet Materials

During the last ten years, permanent magnets based on NdFeB with its higher energy product, lower density, and lower cost have largely supplanted those made of SmCo. However, NdFeB vis-a-vis SmCo has a relatively lower Curie Temperature, 600 K versus 1000 K, and an apparent sensitivity to radiation damage [Zel87,Kra94a]. One important application of permanent magnetic materials is actuators and motors used in satellites where they are subjected to large doses of radiation due to their repeated passes through the Van Allen Belts and from solar flares. The high cost of putting materials into low earth orbit ($10-20k/lb) dictates materials which are as light as possible and have a high radiation resistance. Within the laboratory, permanent magnet accelerator applications which would also require a high radiation resistance, such as for the Room Temperature ECR and the K1200 injection channel, are also being considered.

The effect of temperature on magnetic materials is well known with both the remanent magnetization and the coercivity decreasing with temperature until, at the Curie Temperature, they disappear completely. The effects of radiation are similar in that the portion of the material with the highest demagnetization stress undergoes the most damage (as when the material is heated), with less stressed portions becoming progressively damaged with increasing dose. The damage has been found to depend on the dose and the type of radiation. Charged particles have been found to induce effects at doses lower by several orders of magnitude than, for example, that caused by photon radiation [Zel87, Kra94a, Cos88, Cos87, Bla85]. Charged particle irradiation is thus a rapid way to determine radiation sensitivity. At present there is no consensus on the cause of the damage sensitivity in NdFeB materials. Several different mechanisms have been proposed [Kra94a, Zel90, Käh93]; additional experiments will provide a basis for evaluating these suggestions to move toward a more complete understanding of the basic mechanisms involved.

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5 Publications Relevant to Proposal:

1. G.D. Westfall, T.J.M. Symons, D.E. Greiner, H.H. Heckman, P.J. Lindstrom, J. Mahoney, A.C. Shotter, D.K. Scott, H.J. Crawford, C. McParland, T.C. Awes, C.K. Gelbke and J.M. Kidd, "Production of neutron-rich nuclides by fragmentation of 212-MeV/amu ^{48}Ca", Phys. Rev. Lett. **43** (1979) 1859.
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3. D.R. Bowman, G.F. Peaslee, R.T. de Souza, N. Carlin, C.K. Gelbke, W.G. Gong, Y.D. Kim, M.A. Lisa, W.G. Lynch, L. Phair, M.B. Tsang, C. Williams, N. Colonna, K. Hanold, M.A. McMahan, G.J. Wozniak, L.G. Moretto, and W.A. Friedman, "Multifragment disintegration of the ^{129}Xe + ^{197}Au system at E/A=50 MeV", Phys. Rev. Lett. **67** (1991) 1527.
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5. M.A. Lisa, C.K. Gelbke, P. Decowski, W.G. Gong, E. Gualtieri, S. Hannuschke, R. Lacey, T. Li, W.G. Lynch, G.F. Peaslee, S. Pratt, T. Reposeur, A.M. Vander Molen, G.D. Westfall, J. Yee, and S.J. Yennello, "Observation of lifetime effects in two-proton correlation functions for well-characterized sources", Phys. Rev. Lett. **71** (1993) 2863.

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Michigan State University, University Distinguished Professor (7/90-present)
NSCL/Michigan State University, Associate Director (10/76-7/79)
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1. "Mechanism of the (^{6}Li,^{6}He) reaction at intermediate energies and its suitability as a spin probe", J.S. Winfield, N. Anantaraman, Sam M. Austin, Ziping Chen, A. Galonsky, J. Vanderplicht, H.L. Wu, C.C. Chang and G. Ciangaru, Phys. Rev **C35**, 1734 (1987).
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Visiting Fellow, Australian National Univ. (1968)
Visiting Professor, Univ. of Grenoble (1970)
Professor, Michigan State Univ. (1973-present)
Visiting Scientist, Lawrence Berkeley Lab. (1978-1979)
Associate Director, Michigan State Cyclotron (1980-1982)
Associate Director, National Superconducting Cyclotron Lab (1990-present)
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MSU Golden Key Research Award (1994)
MSU Distinguished Faculty Award (1993)

Publication Statistics: Refereed Papers: 121, Invited Talks: 42

5 Publications Relevant to Proposal:

1. Isobaric Quartets in Nuclei, W. Benenson and E. Kashy, Rev. Mod. Phys. 51, 527 (1979).
2. Low Energy Pion Production at 0° with Heavy Ions from 125 to 400 Mev/Nucleon, W. Benenson, G. Bertsch, G.M. Crawley, E. Kashy, J.A. Nolen, H. Bowman, J.G. Ingersoll, J.O. Rasmussen, J. Sullivan, M. Sasao and M. Koike, Phys. Rev. Lett. C21, 462 (1980).
3. Identification of New Nuclei Near the Proton Drip Line for $31<Z<37$, M.F. Mohar, D. Bazin, W. Benenson, D.J. Morrissey, N.A. Orr, B.M. Sherrill, D. Swan, J.A. Winger, A. Mueller, D. Guillemaud-Mueller, Phys Rev Lett. 66, 1571 (1991).
4. Mass of ^{11}Li from the ^{14}C(^{11}B,^{11}Li) Reaction, B.M. Young, W. Benenson, M. Fauerbach, J.H. Kelley, R. Pfaff, B.M. Sherrill, M. Steiner, J.S. Winfield, T. Kubo, M. Hellström, N.A. Orr, J. Stetson, J.A. Winger, and S.J. Yennello, Phys. Rev. Lett. 71,4124(1993).
5. Measurement of Temperature in Nuclear Reactions, D.J. Morrissey, W. Benenson, and W.A. Friedman, Ann. Rev. Nuc. Part. Sci. 44:27-63(1994).

5 Other Publications:

1. The Use of Radioactive Nuclear Beams to Study the Equilibrium of the N/Z Degree of Freedom in Intermediate Energy Heavy-Ion Reactions, S.J. Yennello, B. Young, J. Yee, J.A. Winger, J.S. Winfield, G.D. Westfall, A. VanderMolen, B.M. Sherrill, J. Shea, E. Norbeck, D.J. Morrissey, T. Li, E. Gualtieri, D. Craig, W. Benenson and D. Bazin, Phys. Lett. B321,15(1994).
2. Excited State Production and Temperature Measurement in a Heavy Ion Reaction, D.J. Morrissey, W. Benenson, E. Kashy, B. Sherrill, A.D. Panagiotou, R.A. Blue, R.M. Ronningen, J. van der Plicht, and H. Utsunomiya, Phys. Letters 148B, 423 (1984).
3. Observation of High Energy Gamma Rays in Intermediate Energy Heavy Ion Collisions. K.B. Beard, W. Benenson, C. Bloch, E. Kashy, J. Stevenson, D.J. Morrissey, J. van der Plicht, Phys. Rev. C32, 1111(1985).
4. Halflife Measurement for the rp-process Nuclei ^{61}Ga, ^{63}Ga, and ^{65}As, J.A. Winger, D.P. Bazin, W. Benenson, G.M. Crawley, D.J. Morrissey, N.A. Orr, R. Pfaff, B.M. Sherrill, M. Steiner, M. Thoennessen, S.J. Yennello, and B.M. Young, Phys. Lett. 299B, 214 (1993)
5. Measurement of the Low-Lying Structure of ^{10}Li in the Reaction ^{11}B(^{7}Li,^{8}B)^{10}Li Reaction, B.M. Young, W. Benenson, J.H. Kelley, N.A. Orr, R. Pfaff, B.M. Sherrill, M. Steiner, M. Thoennessen, J.S. Winfield, J.A. Winger, S.J. Yennello, and A. Zeller, Phys. Rev. C49,279(1994).

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Director, Cyclotron Laboratory, Michigan State University (1958-1966); (1969-1980)
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Co-Director, NSCL, Michigan State University (1985-1989)
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5 Publications Relevant to Proposal:

1. Superconducting Cyclotrons at Michigan State University; H.G. Blosser, Nucl. Instr. and Meth. B24/25(1987)752
2. Focusing Properties of Superconducting Cyclotron Magnets, H.G. Blosser and D.A. Johnson, Nucl. Instr. and Meth. 121(1974)301
3. Magnetic Structure for a Superconducting Variable Frequency Electron Cyclotron Resonance Ion Source; T.A. Antaya, A.F. Zeller, J.M. Moskalik, H.G. Blosser, J.A. Nolen, and K.A. Harrison, IEEE Trans. on Magnetics 25(1989)1671
4. Ultra-High Resolution System for Charged Particle Studies of Nuclei; H.G. Blosser, G.M. Crawley, R. deForest, E. Kashy, and B.H. Wildenthal, Nucl. Instr. and Meth. 91(1971)61
5. A Superconducting Cyclotron for Neutron Therapy, R.L. Maughan, W.E. Powers & H.G. Blosser, Medical Physics 21(1994)779

5 Other Publications:

1. Four-Sector Azimuthally Varying Field Cyclotron; H.G. Blosser, R.E. Worsham, C.D. Goodman, R.S. Livingston, J.E. Mann, H.M. Moseley, G.T. Trammel, and T.A. Welton, Rev. Sci. Inst. 29(1958)819
2. The MSU 53 MeV Cyclotron: H.G. Blosser and A. Galonsky, IEEE Trans. on Nucl. Sci. 13(1966)466
3. Performance Estimates for Injector Cyclotrons; H.G. Blosser and M.M. Gordon, Nucl. Instr. 13(1961)101
4. Application of Superconductivity in Cyclotron Construction; H.G. Blosser, Ninth International Conference on Cyclotrons and Their Applications, Courteboeuf, Les Wis. France (1981)147
5. Medical Cyclotrons, Henry G. Blosser, Physics Today (Oct. 1993)70

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Research Associate, Michigan State University 1965-66
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Associate Professor, Michigan State University 1970-74
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Fulbright Scholarship, 1961-66
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Fellow, American Physics Society, elected January 1979

Publication Statistics: Refereed Papers: 135, Invited Talks: 80

5 Publications Relevant to Proposal:

1. ^{12}C-Induced Single Particle Transfer Reactions at E/A=50 MeV; J.S. Winfield, E. Adamides, S.M. Austin, G.M. Crawley, M.F. Mohar, C.A. Ogilvie, B. Sherrill, M. Torres, G. Yoo and A. Nadasen, Phys. Rev. **C39**, 1395 (1989).
2. Disappearance of Flow in Heavy Ion Collisions; D. Krofcheck, W. Bauer, G.M. Crawley, C. Djalali, D. Howden, C.A. Ogilvie, A. Vander Molen, G.D. Westfall, W.K. Wilson, R.S. Tickle, C. Gale, Phys. Rev. Lett. **63**, 2028 (1989).
3. Disappearance of Flow as a Probe of the Nuclear Equation of State; D. Krofcheck, W. Bauer, G.M. Crawley, S. Howden, C.A. Ogilvie, A. Vander Molen, G.D. Westfall, W.K. Wilson, R.S. Tickle, C. Djalali, C. Gale, Phys. Rev. **C46**, 1416 (1992).
4. Halflife Measurements of the rp-process Nuclei ^{61}Ga, ^{63}Ge and ^{65}As; J.A. Winger, D.P. Bazin, W. Benenson, G.M. Crawley, D.J. Morrissey, N.A. Orr, R. Pfaff, B.M. Sherrill, M. Steiner, M. Thoennessen, S.J. Yennello, B.M. Young, Phys. Lett. **B299**, 214 (1993).
5. High-Lying Resonances Observed in Heavy-Ion Transfer Reactions; G.H. Yoo, G.M. Crawley, N.A. Orr, J.S. Winfield, J.E. Finck, S. Gales, Ph. Chomaz, I. Lhenry, T. Suomijarvi, Phys. Rev. **C47**, 1200 (1993).

5 Other Publications:

1. High Resolution Studies of the Particle-Hole Multiplets in ^{208}Bi; G.M. Crawley, E. Kashy, W. Lanford, H. Blosser, Phys. Rev. **C8**, 2477 (1973).
2. The Observation of Hole States at High Excitation in (p,t) Reactions; G.M. Crawley, W. Benenson, D. Weber, B. Zwieglinski, Phys. Rev. Lett. **39**, 1451 (1973).
3. The Observation of the T=45/2 Components of Deep Hole States in ^{207}Pb via the (^{3}He,a) Reaction at 70 Mev; S. Gales, G.M. Crawley, D. Weber, B. Zwieglinski, Phys. Rev. Lett. **41**, 292 (1978).
4. Observation of M1 Strength by the Inelastic Scattering of 200 MeV Protons; N. Anantaraman, G.M. Crawley, A. Galonsky, C. Djalali, N. Marty, M. Morlet, A. Willis, J.C. Jourdain, Phys. Rev. Lett. **46**, 1318 (1981).
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Acting Director, MSU Cyclotron Lab (1966-67)
Director, MSU Cyclotron Lab (1967-69)
Associate Director, MSU Cyclotron Lab (1979-80)
Guest Professor, Institute for Nuclear Physics, Jülich (1975-76)
Senior Referee for Physical Review Letters (1980-81)
Member of Physical Review C Editorial Board (1982-85)
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Phi Beta Kappa
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Publication Statistics: Refereed Papers: 126 , Invited Talks: 20

5 Publications Relevant to Proposal:

1. Method for the Study of Neutron Emission from Light Fragments in ^{14}N + ^{165}Ho Collisions at 35 MeV/u, F. Deak, A. Kiss, Z. Seres, G. Caskey, A. Galonsky, and B. Remington, Nucl. Instr. & Meth. in Physics Research A258(1987)67
2. Temperatures Determined from Neutron Emission in Nucleus-Nucleus Collisions, A. Galonsky, G. Caskey, L. Heilbronn, H. Schelin, B. Remington, F. Deak, A. Kiss, Z. Seres, and J. Kasagi, Phys. Lett. B197(1987)511
3. Dependence of ^{12}B Excitation Energy on its Kinetic Energy in the ^{14}N + Ag Reaction at E/A = 35 MeV, F. Deak, A. Kiss, Z. Seres, A. Galonsky, C.K. Gelbke, L. Heilbronn, W. Lynch, T. Murakami, H. Schelin, M.B. Tsang, B.A. Remington, and J. Kasagi, Phys. Rev. C39(1989)733
4. Coulomb Dissociation of ^{11}Li, K. Ieki, D. Sackett, A. Galonsky, C.A. Bertulani, J.J. Kruse, W.G. Lynch, D.J. Morrissey, N.A. Orr, H. Schulz, B.M. Sherrill. A. Sustich, J.A. Winger, F.

Deak, A. Horvath, A. Kiss, Z. Seres, J.J. Kolata, R.E. Warner, and D.L. Humphrey, Phys. Rev. Lett. 70(1993)730

5. Coulomb Dissociation of ^{11}Li, D. Sackett, K. Ieki, A. Galonsky, C.A. Bertulani, J.J. Kruse, W.G. Lynch, D.J. Morrissey, N.A. Orr, H. Schulz, B.M. Sherrill. A. Sustich, J.A. Winger, F. Deak, A. Horvath, A. Kiss, Z. Seres, J.J. Kolata, R.E. Warner, and D.L. Humphrey, Phys. Rev. C48(1993)118

5 Other Publications:

1. Energy Levels of Li^6 from the Deuteron-Helium Differential Cross Sections; A. Galonsky, M.T. McEllistrem, Phys. 98(1955)590
2. S-Wave Detector of Deutereon Polarization and 14-Mev Polarized-Neutron Souce; A. Galonsky, H.B. Willard, and T.A. Welton, Phys. Rev. Lett. 2(1959)349
3. A Precision Measurement of the Longitudinal Polarization of Betas following P^{32} Decay; A.R. Brosi, A.I. Galonsky, B.H. Ketelle, H.B. Willard, Nuc Phys. 33(1962)353
4. Observation of Gamow-Teller Strength in (p,n) Reactions; R.R. Doering, A. Galonsky, D.M. Patterson, G.F. Bertsch, Phys. Rev. Lett. 35(1975)1691
5. Observation of l=0, Spin-Flip Transitions in Ca, G.M. Crawley, N. Anantaraman, A. Galonsky, C. Djalali, N. Marty, M. Morlet, A. Willis and J.C. Jourdain, Phys. Lett. 127B(1983)322

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5 Publications Relevant to Proposal:

1. The Neutron Halo of Extremely Neutron-rich Nuclei, P.G. Hansen and B. Jonson, Europhys. Lett. **4** (1987) 409.
2. Observation of the Forward Neutrons from the Breakup of the ^{11}Li Neutron Halo, R. Anne, S.E. Arnell, R. Bimbot, H. Emling, D. Guillemaud-Mueller, P.G. Hansen, L. Johannsen, B. Jonson, M. Lewitowicz, S. Mattsson, A.C. Mueller, R. Neugart, G. Nyman, F. Pougheon, A. Richter, K. Riisager, M.G. Saint-Laurent, G. Schrieder, O. Sorlin, and K. Wilhelmsen, Phys. Lett. **B250** (1990) 19-23.
3. Super-allowed Beta Decay of Nuclei at the Drip Line, M.J.G. Borge, P.G. Hansen, L. Johannsen, B. Jonson, T. Nilsson, G. Nyman, A. Richter, K. Riisager, O. Tengblad, K. Wilhelmsen, and the ISOLDE Collaboration, Z. Physik **A340** (1991) 255.
4. Two-neutron Removal Reactions for Very Neutron-rich Nuclei, K. Riisager, R. Anne, S.E. Arnell, R. Bimbot, H. Emling, D. Guillemaud-Mueller, P.G. Hansen, L. Johannsen, B. Jonson, A. Latimier, M. Lewitowicz, S. Mattsson, A.C. Mueller, R. Neugart, G. Nyman, F. Pougheon, A. Richard, A. Richter, M.G. Saint-Laurent, G. Schrieder, O. Sorlin, and K. Wilhelmsen, Nucl. Phys. **A540** (1992) 365.

5. Exclusive and Restricted Inclusive Reactions Involving the ^{11}Be One-Neutron Halo, R. Anne, R. Bimbot, S. Dogny, H. Emling, D. Guillemaud-Mueller, P.G. Hansen, P. Hornshøj, F. Humbert, B. Jonson, M. Keim, M. Lewitowicz, P. Møller, A.C. Mueller, R. Neugart, T. Nilsson, G. Nyman, F. Pougheon, K. Riisager, M.G. Saint-Laurent, G. Schrieder, O. Sorlin, O. Tengblad and K. Wilhelmsen Rolander, Nucl. Phys. **A575** (1994) 125.

5 Other Publications:

1. Fermi Matrix Elements in the Decay of 234Np, P.G. Hansen, H.L. Nielsen, K. Wilsky, and J.G. Cuninghame, Phys. Lett. **B24** (1967) 95.
2. The Beta Strength Function, P.G. Hansen, Adv. in Nucl. Phys. (eds. M. Baranger and E. Vogt) **7** (1973) 159.
3. Shifts in the Energies of Holmium K X-rays and the Role of Atomic Structure, G.L. Borchert, P.G. Hansen, B. Jonson, I. Lindgren, H.L. Ravn, O.W.B. Schult, and P. Tidemand-Petersson, Phys. Lett. **A66** (1978) 374.
4. First Observation of Beta-delayed Two-neutron Radioactivity: ^{11}Li, R.E. Azuma, L.C. Carraz, P.G. Hansen, B. Jonson, K.L. Kratz, S. Mattsson, G. Nyman, H. Ohm, H.L. Ravn, A. Schröder, and W. Ziegert, Phys. Rev. Lett. **43** (1979) 1652.
5. Atomic Effects in Low-Energy Beta Decay, J. Lindhard, and P.G. Hansen, Phys. Rev. Lett. **57** (1986) 965.

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Acting Director, Cyclotron Lab. (1972-1973)
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Publication Statistics: Refereed Papers: 120, Invited Talks: 8

5 Publications Relevant to Proposal:

1. Isobaric Quartets in Nuclei; W. Benenson, E. Kashy, Revs. Mod. Phys. 51(1979)527
2. Nuclear Temperatures in the Reaction of ^{14}N with Ag at 35 MeV/nucleon D.J. Morrissey, W. Benenson, E. Kashy, C. Bloch, M. Lowe, R.A. Blue, R.M. Ronningen, B. Sherrill, H. Utsunomiya, I. Kelson, Phys. Rev. C32(1985)877
3. A Method for the Uniform Irradiation of Large Targets}; E. Kashy and B. Sherrill, Nucl. Instr. and Meth. B26(1987)610. Also US Patent Number 4,736,106 for “Method and apparatus for Uniform Charge Particle Irradiation of a Surface”
4. High-Energy Gamma-Ray Production in Light-Ion Induced Reactions}; C.L. Tam, J. Stevenson, W. Benenson, J. Clayton, Y. Chen, E. Kashy, A.R. Lampis, D.J. Morrissey, M. Samuel, T.K. Murakami, J.S. Winfield, Phys. Rev. C38(1988)2526
5. A large solid-angle array for heavy ions from APEX, D.J. Mercer et al., Nucl. Inst. and Meth. A350,491(1994)

5 Other Publications:

1. Electricity and Magnetism; E. Kashy, S. McGrayne, article in Encyclopaedia Britanica, 15th edition (1990), Vol 18, pp. 159-194
2. Nuclear Scattering; G. F. Bertsh, E. Kashy, Am. J. Phys 61(1993)858
3. CAPA - An Integrated Computer Assisted Personalized Assignment System, E. Kashy, B.M. Sherrill, Y. Tsai, D. Thaler, D. Weinshank, M. Engelmann, D.J. Morrissey, American Journal of Physics 61,(12)1993, 1124-1130
4. A Model to Illustrate Forces in Nuclear Fusion}, E. Kashy, D.A. Johnson, American Journal of Physics 62(9)1994, 804
5. Using Computer-Assisted Personalized Assignments in Freshman Chemistry, D.J. Morrissey, E. Kashy, Y. Tsai, Journal of Chemical Education, 72,(2)1995, 141

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I. Ahmad, S.M. Austin, B. Back, D. Bazin, R.R. Betts, R.A. Blue, B.A. Brown, F.P. Calaprice, Patrick W. Dickson, J. Duffy, R. Dunford, S.J. Freedman, S. Gaff, A.L. Hallin, D.J. Henderson, W. Kutshera, J. Krishnamoorthy, D. Kataria, M. Maier, C.J. Lister, M. Liu, Ontario, D.J. Mercer, D. Mikolas, A.C. Mueller, D. Guillemaud-Mueller, R.M. Ronningen, P. Roussel, M. Roy-Stephan, J.P. Schiffer, T. Trainer, J.S. Winfield, F.L.S. Wolfs, A.H. Wuosmaa, J. Yurkon

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5 Publications Relevant to Proposal:

1. F. Zhu, W.G. Lynch, D.R. Bowman, R.T. de Souza, C.K. Gelbke, Y.D. Kim, L. Phair, M.B. Tsang, C. Williams, H.M. Xu, and J. Dinius, "Thermalization in Nucleus-Nucleus Collisions", Phys. Lett. B, **282**, (1992) 299.
2. M.B. Tsang, P. Danielewicz, D.R. Bowman, N. Carlin, C.K. Gelbke, W.G. Gong, Y.D. Kim, W.G. Lynch, L. Phair, R.T. de Souza, and F. Zhu, "Reaction Dynamics and Deuteron Production", Phys. Lett. B, **297**, (1992) 243.
3. G.F. Peaslee, M.B. Tsang, C. Schwarz, M.J. Huang, W.S. Huang, W.C. Hsi, C. Williams, W. Bauer, D.R. Bowman, M.A. Lisa, W.G. Lynch, C.M. Mader, L. Phair, J. Dinius, C.K. Gelbke, D.O. Handzy, M-C. Lemaire, S. R. Souza, G. Van Buren, R.J. Charity, L.G. Sobotka, G.J. Kunde, U. Lynen, J. Pochodzalla, H. Sann, W. Trautmann, D. Fox, R.T. de Souza, G. Peilert, W.A. Friedman, and N. Carlin, "Energy Dependence of Multifragmentation in ^{84}Kr+^{197}Au Reactions", Phys. Rev. **C49** (1994) R2271.
4. W.C. Hsi, G.J. Kunde, J. Pochodzalla, W.G. Lynch, M.B. Tsang, M.L. Begemann-Blaich, D.R. Bowman, R.J. Charity, A. Cosmo, A. Ferrero, C.K. Gelbke, T. Glasmacher, T. Hofmann, J. Hubele, G. Imme, I. Iori, J. Kempter, P. Kreutz, W.D. Kunze, V. Lindenstruth, M.A. Lisa, U. Lynen, M. Mang, A. Moroni, W.F.J. Müller, N. Neumann, B. Ocker, C.A. Ogilvie, G.F. Peaslee, G. Raciti, F. Rosenberger, H. Sann, R. Scardaoni, A. Schüttauf, C. Schwarz, W. Seidel, V. Serfling, L.G. Sobotka, L. Stuttge, W. Trautmann, A. Tucholski, C. Williams, A. Wörner, and B. Zwieglinski, "Collective Expansion in Central Au+Au Collisions", Phy. Rev. Lett. **73**, (1994)3367.

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5 Other Publications:

1. R.T. de Souza, L. Phair, D.R. Bowman, N. Carlin, C.K. Gelbke, W.G. Gong, Y.D. Kim, M.A. Lisa, W.G. Lynch, G.F. Peaslee, M.B. Tsang, H.M. Xu, F. Zhu, and W.A. Friedman, "Multifragment Emission in the Reaction ^{36}Ar+^{197}Au at E/A = 35, 50, 80,
2. W.G. Gong, W. Bauer, C.K. Gelbke, N. Carlin, R.T. de Souza, Y.D. Kim, W.G. Lynch, T. Murakami, G. Poggi, D.P. Sanderson, M.B. Tsang, H.M. Xu, S. Pratt, D.E. Fields, K. Kwiatkowski, R. Planeta, V.E. Viola, and S.J. Yennello, "Intensity-Interferometric Test of Nuclear Collision Geometries Obtained from the Boltzmann-Uehling Uhlenbeck Equation", Phys. Rev. Lett. **65**, 2114 (1990).
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4. M.B. Tsang, R.M. Ronningen, G. Bertsch, Z. Chen, C.B. Chitwood, D.J. Fields, C.K. Gelbke, W.G. Lynch, T. Nayak, J. Pochodzalla, T. Shea, and W. Trautmann, "Deflection on Non-equilibrium Light Particles By The Nuclear Mean Field", Phys. Rev. Lett. **57**, (1986) 59.
5. G.F. Bertsch, W.G. Lynch and M.B. Tsang, "Transverse Momentum Distributions in Intermediate Energy Heavy-Ion Collisions", Phys. Lett. B **189**, (1987) 384.

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Professor, Michigan State University (1991-present)
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Publication Statistics: Refereed Papers: 89, Invited Talks: 18

5 Publications Relevant to Proposal:
1. Thermal Production of Nuclear Excited States; D.J. Morrissey, C. Bloch, W. Benenson, E. Kashy, R.A. Blue, R.M. Ronningen and R. Aryaeinejad, Phys. Rev. C34(1986)761
2. Systematics of Momentum Distributions from Reactions with Relativistic Ions; D.J. Morrissey, Phys. Rev. C39(1989)460
3. Identification of New Nuclei Near the Proton-Drip Line for 30 > Z > 37; M.F. Mohar, D. Bazin, W. Benenson, D.J. Morrissey, N.A. Orr, B.M. Sherrill, D. Swan, J.A. Winger, A. Mueller, D. Guillemaud-Mueller, Phys. Rev. Lett. 66(1991)1571
4. Halflife Measurements of the rp-process Nuclei ^{61}Ga, ^{63}Ge, and ^{65}As; J.A. Winger, D.P. Bazin, W. Benenson, G.M. Crawley, D.J. Morrissey, N.A. Orr, R. Pfaff, B.M. Sherrill, M. Steiner, M. Thoennessen, S.J. Yennello, and B.M. Young, Phys. Lett. B299(1993)214
5. Measurement of Temperature in Nuclear Reactions; D.J. Morrissey, W. Benenson, W.A. Friedman, Annl. Rev. Nucl. Part. Sci. 44(1994)27

5 Other Publications:
1. Systematic Behavior of Ejectile Spin Polarization in the Projectile Fragmentation Reaction, H. Okuno, K. Asahi, H. Sato, H. Ueno, J. Kura, M. Adachi, T. Nakamura, T. Kubo, N. Inabe, A. Yoshida, T. Ichihara, Y. Kobayashi, Y. Ohkubo, I. Iwamoto, F. Ambe, T. Shimoda, H. Miyatake, N. Takahashi, J. Nakamura, D. Beaumel, D.J. Morrissey, W.-D. Schmidt-Ott, and M. Ishihara, Phys. Lett. B335, 29 (1994).

2. The Use of Radioactive Nuclear Beams to Study the Equilibration of the N/Z Degree of Freedom in Intermediate-energy Heavy-ion Collisions, S.J. Yennello, B. Young, J. Yee, J.A. Winger, J.S. Winfield, G.D. Westfall, A. Vander Molen, B.M. Sherrill, J. Shea, E. Norbeck, D.J. Morrissey, T. Li, E. Gaultieri, D. Craig, W. Benenson, and D. Bazin, Phys. Lett. B321, 15 (1994).

3. The Identification of New Nuclei Near the Proton-drip Line, M. Hencheck, R.N. Boyd, M. Hellström, D.J. Morrissey, M.J. Bables, F.R. Chloupek, M. Fauerbach, C.A. Mitchell, R. Pfaff,

C. Powell, G. Raimann, B.M. Sherrill, M. Steiner, J. Vandergriff, and S.J. Yennello, Phys. Rev. C50, 2219 (1994).

4. Study of the β-Delayed Neutron Decay of ^{18}N, K.W. Scheller, J. Goerres, J.G. Ross, M. Weischer, D.J. Morrissey, B.M. Sherrill, M. Steiner, N.A. Orr, and J.A. Winger, Phys. Rev. C49, 46 (1994).
5. Using Computer-Assisted Personalized Assignments in Freshman Chemistry, D.J. Morrissey, E. Kashy, and I. Tsai, J. Chem. Ed., 72, 141 (1995).

Other collaborators within last 48 months:

S.M. Austin, D.R. Bowman, J. Clayton, A. Galonsky, R. Harkewicz, J.J. Kolata, L.G. Moretto, C. Ogilvie, K.W. Scheller, R.E. Warner, G.J. Wozniak, B.A. Brown, R.N. Boyd, H. Esbensen, J. Görres, M. Ishihara, W. Kutschera, J.A. Nolen, Jr., G.F. Peaslee, I. Tanihata, M. Weisher

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Publication Statistics: Refereed Papers: 64, Invited Talks: 21

5 Publications Relevant to Proposal:

1. Identification of New Nuclei Near the Proton-Drip Line; M.F. Mohar et al., Phy. Rev. Lett. **66**(1991)1571
2. Momentum Distributions of ^{9}Li Fragments following the Breakup of ^{11}Li; Orr et al., Phys. Rev. Lett. **69**(1992)2050
3. Quasielastic Scattering of ^{11}Li and ^{11}C at 60 MeV/nucleon; J.J. Kolata et al., Phys. Rev. Lett. **69**(1992)2631
4. Parallel Momentum Distributions as a Probe of Halo Wave Functions; J.H. Kelley, et al., Phy. Rev. Lett. **74**(1995)30

5. Importance of Nuclear Effects in the Dissociation of ^{6}He and ^{6}Li at E/A = 65 MeV; D.P. Balamuth, K.A. Griffioen, J.E. Bush, K.R. Pohl, D.O. Handzy, A. Aguirre, B.M. Sherrill, J.S. Winfield, D.J. Morrissey, and M. Thoennessen, Phy. Rev. Lett. **72**(1994)2355

5 Other Publications:

1. Nuclei at the Limits of Stability; A.C.Mueller and B.M.Sherrill, Ann. Rev. Nucl. and Part. Sci., Vol. **43**(1993)529
2. Transport Integral: A Method to Calculate the Time Evolution of Phase Space Distributions; D. Bazin and B.M. Sherrill, Phy. Rev. **E50**(1994)4017
3. Radioactive nuclear beam facilities based on projectile fragmentation, B.M. Sherrill, Radioactive Nuclear Beams, Ed. Th. Delbar, (Adam Hilger, Bristol, 1991)3
4. The Isospin Laboratory: Research Opportunities with Radioactive Nuclear Beams; R.F. Casten, J. D'Auria, C.N. Davids, J.D. Garrett, J.M. Nitsche, B.M. Sherrill, D.J. Vieira, M. Wiescher, E.F. Zganjar, Los Alamos National Lab Report, NALP 91-51
5. Nuclear Halos, printed in Physics News in 1992; B.M. Sherrill, G.F. Bertsch, Ed. P.F. Schewe (AIP: New York, 1992)66

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F. Humbert, T. Nilsson, W. Schwab, M. Zinser, Th. Blaich, M.J.G. Borge, L.V. Chulkov, H. Eickhoff, Th.W. Elze, H. Emling, B. Franzke, H. Freiesleben, H. Geissel, K. Grimm, D. Guillemaud-Mueller, P.G. Hansen, R. Holzmann, H. Irnich, L. Johannsen, B. Jonson, J.G. Keller, O. Klepper, H. Klingler, J.V. Kratz, R. Kulessa, D. Lambrecht, Y. Leifels, A. Magel, M. Mohar, E.F. Moore, A.C. Mueller, G. Münzenberg, P. Moller, F. Nickel, G. Nyman, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, H. Simon, K. Stelzer, J. Stroth, O. Tenglad, W. Trautmann, E. Wajda, E. Zude

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Publication Statistics: Refereed Papers: 31, Invited Talks: 19

5 Publications Relevant to Proposal:

1. High Energy Target Excitations in Heavy Ion Inelastic Scattering; M. Thoennessen, J. R. Beene, F. E. Bertrand, D. J. Horen, M. L. Halbert, D. C. Hensley, J. E. Lissanti, W. Mittig, Y. Schutz, N. Alamanos, F. Auger, J. Barrette, B. Fernandez, A. Gillibert, B. Haas, J. P. Vivien, and A. M. Nathan, Phys. Rev. C43(1991)R12.
2. Momentum Distributions of ^{9}Li Fragments Follwing the Break-up of ^{11}Li; N.A. Orr, B.M. Sherrill, N. Anantaraman, S.M. Austin, C.A. Bertulani, K. Hanold, J.H. Kelley, D.J. Morrissey, G.A. Souliotis, M. Thoennessen, J.S. Winfield, J.A. Winger, Phys. Rev. Lett. 69(1992)2050.
3. Ground State Two Proton Decay of ^{12}O,R.A. Kryger, A. Azhari, M. Hellstrom, J.H. Kelley, T. Kubo, R. Pfaff, E. Ramakrishnan, B.M. Sherrill, M. Thoennessen, S. Yokoyama, R.J. Charity, J. Dempsey, A. Kirov, N. Robertson, D.G. Sarantites, L.G. Sobotka, and J.A. Winger, Phys. Rev. Lett. 76(1995)860.
4. Neutron Decay of ^{10}Li Produced by Fragmentation; R. A. Kryger, A. Azhari, A. Galonsky, J. H. Kelley, R. Pfaff, E. Ramakrishnan, D. Sackett, B. M. Sherrill, M. Thoennessen, J. A. Winger, and S. Yokoyama, Phys. Rev. C47(1993)R2439.
5. Coulomb and Nuclear Dissociation of ^{6}He and ^{6}Li; D.P. Balamuth, K.A. Griffoen, J.E. Bush, K.R. Pohl, D. Handzy, A. Aguirre, B.M. Sherrill, J.S. Winfield, D.J. Morrissey, M. Thoennessen, Phys. Rev. Lett. 72(1994)2355.

5 Other Publications:

1. Giant Dipole Resonance in Highly Excited Thorium: Evidence for Strong Fission Hindrance; M. Thoennessen, D. R. Chakrabarty, M. G. Herman, R. Butsch, and P. Paul, Phys. Rev. Lett. 59(1987)2860.
2. Time Scales for Fusion-Fission and Quasi-Fission from Giant Dipole Resonance Decay; R. Butsch, D. J. Hofman, C. P. Montoya, P. Paul, and M. Thoennessen, Phys. Rev. C44(1991)1515.
3. Nuclear Dissipation and the Feeding of Superdeformed Bands; M. Thoennessen and J. R. Beene, Phys. Rev. C45(1992)873.

4. Evidence for Long Formation Times of Near Barrier Fusion Reactions; M. Thoennessen, J. R. Beene, F. E. Bertrand, C. Baktash, M. L. Halbert, D. J. Horen, D. G. Sarantites, W. Spang, and D. W. Stracener, Phys. Rev. Lett. 70(1993)4055.
5. A Threshold for Dissipative Fission; M. Thoennessen, and G. F. Bertsch, Phys. Rev. Lett. 71(1993)4303.

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Publication Statistics: Refereed Papers: 84, Invited Talks: 35

5 Publications Relevant to Proposal:

1. Event Shape Analysis: Sequential Versus Simultaneous Multifragment Emission; D.A. Cebra, S. Howden, J. Karn, A. Nadasen, C.A. Ogilvie, A. Vander Molen, G.D. Westfall, W.K. Wilson, J.S. Winfield, and E. Norbeck, Phys. Rev. Lett. 64(1990)2246
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3. Intermediate Mass Fragment Production in Central Collisions of Intermediate Energy Heavy Ions; T. Li, W. Bauer, D. Craig, M. Cronqvist, E. Gualtieri, S. Hannuschke, R. Lacey, W.J. Llope, T. Reposeur, A.M. Vander Molen, G.D. Westfall, W.K. Wilson, J.S. Winfield, J. Yee, S.J. Yennello, A. Nadasen, R.S. Tickle, E. Norbeck, Phys. Rev. Lett. 70(1993)1924
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F. Budget Justification

The proposed annual budgets assume a constant FY94-effort level with some minor adjustments for increased electricity costs ($84.4k, see also below) and modest support (summer salaries, $71.9k; two graduate students, $61k; and one postdoctoral research associate, $69.9k -- all costs are fully burdened) for three new experimental faculty joining the NSCL in 1995 (Hannah Professor Gregers Hansen, Assistant Professor Thomas Glasmacher, plus a position to be filled in nuclear chemistry). Minimum funding of NSCL operations at the constant-effort FY94 level is a prerequisite for the cost-reduction package (from roughly $19M to $11M, in FY94$) offered by MSU to help facilitate the K500⊗K1200 project. The detailed funding profile presented is predicated on funding and initiation of the K500⊗K1200 project following the schedule included in the proposal (PHY-9423946) submitted to the NSF in September 1994. (Alternative construction schedules for the K500⊗K1200 project can be readily accommodated within the proposed constant-effort operating budget -- should this prove necessary.) The major impact of the K500⊗K1200 project is a reduced demand for electricity and cryogens during the shutdown necessary for equipment installation. The costs avoided during the shutdown period will be used to augment the severely restricted equipment allocation. During the final two years of the proposal period, the total requested funds increase slightly in order to maintain a viable equipment allocation and still provide for the needed electricity and cryogens.

Materials and supplies include: cyclotron and beam line operation & maintenance ($205k); experimental facilities maintenance and operation ($40k); shops, laboratories & engineering supplies ($135k); general administrative items ($120k); and research support supplies ($35k). These costs plus travel, publications, consultant services and computer maintenance remain at their FY94 levels after accounting for inflation.

Electricity costs in FY96 are impacted by the termination of a rate abatement from MSU on June 30, 1995 (added cost in FY96: $84.4k) and increased consumption (by $91.2k) which contributes the remainder of the additional costs. Since our electrical bills are based on the usage over the previous year, much of the data needed to determine next year's costs are available now, and the uncertainty in the cost projection is minimal. (In FY95, the electricity cost was low because of the 1994 shutdown for the A1200 upgrade, see Fig. A1 of the Appendix.) Cryogenic costs will increase (by $80.3k) because of the additional demand created by operation of the K500 cyclotron for beam dynamics studies (needed for the K500⊗K1200 project) and operation of the S800 spectrograph. The cost for additional electricity and cryogen consumption are absorbed during the first few years by reducing the request for equipment funds, but we request that the equipment funds be brought back to a more acceptable and historic level during the last few years of the operating period.

Table F-1 provides a schedule of the funds requested over the five year period of the proposal in constant FY96$. The funding authorized for the reference year (FY94) is also provided, inflated to FY96$. At the bottom of the table are the fringe and overhead rates used and the DOE-supplied inflation factor applied. The total request for FY96 is $273k above the constant-effort FY94 level after accounting for inflation. The Budget Summary forms (NSF Form 1030) which follow this justification display all costs in then-year dollars.

Equipment Funds

Equipment expenditures are subdivided into three categories: Facility Operations, User Services & Support, and Experimental Equipment. Purchases of some anticipated major replacement items are distributed over the grant period for budgeting purposes. For ease of reference, a summary of the requested equipment funds is also provided in Table A3.

Facility operations: The replacement of two sets of K1200 rf-amplifier tubes, the main amplifier and drive tubes, are anticipated ($88k, 2nd and 4th years) and an ECR klystron tube ($30k, 4th yr). An LCW cooling tower and heat exchanger are needed ($58k and $15k, 2nd yr), and pumps and air conditioning equipment ($30k, 4th yr). Turbo pump replacements on the ECRs, K1200 cyclotron, and beamlines are typically three per year ($27k/yr); in addition, two large turbo pumps on the 92-inch chamber and the 4π-Array are nearing the end of their expected lifetimes and will need to be replaced ($23k, 1st and 5th yr). A new leak detector will be needed ($16k, 4th yr). Each year $30k is requested for repairs and upgrades of the accelerator control-system; and $15k is requested for electronics instruments and test equipment. The refrigerator control system must be upgraded and modernized ($30k). Machining tools which must be refurbished are: the Hurco mill ($30k), an aging and failure-prone welding machine ($5k), and the old Bridgeport mills ($14k). Funds for other cyclotron improvement projects and diagnostic equipment are included each year.

User Service and Support: The laboratory's electronics pool and computing resources require the continued purchase of new equipment to replace outdated and failed equipment for which expensive repairs are not justified. The proposed expenditures are based on the current inventories and expenditures necessary to meet the users' needs. A minimum of $90k/yr is needed to maintain the Nuclear Electronics Pool; an increase to $140k is budgeted for the fifth year in anticipation of coupled cyclotron operation. Similarly, a minimum of $100k/yr is needed to maintain and update the NSCL computers and data acquisition systems. A modest increase to $120k is projected for the 5th year. Needs for the detector and target laboratories are: a dedicated data-acquisition system ($18k) to permit detector tests without interference with cyclotron operations, a wire-bonding machine ($14k), a detector test vacuum chamber ($9k) plus a cryopump ($4k), and an electron-beam evaporator ($25k). Mechanical pumps for equipment in the experimental vaults will need to be replaced ($21k and $3k, 1st and 2nd yrs), and the RPMS and N4-vaults will need dedicated vacuum systems for radioactive beam experiments ($30k, 3rd and 4th yrs), $25k for general needs are requested for the last year.

Experimental Equipment: In the first year, funds are requested for a coincidence scattering chamber for the S800 ($90k), and the first part of a high resolution silicon-based array for S800 coincidence experiments will be built ($80k). In the second year, the silicon-based array will be completed ($50k), and the S800 focal plane detector will be improved to allow multiparticle detection ($50k). Barium fluoride gamma-ray detectors for the ORNL/MSU/TAMU will be built during the second and third years ($139k/yr), and the granularity of the most forward ring of five hexagons in the 4π-Array will be increased by a factor of four during the 3rd year ($243k) for experiments with the heaviest beams. The Miniball electronics will be adapted for high-rate operation at the S800 target position ($60k), and $80k are requested for other coincidence equipment for physics with the S800 in the 4th year. The stopped-pion detector will be constructed for experiments with high intensities of exotic beams ($90k, 4th yr). Funds are reserved for other research equipment in the fourth ($90k) and fifth year ($350k) in anticipation of the coupled cyclotron research effort.

	Ref (FY96$)		**Proposed (FY96$)**									
CATEGORY	**FY1994**		**FY1996**		**FY1997**		**FY1998**		**FY1999**		**FY2000**	
	FTE	K$	FTE	K$	FTE	K$	FTE	K$	FTE	K$	FTE	K$
SALARY & WAGES												
PD's, PI's & Faculty	4.6	465.5	3.0	313.3	3.0	313.3	3.0	313.3	3.0	313.3	3.0	313.3
Other Senior Personnel	23.3	1383.2	22.3	1399.4	22.3	1399.4	22.3	1399.4	22.3	1399.4	22.3	1399.4
Total Senior	27.9	1848.7	25.3	1712.7	25.3	1712.7	25.3	1712.7	25.3	1712.7	25.3	1712.7
Post Doctoral Associates	6.5	250.6	7.5	266.0	7.5	266.0	7.5	266.0	7.5	266.0	7.5	266.0
Other Professionals	13.5	594.9	18.0	777.2	18.0	777.2	18.0	777.2	18.0	777.2	18.0	777.2
Graduate Students	13.0	463.1	14.0	474.2	14.0	474.2	14.0	474.2	14.0	474.2	14.0	474.2
Undergraduate Students	5.0	63.1	5.0	63.1	5.0	63.1	5.0	63.1	5.0	63.1	5.0	63.1
Secretarial-Clerical	1.5	43.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other (Assembly/Shop)	8.7	367.1	8.7	359.6	8.7	359.6	8.7	359.6	8.7	359.6	8.7	359.6
Total Salaries & Wages	76.1	3631.1	78.5	3652.7	78.5	3652.7	78.5	3652.7	78.5	3652.7	78.5	3652.7
Fringes		1141.0		1166.1		1188.1		1210.5		1233.2		1256.5
Total with Fringes		**4772.1**		**4818.8**		**4840.8**		**4863.2**		**4885.9**		**4909.2**
EQUIPMENT		**732.1**		**579.0**		**701.0**		**768.0**		**814.0**		**819.0**
TRAVEL		**140.4**		**135.1**		**135.1**		**135.1**		**135.1**		**135.1**
OTHER DIRECT												
Materials and Supplies		550.8		535.1		535.1		535.1		535.1		535.1
Publication & Page Charges		18.4		17.7		17.7		17.7		17.7		17.7
Consultant Services		21.6		20.8		20.8		20.8		20.8		20.8
Computer Maintenance		89.6		88.3		88.3		88.3		88.3		88.3
Electricity		394.2		569.4		439.3		435.2		198.4		180.4
Cryogens		140.4		210.3		191.0		126.3		252.8		290.7
Total other direct		**1215.0**		**1441.5**		**1292.1**		**1223.3**		**1113.0**		**1132.9**
TOTAL DIRECT COSTS		**6859.6**		**6974.4**		**6969.0**		**6989.6**		**6948.0**		**6996.2**
INDIRECT COSTS		**2580.0**		**2738.2**		**2739.5**		**2719.6**		**2789.7**		**2818.5**
TOTAL		**9439.6**		**9712.6**		**9708.5**		**9709.2**		**9737.8**		**9814.7**
Standard Fringe Rate		34.0%		34.0%		34.5%		35.0%		35.5%		36.0%
Graduate Waiver & Insur.		$3,281		$3,816		$4,045		$4,288		$4,545		$4,818
Overhead Rate		45.0%		47.0%		47.0%		47.0%		47.0%		47.0%
Inflation Factor		0.962		1.039		1.079		1.120		1.160		1.202

Table F-1: Schedule of requested funds. For ease of comparison, all costs (including those for the FY94 reference budget) are given in FY96 dollars, using DOE-supplied inflation factors (bottom row).

G. Current and Pending Support

H. Facilities, Equipment and Other Resources

The NSCL is a national user facility devoted to basic nuclear physics research, and accelerator and instrumentation R&D, including applications to meet societal needs. During its history, the laboratory has designed and built four cyclotrons, three of which are based upon modern superconducting technology. At present, the laboratory operates a national user facility for experimental nuclear physics research. The K1200 superconducting cyclotron of the NSCL is the highest-energy continuous-beam-accelerator in the world and provides high quality beams ranging from 155 MeV protons to 5.9 GeV uranium ions (see also Fig. C-1 and Table A1 of the Appendix). The NSCL staff has a strong international reputation for innovative research, technical innovation, and excellence, and the traditional close interaction of experimental and theoretical physicists provides an intellectually stimulating atmosphere for research on a broad range of topics. The laboratory's experimental and theoretical nuclear physics research groups address important questions concerning quantum statistics and transport phenomena in finite, strongly interacting many body systems, including the liquid-gas transition and the equation of state of nuclear matter; the shell structure of nuclei; fundamental modes of excitation; the properties of nuclei far from stability, including those with extended neutron halos; and problems of element formation in stellar environments. The accelerator physics group has made many important contributions in the areas of cyclotron and beam transport design, the theory of beam dynamics, and beam diagnostics. Modern CAD/CAM capabilities, an excellent engineering staff, and highly skilled fabrication and assembly groups provide a strong technical base for continued excellence in accelerator and beam transport system design and construction.

Technical know-how at the NSCL often serves as a national resource which not only benefits other laboratories but also addresses societal needs. For example, the Princeton K50 cyclotron is a copy of the first cyclotron built at MSU, and the theoretical basis for the IUCF class of separated sector cyclotrons was developed by MSU Professor Morton Gordon. More recently, the design of the K500 superconducting cyclotron at Texas A&M University was closely based on the K500 at the NSCL. Its superconducting main coil was wound at the NSCL. The NSCL designed, built and commissioned the first superconducting cyclotron for (neutron) cancer radiation-therapy at Harper Hospital in Detroit.

MSU has a demonstrated commitment to maintain the strength of its nuclear science faculty. During the last year, four new nuclear physics faculty were hired (two theorists and two experimentalists), and the search to fill an additional experimental faculty position in nuclear chemistry is underway.

The NSCL has recently submitted a proposal to the NSF (PHY-9423946) for a major intensity upgrade of its facility. If funded, large increases in primary and secondary (radioactive) beam intensities will be achieved in a cost-effective fashion by the coupled operation of the two existing superconducting cyclotrons [MSU94]. To illustrate the scope of the proposed upgrade, Fig. H-1 shows the proposed reconfiguration of the West section of the NSCL high bay (the present high-bay configuration is depicted in Fig. H-2, below). Michigan State University supports the NSCL and the proposed K500⊗K1200 project strongly. As an up-front investment, MSU is presently constructing a high-bay extension which is needed as a construction and staging area for the upgrade project. As mentioned earlier, MSU has further agreed to share the cost of the proposed facility upgrade, thereby reducing the need for new NSF funds to $11M (FY94 dollars) from a total cost of roughly $19M (which includes the high-bay addition). MSU's commitment assumes that the NSF operating support of the NSCL facility during the next five-year period will remain at least at the constant-effort FY94 funding level.

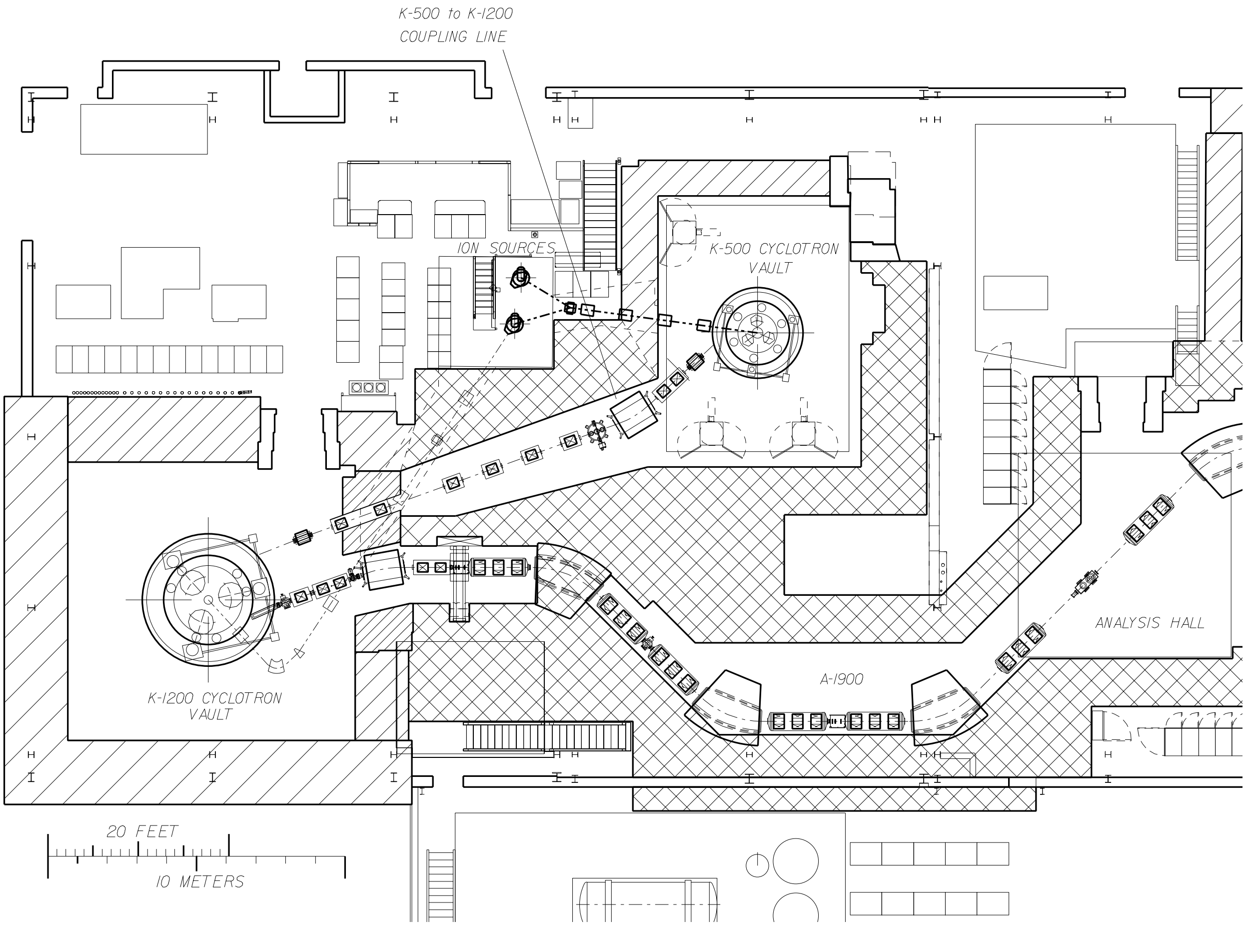

Fig. H-1: Proposed reconfiguration of high bay for the K500⊗K1200 Project showing the locations of the K500 and K1200 cyclotrons, the coupling line, and the A1900 beam analysis system.

In the following we give a brief description of the NSCL facility, technical staff, design and construction capabilities, and the envisaged project supervision.

NSCL Facility and Major Experimental Apparatus

The present floor plan of the high bay experimental area is shown in Fig. H-2. Two superconducting cyclotrons (the K500 and the K1200) and a diverse array of experimental apparatus are available at the NSCL. Nearly all beam line magnets use superconducting technology developed at the NSCL. Three electron cyclotron resonance (ECR) ion sources, which were designed and constructed at the NSCL, are coupled to a beam switch yard that allows injection from any of these sources into either cyclotron. The "RTECR" ion source, with room temperature coils, can produce beams of all species, including rare isotopes, with high efficiency. The compact "CPECR" ion source is used for the production of alkali metal ion beams. The new superconducting "SCECR" ion source produces the most intense beams of very highly charged ions.

A brief description of major instruments is given below (in counterclockwise sequence in Fig. H-1, starting from the exit of the K1200 cyclotron). Many of these instruments have been constructed by or with the help of outside users, and their continued effective use is an integral part of the proposed facility upgrade plan.

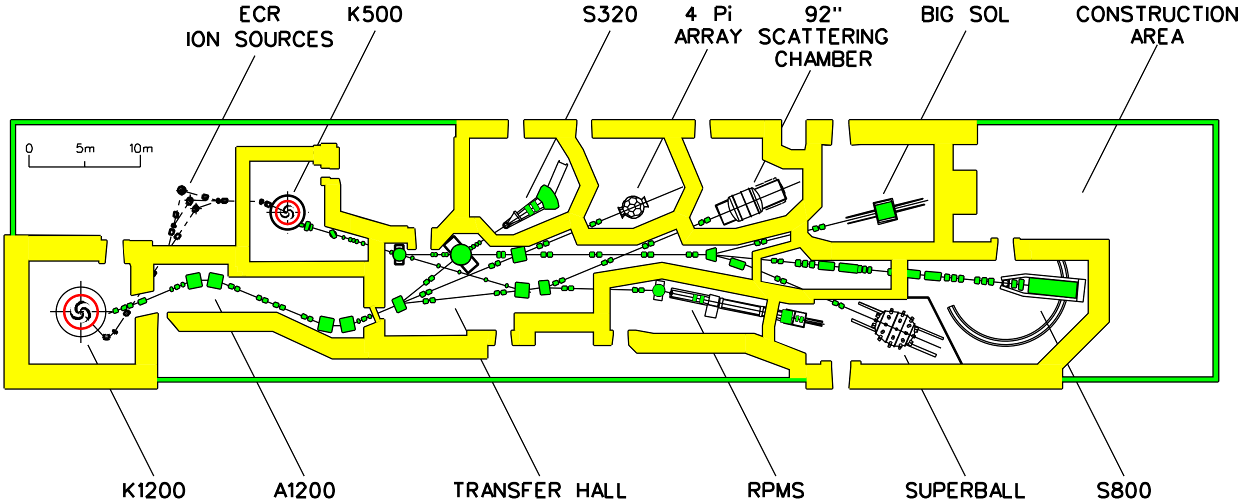

Fig. H-2: Present floor plan of the NSCL high bay experimental area showing the two superconducting cyclotrons (K500 and K1200), the superconducting A1200 beam analysis system and subsequent beamlines, the various experimental vaults, and the heavy equipment construction area.

The A1200 beam analysis system (momentum acceptance $\Delta p/p = 3\%$, maximum rigidity $B\rho_{max} = 5.35$ Tm) can be used as a monochromator which defines the energy and emittance of the beam from the K1200, as a zero-degree magnetic spectrograph, or, most importantly, as a reaction product filter to select radioactive beams produced by projectile fragmentation. For the most commonly used production-target location, the solid angle for accepting projectile fragments is $\Delta\Omega = 2.2$ msr, and the momentum resolution is 2000. Since the A1200 is located upstream of the beam switchyard, it is possible to transport radioactive beams selected by the A1200 to any experimental station at the NSCL and thus utilize the full complement of instruments available for research with radioactive beams. As shown in Fig. H-1 and discussed in detail in [MSU94], we propose to replace the A1200 with a A1900 beam analysis system of much improved acceptance (but otherwise matched to the remaining beam transport system). Thus major experimental apparatus remains fully utilized at the coupled cyclotron facility.

The reaction product mass separator (RPMS) is used for low-background studies of nuclei far from stability and for further purification of radioactive beams produced in the A1200 when necessary. The instrument consists of a Wien velocity filter followed by a magnetic dipole for m/Q selection; it achieves a mass resolution of 10^2 and a primary beam suppression of approximately 10^8.

The "Superball" is a high-efficiency neutron multiplicity meter constructed by a group from the University of Rochester. The device contains approximately 17 m^3 of Gd-doped scintillator for the detection of neutrons in 4π geometry. Its central scattering chamber is large enough to house other complex detection equipment such as the Miniball/Miniwall array described below.

The S800 is a superconducting high resolution magnetic spectrograph presently nearing completion; commissioning of the S800 is planned for early 1996. The main specifications are: energy resolution = 10^4; maximum rigidity $B\rho_{max}$ = 4.2 Tm; momentum acceptance $\Delta p/p$ = 5%; solid angle $\Delta\Omega$ = 20 msr. Also under construction is the S800 superconducting beam line which can be used to dispersion-match the beam on target. Alternatively, it can be operated as a fragment separator with momentum acceptance $\Delta p/p$ = 6%, maximum rigidity $B\rho_{max}$ = 5.35 Tm, momentum resolution = 2000, and solid angle $\Delta\Omega$ = 6 msr. Both the S800 spectrograph and its beamline bend the ions vertically.

BIG SOL is a 7 Tesla superconducting solenoid constructed by a group from the University of Michigan for various studies including radioactive beam experiments.

The 92" scattering chamber is a large cylindrical multi-purpose scattering chamber (diameter: 231 cm, length: 271 cm) used for a variety of reaction studies and radioactive beam experiments.

The 4π Array is a low-threshold "logarithmic" 4π detector consisting of 30 position sensitive parallel plate multiwire detectors, backed by segmented Bragg ionization chambers, backed in turn by an array of 215 phoswich detectors, each consisting of a fast-slow plastic scintillator combination. A number of forward arrays have been constructed by outside user groups for experiments requiring higher resolution and/or granularity at small angles. For studies of very heavy systems at higher energy (e.g. Au+Au at $E/A \geq 40$ MeV), the granularity in the forward hemisphere must be increased.

The S320 spectrograph is a small solid-angle ($\Delta\Omega$ = 0.6 msr) magnetic spectrograph with bending power ($B\rho_{max}$ = 2.55 Tm) matched to the K500, but insufficient for the energetic beams from the K1200. The device has a modest energy resolution of 500 and a momentum acceptance $\Delta p/p$ = 10%. The S320 was extensively used for the early nuclear structure program with beams from the K500 cyclotron; it will be decommissioned when the S800 has become fully operational.

Apart from the fixed major equipment described above, a number of special purpose detector arrays exist for the coincident detection of γ-rays, neutrons, and charged particles.

Among those is the Miniball multifragment detection array, a transportable and granular, low threshold, 4π - plastic-scintillator-CsI(Tl) phoswich detector. Typically, it is mounted in the 92" chamber, but it is presently mounted inside the Superball to allow simultaneous 4π coverage of neutrons and charged particles. For coincidence-experimentation with the S800, the count-rate capability of the device must be improved by replacing the currently existing low-current photomultiplier bases with high-current bases.

Technical Staff

Fig. H-3 presents an organizational chart of the NSCL for the present operations. The Laboratory has a large and highly skilled technical staff experienced in the design and construction of large apparatus, including superconducting cyclotrons and beam transport and analysis systems. The following gives a brief overview of these major departments and their areas of technical expertise.

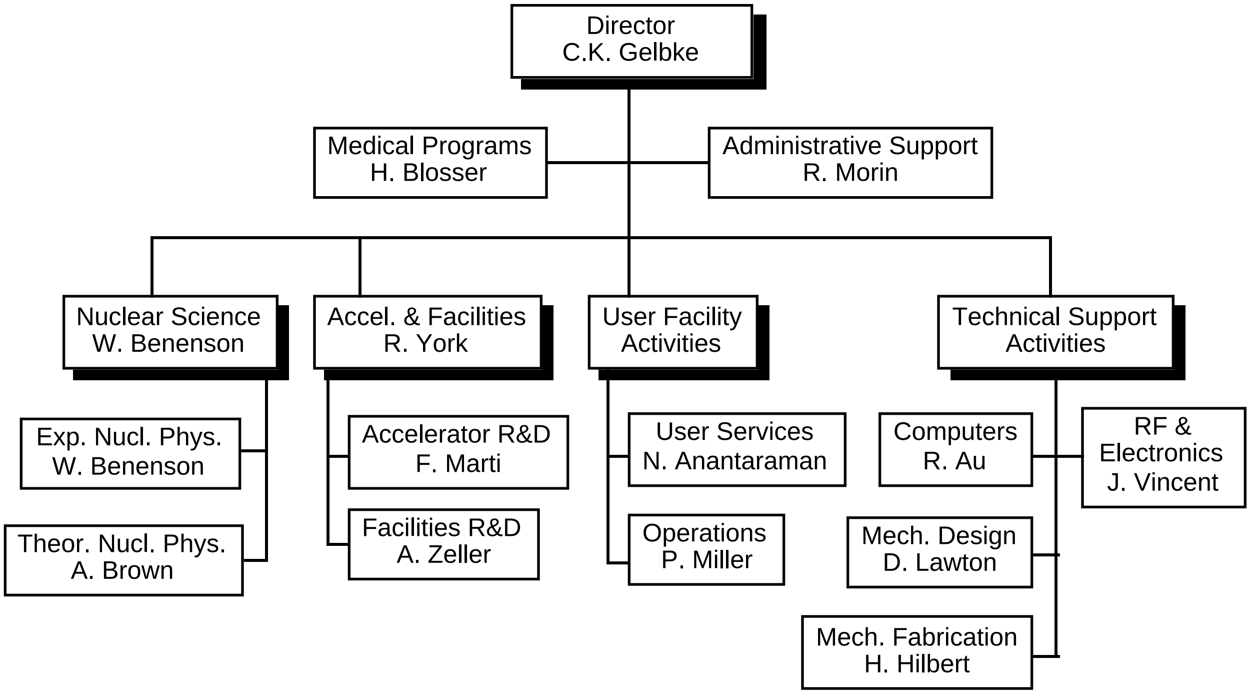

Fig. H-3: NSCL organizational chart. Professor David Morrissey will assume the responsibilities of Associate Director for Nuclear Science, starting September 1995.

The in-house nuclear physics research activities, including the hiring and training of NSCL-supported graduate students and postdoctoral researchers, are comprised in the Nuclear Science Section of the NSCL, headed by the Associate Director for Nuclear Science, Professor Walter Benenson. Professor David Morrissey will assume the responsibilities of Associate Director for Nuclear Science, starting September 1995.

Administrative and clerical support, budgetary supervision, and labor relations services are provided by the Administrative Support Section of the Laboratory, headed by Executive Director Rex Morin.

The Accelerators & Facilities Section of the NSCL is led by Associate Director for Accelerators, Dr. Richard York. The section comprises the Accelerator R&D Department, headed by Dr. Felix Marti, and the Facilities R&D Department, headed by Dr. Al Zeller.

Accelerator R&D Department: Three members of the Accelerator R&D Department (Dr. Henry Blosser, Dr. Martin Berz, and Dr. Richard York) have tenured faculty status at Michigan State University. Dr. Mort Gordon is a professor emeritus well known for his contributions to the fundamental understanding of cyclotron orbit dynamics. The other members of the Department are appointed within the NSCL Continuing Appointment system. The group has a proven track record in accelerator design and a broad range of expertise, including 3D magnetic field calculations, nonlinear beam dynamics, and cyclotron orbit calculations. Dr. Blosser is the founding Director of the NSCL, and he has been the principal investigator and leading designer on all of MSU's many cyclotron projects. Dr. York has a broad background in accelerator physics and project management. Before he joined the NSCL in February 1993, he was in charge of the Low and High Energy Boosters at the SSC. Department Head Dr. Marti is an expert in beam diagnostics, 3D relaxation calculations, and cyclotron orbit calculations. Mr. Johnson has over 30 years of experience in the design of and code development for cyclotrons. In the past year, two young accelerator physics staff have been added; Dr. Wu, whose thesis work was on cyclotron design and who made important optics calculations for the SSC Low Energy Booster and Dr. Grimm, whose thesis work was on high frequency rf sources and who played an important role in the development of the SSC Low Energy rf structure design.

Facilities R&D Department: The Facilities R&D Department, headed by Dr. Al Zeller, is comprised of a staff of ten scientists, engineers, and technicians; it provides technical expertise and help in construction and operation of large equipment. Areas of unique expertise and technical know-how include ion source technology, refrigeration and cryogenics, design and fabrication of superconducting and room-temperature magnets, stress calculations, vacuum technology, precision welding, beam-line design and construction, and radiation shielding. The facilities group plays a key role in the construction of virtually all major experimental apparatus, including the S800 superconducting magnet spectrograph and the beam transport system. Members of the group develop and operate the ECR ion sources of the NSCL. In addition, the group operates and maintains the liquid He refrigeration and distribution system. Department Head Dr. Al Zeller is an expert in superconducting beam-line magnet design, and he is currently the construction manager for the S800 Spectrograph.

The four Technical Support Departments report directly to the NSCL Director.

Mechanical Design Department: The Mechanical Design Department, headed by Mr. Don Lawton, consists of nine engineers, designers, and detailers. The department has a broad expertise in computer aided design (CAD) techniques, and it is well equipped with CAD workstations. Virtually all non-commercially available mechanical hardware components at the NSCL were designed by this group which has acquired significant expertise in the design of superconducting magnets, cyclotron, ion source and rf system components, as well as complex detection equipment. The expertise of the design group is recognized outside the NSCL, and in several instances the group has helped other laboratories solve mechanical design problems. The close interaction of the design staff with the mechanical shop and their active participation in hardware assembly generally lead to early detection of possible design and/or fabrication errors thus reducing the cost of retrofitting.

<u>Mechanical Fabrication Department</u>: The Mechanical Fabrication, headed by Mr. Harold Hilbert, consists of a highly trained staff of seven machinists, a welder, a five-person electro-mechanical assembly group, and a person handling shipping and receiving. The department meets the mechanical construction needs of the NSCL and its users and provides maintenance support for all mechanical aspects of the facility. Over the years, the NSCL has made considerable investments in its technical infrastructure. As a consequence, the mechanical workshop is well equipped with a broad range of machining tools, several of which are computer controlled (CAM) allowing cost-effective precision fabrication of complicated mechanical parts. Experience has shown that the NSCL shop has better cost and quality control than many commercial suppliers, and it is customary at the NSCL to entrust the in-house shop with the most delicate machining tasks.

<u>RF & Electronics Department:</u> The RF & Electronics Department, headed by Mr. John Vincent, consists of five engineers and seven technicians. The group has considerable expertise in the design and operation of high power radio-frequency systems, high quality power supplies, design and implementation of control systems (including embedded controllers and servo controllers), and circuit design. This group mastered difficult engineering challenges in bringing the variable energy K500 and K1200 cyclotrons on line, and their innovative solutions to problems have been key to NSCL operations.

<u>Computer Department:</u> The Computer Department, headed by Mr. Richard Au, has a staff of five permanent persons, plus typically 2-3 student helpers. In cooperation with the NSCL Computer Committee, the department plans, implements, maintains and documents data acquisition, analysis and scientific computing systems that provide NSCL users with state-of-the-art capability, as well as shared electronic processing services such as University and world wide network access, mail & printing services, and file server, backup and archival storage. In addition, the department assists NSCL users in resolving problems during data taking and analysis.

User Facility Activities are organized in two departments which report directly to the NSCL Director:

<u>Operations Department</u>: The Operations Department, headed by Dr. Peter Miller, has a staff of nine operators and technicians. The Department operates, maintains and repairs the NSCL cyclotrons, develops new beams, and provides beam transport optics calculations and beamline tuning for NSCL users. Together with other technical service departments, the Operations Department initiates and participates in technical R&D projects aimed at improving K1200 reliability.

User Services Department: The User Service Department, headed by Dr. Raman Anantaraman, has a staff of seven physicists and technicians. The Department serves as the interface between users and the NSCL technical staff, management and lab director to facilitate preparation and safe conduct of experiments. It monitors the status of beam lines and calls technical services for needed maintenance and repairs, participates in safety supervision and upgrades of the laboratory (including radiation shielding and safety instrumentation), and provides the interface between the Laboratory and safety organizations. The department further operates the user support laboratories for detectors, targets and nuclear electronics, and is responsible for scheduling experiments and coordinating related construction and fabrication issues. This department is also responsible for planning, monitoring and enforcing the radiation safety procedures of the Laboratory with assistance from the NSCL Radiation Safety Committee and the MSU Office of Radiation Chemical and Biological Safety.

Project Management and Oversight

Overall project supervision and resource allocation will be the responsibility of the NSCL Director, Dr. Konrad Gelbke. Fiscal planning, procurement, budget projections, and accounting will be the responsibility of the NSCL Executive Director, Mr. Rex Morin. Management of the in-house nuclear physics research program is the responsibility of the Associate Director for Nuclear Science, Professor Walter Benenson. Professor David Morrissey will assume the responsibilities of Associate Director for Nuclear Science, starting September 1995. Technical supervision, planning and management of accelerator improvement projects will be the responsibility of the Associate Director for Accelerators, Dr. Richard York. Supervision of cyclotron operations is the responsibility of the Head of the Operations Department, Dr. Peter Miller. Beam scheduling and user service coordination is the responsibility of the Head of the User Service Department, Dr. Raman Anantaraman.

Appendix

Ion	Energy (MeV/A)	I (pnA)	Ion	Energy (MeV/A)	I (pnA)	Ion	Energy (MeV/A)	I (pnA)
#H_2+	140.	6.0	16 O 5+	70.	22.0	52 Cr 14+	60.	2.5
#H_2+	155.	1.0	16 O 6+	80.	50.0			
H_2+	200.	2.5	*16 O 7+	150.	20.0	55 Mn 14+	70.	5.0
			*16 O 8+	200.	0.125			
#3 D-H 1+	70.	25.0				58 Ni 13+	50.	8.5
			17 O 3+	25.	20.0	58 Ni 15+	65.	1.0
4 He 1+	40.	50.0				*58 Ni 15+	70.	1.5
4 He 1+	60.	50.0	*18 O 3+	22.	20.0			
4 He 2+	140.	20.0	18 O 4+	35.	5.0	84 Kr 14+	22.	8.6
4 He 2+	155.	20.0	18 O 6+	80.	53.0	84 Kr 15+	30.	15.0
4 He 2+	170.	20.0	18 O 6+	100.	60.0	84 Kr 19+	50.	2.0
4 He 2+	200.	2.2				84 Kr 21+	60.	0.5
			20 Ne 4+	30.	7.5	84 Kr 23+	70.	0.0065
#5H-He1+	30.	1.5	20 Ne 4+	40.	6.0	*84 Kr 30+	125.	0.005
#5H-He1+	35.	6.0	20 Ne 5+	60.	100.0			
			20 Ne 7+	80.	21.4	86 Kr 16+	35.	5.0
#6D-He1+	26.	1.5	20 Ne 6+	100.	50.0	*86 Kr 19+	50.	5.0
			20 Ne 8+	110.	22.0	86 Kr 22+	70.	0.055
6 Li 2+	65.	5.0	20 Ne 9+	115.	0.3	86 Kr 23+	75.	0.011
6 Li 2+	100.	5.0	20 Ne 9+	125.	0.3	86 Kr 24+	80.	0.016
			20 Ne 10+	140.	0.06	*86 Kr 26+	100.	0.004
7 Li 1+	19.	10.0	20 Ne 10+	170.	0.08			
7 Li 2+	50.	5.0				92 Mo 25+	70.	0.024
7 Li 2+	70.	5.0	22 Ne 6+	70.	23.3			
						106 Cd 26+	60.	0.044
#11 B 2+	32.	55.0	24 Mg 7+	60.	0.17			
						129 Xe 19+	20.	0.6
12 C 2+	22.	18.0	28 Si 8+	50.	5.0	129 Xe 21+	25.	1.4
12 C 3+	40.	50.0	28 Si 9+	80.	1.3	129 Xe 23+	30.	1.6
12 C 4+	75.	6.0				129 Xe 26+	40.	0.5
12 C 4+	90.	2.5	36 Ar 6+	22.	2.0	*129 Xe 27+	45.	4.4
12 C 5+	95.	0.5	36 Ar 12+	80.	7.0	129 Xe 28+	50.	0.025
12 C 5+	125.	1.0	36 Ar 15+	110.	0.05	129 Xe 29+	55.	0.045
12 C 6+	145.	0.05	36 Ar 16+	120.	0.017	129 Xe 30+	60.	0.012
12 C 6+	155.	0.1	*36 Ar 17+	160.	0.007	*129 Xe 31+	65.	.0018
12C 6+	200.	0.125				129 Xe 32+	70.	0.001
			38 Ar 15+	100.	0.73	*129 Xe 40+	100.	0.005
14 N 3+	35.	83.0						
14 N 4+	50.	50.0	40 Ar 7+	25.	5.4	136 Xe 24+	30.	1.8
14 N 4+	70.	70.0	40 Ar 10+	40.	15.0	136 Xe 25+	35.	0.6
14 N 4+	90.	15.0	40 Ar 10+	60.	10.0			
14 N 6+	100.	2.0	40 Ar 12+	80.	15.0	197 Au 29+	20.	0.6
14 N 6+	120.	20.0	*40 Ar 12+	90.	20.0	197 Au 32+	25.	0.06
14 N 6+	130.	8.0	*40 Ar 12+	100.	30.0	197 Au 34+	30.	0.004
			40 Ar 16+	115.	0.09	197 Au 36+	35.	0.002
						*197 Au 38+	40.	0.0003
15 N 5+	90.	50.0	40 Ca 11+	55.	3.2	*197Au 41+	45.	0.00002
15 N 6+	100.	50.0						
			48 Ca 11+	55.	2.7	238 U 35+	20.	0.014
16 O 3+	25.	167.0	48 Ca 16+	100.	0.11	238 U 39+	25.	0.0004
16 O 4+	40.	37.5						
16 O 4+	60.	50.0	51 V 13+	50.	1.0			

Table A1: Beams marked by # or * are from compact or superconducting ECR source, respectively; all others are from room-temperature source.

Journal	Year	Inside	Outside	Theory only	Total

Phys. Rev. Lett.	1989	3	0	2	5
Phys. Rev. Lett.	1990	3	0	3	6
Phys. Rev. Lett.	1991	3	0	3	6
Phys. Rev. Lett.	1992	1	2	3	6
Phys. Rev. Lett.	1993	10	3	4	17
Phys. Rev. Lett.	1994	3	1	4	8
Phys. Rev. Lett.	**Subtotal**	**23**	**6**	**19**	**48**
Phys. Lett. B	1989	3	1	5	9
Phys. Lett. B	1990	1	2	1	4
Phys. Lett. B	1991	2	3	4	9
Phys. Lett. B	1992	5	0	5	10
Phys. Lett. B	1993	4	3	5	12
Phys. Lett. B	1994	2	2	3	7
Phys. Lett. B	**Subtotal**	**17**	**11**	**23**	**51**
Nucl. Phys. A	1989	0	3	3	6
Nucl. Phys. A	1990	0	4	2	6
Nucl. Phys. A	1991	0	3	7	10
Nucl. Phys. A	1992	1	0	2	3
Nucl. Phys. A	1993	1	0	4	5
Nucl. Phys. A	1994	0	0	4	4
Nucl. Phys. A	**Subtotal**	**2**	**10**	**22**	**34**
Phys. Rev. C	1989	13	7	12	32
Phys. Rev. C	1990	7	9	9	25
Phys. Rev. C	1991	11	5	6	22
Phys. Rev. C	1992	13	7	14	34
Phys. Rev. C	1993	10	8	9	27
Phys. Rev. C	1994	8	10	12	30
Phys. Rev. C	**Subtotal**	**62**	**46**	**62**	**170**
Nucl. Instr. & Meth.	1989	6	3	0	9
Nucl. Instr. & Meth.	1990	6	0	0	6
Nucl. Instr. & Meth.	1991	7	0	0	7
Nucl. Instr. & Meth.	1992	1	3	0	4
Nucl. Instr. & Meth.	1993	1	1	0	2
Nucl. Instr. & Meth.	1994	4	1	0	4
Nucl. Instr. & Meth.	**Subtotal**	**25**	**8**	**0**	**33**
Other	1989	5	0	4	9
Other	1990	3	1	7	11
Other	1991	2	0	6	8
Other	1992	5	5	4	14
Other	1993	7	4	11	22
Other	1994	4	4	2	10
Other	**Subtotal**	**26**	**14**	**34**	**74**
Refereed Journals	**Grand Total**	**154**	**92**	**157**	**410**
	Year	**Inside**	**Outside**	**Theory only**	**Total**
Invited Talks	1989	31	7	11	49
Invited Talks	1990	31	9	9	49
Invited Talks	1991	46	17	11	74
Invited Talks	1992	42	17	12	71
Invited Talks	1993	50	14	33	97
Invited Talks	1994	45	16	16	77
Invited Talks	**Grand Total**	**245**	**80**	**92**	**417**

Table A2: Published NSCL output since 1989. "Outside" refers to experiments performed at the NSCL facility, but carried out primarily by non-NSCL scientists.

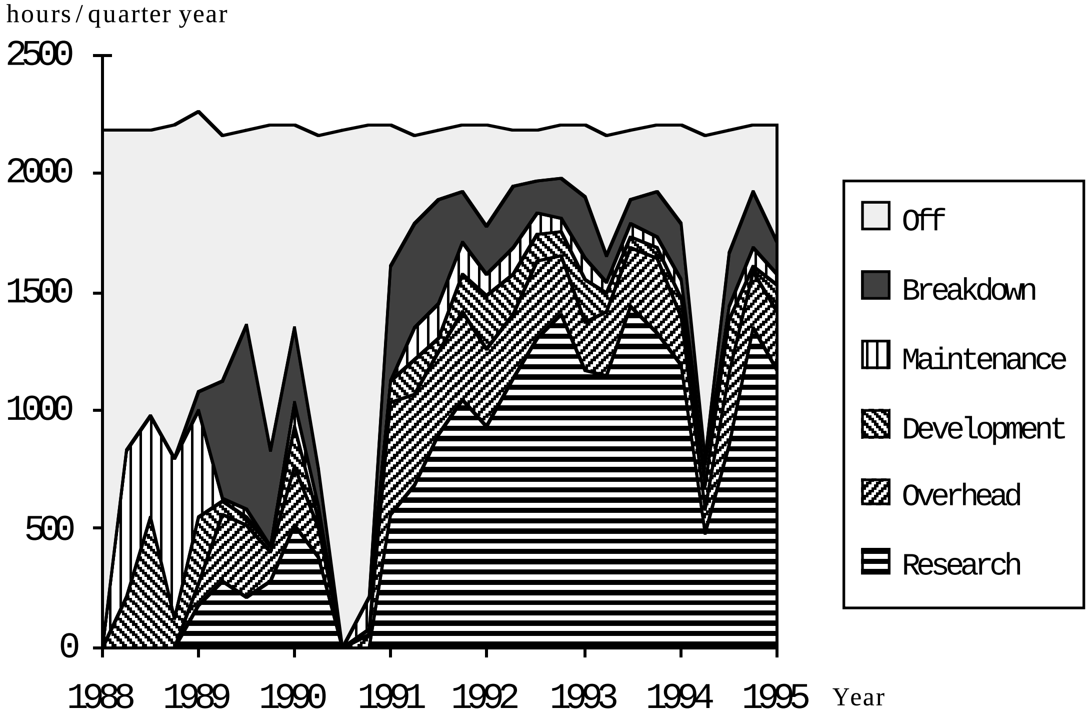

Fig. A1: K1200 usage (hours per quarter year). The large off-time in 1990 is due to the installation of the Phase 2 beamlines and the A1200 beam analysis system; the large off-time in 1994 is due to a two-month shutdown needed for the recent A1200 upgrade. Overhead is the time used for tuning, beam extraction and transport to the experimental station. Maintenance reflects scheduled time needed for short (typically one shift) maintenance jobs. Off-time represents longer (typically weeks to months) scheduled shutdowns needed for the installation of major hardware and maintenance.

FY	Category	Description	K$	K$	K$
1996	Facility	ECR electrostatic optics (20 k), 1GHz digital Oscilloscope(10 k)	30		
	Operations	Electrostatic deflector test stand (25 k), Large pump-92" cham. (23 k)	48		
		Three turbo pumps (27 k), Centralized refrigerator control system (30 k)	57		
		Electronics Instruments and test equipment (15 k)	15		
		Upgrade accel. control system, console, VME and Modicon (30 k)	30	180	
	User Services	Nuclear Elec.Pool (90 k), Detector Lab.DAQ system (18 k)	108		
	and Support	Experimental Data Acquisition and Scientific Computing	100		
		Target area equipment, mechanical pumps (21 k)	21	229	
	Experimental	S800 General Purpose Target Chamber (90 k)	90		
	Equipment	Part of high resolution silicon forward array (80 k)	80	170	579

Table A3: Summary of proposed equipment items (continued on following page).

FY	Category	Description	K$	K$	K$
1997	Facility	ECR injection line chopper (40 k), Rebuild Hurco mill and controls (30 k)	70		
	Operations	Rf amplifier tubes (44 k), LCW cooling tower (58 k)	102		
		Three small turbo pumps (27 k), Hydraulic pumps (8 k)	35		
		LCW heat exchanger (15 k)	15		
		Electronics Instruments and test equipment (15 k)	15		
		Upgrade accel. control system, console, VME and Modicon (30 k)	30	267	
	User Services	Nuclear Electronics Pool (88k)	88		
	and Support	Experimental Data Acquisition and Scientific Computing	100		
		Gas handling mech. pumps (3 k), Detector Lab.cryo-pump (4 k)	7	195	
	Experimental	S800 Multihit focal plane upgrade (50 k)	50		
	Equipment	Finish high resolution Silicon array (50 k)	50		
		19-pack Barium Fluoride array, crystals, PMTs, electronics (139 k)	139	239	701
1998	Facility	Rf spark detector for K1200 (10 k)	10		
	Operations	Turbo pumps (27 k), ECR beamline power supplies (40 k)	67		
		Electronics Instruments and test equipment (15 k)	15		
		Upgrade accel. control system, console, VME and Modicon (30 k)	30		
		Welding machine (5 k), Beam diagnostic equip. (25 k)	30	152	
	User Services	Nuclear Elec.Pool (90 k), Detector Lab. wire bonder (14 k)	104		
	and Support	Experimental Data Acquisition and Scientific Computing	100		
		RPMS vacuum system (30 k)	30	234	
	Experimental	19-pack Barium Fluoride array, crystals, PMTs, electronics (139 k)	139		
	Equipment	High granularity 4-Pi forward array, 120 elements with electronics (243 k)	243	382	768
1999	Facility	Beam diagnostic equipment (25 k), ECR klystron tube (30k)	55		
	Operations	Rf amplifier tubes (44 k), Roof beams to expand N4 vault (28 k)	72		
		Three small turbo pumps (27 k), Leak detector (16 k)	43		
		Electronics Instruments and Magnetic field measurement equip. (25 k)	25		
		Upgrade accel. control system, console, VME and Modicon (30 k)	30		
		Replacement LCW pumps, Air Cond. heat exchangers (30 k)	30	255	
	User Services	Nuclear Elec.Pool (100 k), Detector Lab. test chamber (9 k)	109		
	and Support	Experimental Data Acquisition and Scientific Computing	100		
		N4 vault vacuum system (30 k)	30	239	
	Experimental	S800 coincidence equipment/Adaption of Miniball	140		
	Equipment	Stopped Pion detector	90		
		Other unspecified research equipment	90	320	814
2000	Facility	Large turbo pump (23 k), Three small turbo pumps (27 k)	50		
	Operations	Begin advanced Ion source construction (50 k)	50		
		Electronics Instruments and test equip. (15 k)	15		
		Upgrade accel. control system, console, VME and Modicon (30 k)	30		
		Replacement two Bridgeport machines (14 k)	14	159	
	User Services	Nuclear Elec.Pool (140 k), Detector Lab.E-beam evaporator (25 k)	165		
	and Support	Experimental Data Acquisition and Scientific Computing	120		
		Beam line equipment, power supplies, vacuum, instrumentation (25 k)	25	310	
	Experimental				
	Equipment	Unspecified research equipment	350	350	819

Table A3: Summary of proposed equipment items (continued from preceding page).