Galonsky

PROPOSAL

FOR

SUPPORT

of the

NUCLEAR PHYSICS PROGRAM

OF THE

MICHIGAN STATE UNIVERSITY
CYCLOTRON

July, 1965

PROPOSAL
to the
National Science Foundation

for

SUPPORT
OF THE
NUCLEAR PHYSICS PROGRAM

of the
Michigan State University Cyclotron

for the period

December 16, 1965
to
December 15, 1970

Department of Physics
Michigan State University
East Lansing, Michigan

July 28, 1965

ENDORSEMENT

Henry G. Blosser
Professor of Physics

Truman O. Woodruff
Acting Chairman, Dept. of
Physics & Astronomy

Philip J. May
Vice President for
Business and Finance

TABLE OF CONTENTS

INTRODUCTION

Beginning with an initial grant in October, 1961, the National Science Foundation has supported design and construction of a 55 MeV variable-energy, multi-particle cyclotron at Michigan State University. Major progress benchmarks include: December, 1961—selection of an architect; October, 1962—award of construction contracts for the cyclotron building and placing of orders for the main magnet; July, 1963—magnet yoke received in East Lansing; October, 1963—cyclotron building completed and occupied; December, 1963—cyclotron magnet activated for first time; July, 1964—trimming coil assemblies received in East Lansing; October, 1964—magnet measurements completed; and February, 1965—beam accelerated to full radius for first time. At present (July, 1965) the cyclotron is operating more-or-less on an eighty hour per week basis, roughly half of this time being devoted to a continuing accelerator check out and debugging program and the other half to the nuclear physics program which, happily, is now in a bustling state of activity. Figure 1 is a recent photo of the cyclotron.

This proposal requests support for the Laboratory program for the five-year period beginning December 15, 1965, and extending to December 15, 1970. Total National Science Foundation support of $3,380,000 is requested, the annual level rising from $550,000 in the first year to $760,000 in the final year. Michigan State University will provide an estimated $2,270,000

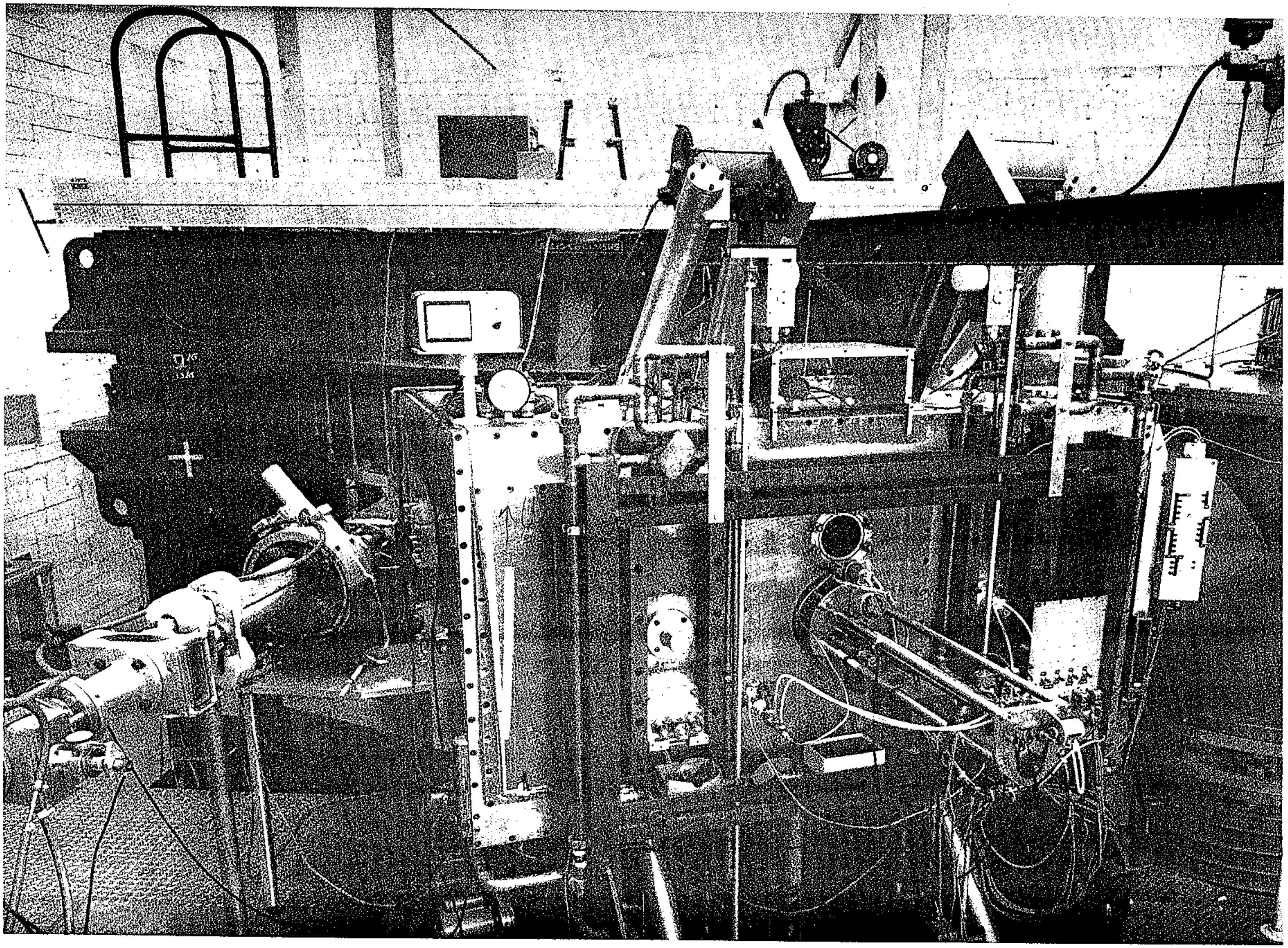


Fig. 1: View of cyclotron from dee stem side with beam pipe assemblies at left and main angle valve and diffusion pump at right.

of services in support of this program.

In this proposal, for clarity, material is grouped on a topical basis; in each section and subsection progress and future plans for a particular topic are treated together in a single unified discussion.

SUMMARY

Cyclotron checkout work is now mainly directed to development of new beams, and to redesign of troublesome components. Presently proton beams are available over the energy range from 22 to 37 MeV. Proton currents of up to 550 μa have been accelerated internally and it appears that the originally estimated 1000 μa can be easily achieved if components can be adequately engineered to withstand the tremendous beam power. The cyclotron operation is particularly noteworthy as regards the fact that in every operating condition the machine has operated with all controls set at calculated values. The validity of orbit computations and electric and magnetic field measurements are thus directly demonstrated.

Attempted operation with protons in the energy range from 37 to 49 MeV has thus far been only partially successful (pulsed operation at 39, 42, and 45 MeV) due to component failures in the rf system—improved designs are in process which should eliminate these difficulties. Operation with protons in the 49-56 MeV energy range has not been attempted nor has any appreciable effort been made to operate with other particles[1].

---

[1] Two brief attempts have been made to accelerate He^3 ions. On both occasions no detectable charge two beam was obtained from the source. Since the gas is relatively expensive, the tests were suspended pending accumulation of greater operating experience with ordinary He sources.

Fabrication work on the conventional deflector system (electrostatic deflector and magnetic channel) is still in progress; external beams are presently obtained by acceleration of H^- ions and use of a stripping foil to bring the ions out of the field. Currents up to 6 μa have been obtained in the scattering chamber using this technique. The $\nu_r = 1$ resonance, as predicted, produces turn separation and energy selection in the extraction process. While precise equipment for directly measuring the energy spread is not yet available the spread is approximately inferred by unfolding the various contributions to the total energy spread in nuclear physics experiments—total energy spreads of 0.4% FWHM have been achieved of which 0.2% is estimated to come from the spread in the beam. The beam spread is expected to improve to the predicted 0.1% when the amplitude feedback loop in the rf system is fully checked out. The external beam emittance has been measured—results are 4 milliradian-cm for the radial area and 10 to 20 milliradian-cm for the axial area depending on the height of the source slit. Axial emittance and source height have been found to be in one to one correspondence indicating no beam loss by axial defocusing anywhere in the machine. The emittance measurements are in close agreement with published predictions[2] made some four years ago.

Instrumentation for the beam handling system is presently

---

[2] H. G. Blosser and M. M. Gordon, Nucl. Instr. and Meth., 13, 101 (1961).

just beginning to take form. The beam is now directly piped to a single target position located roughly 10 feet from the cyclotron. A rudimentary quadrupole system focuses the beam; standardized multi-purpose boxes are utilized for insertion of quartz viewers, scanning electrodes, etc. At present no energy analysis is available other than that provided by the cyclotron. Figure 2 shows a view of the beam pipe, scattering chamber, and related hardware. Figure 3 is a view of the beam on a quartz viewing plate at the far side of the scattering chamber. The O-ring which shows as a black circle in the figure is 3" in inside diameter and no slits were in use when the picture was taken. (The beam is in fact sufficiently compact that most experiments are run without slits.)

Shielding and radiation safety systems are now in an advanced state of construction and should be completed by early fall. Figure 4 is a view showing a portion of the walls in place. Delivery of roof slabs is scheduled to begin in early August. Prior to installation of the walls shielding calculations were thoroughly reviewed and in several locations thicknesses were increased (particularly along the south wall where thickness was increased from 3' to 5' over a large region). The radiation safety system is in operation—a thorough and heavily redundant system of safeguards is provided to keep "beam on" areas clear of personnel. Radiation protection facilities and procedures have performed splendidly thus far as is attested by low neutron and beta-gamma film badge readings throughout the lab.

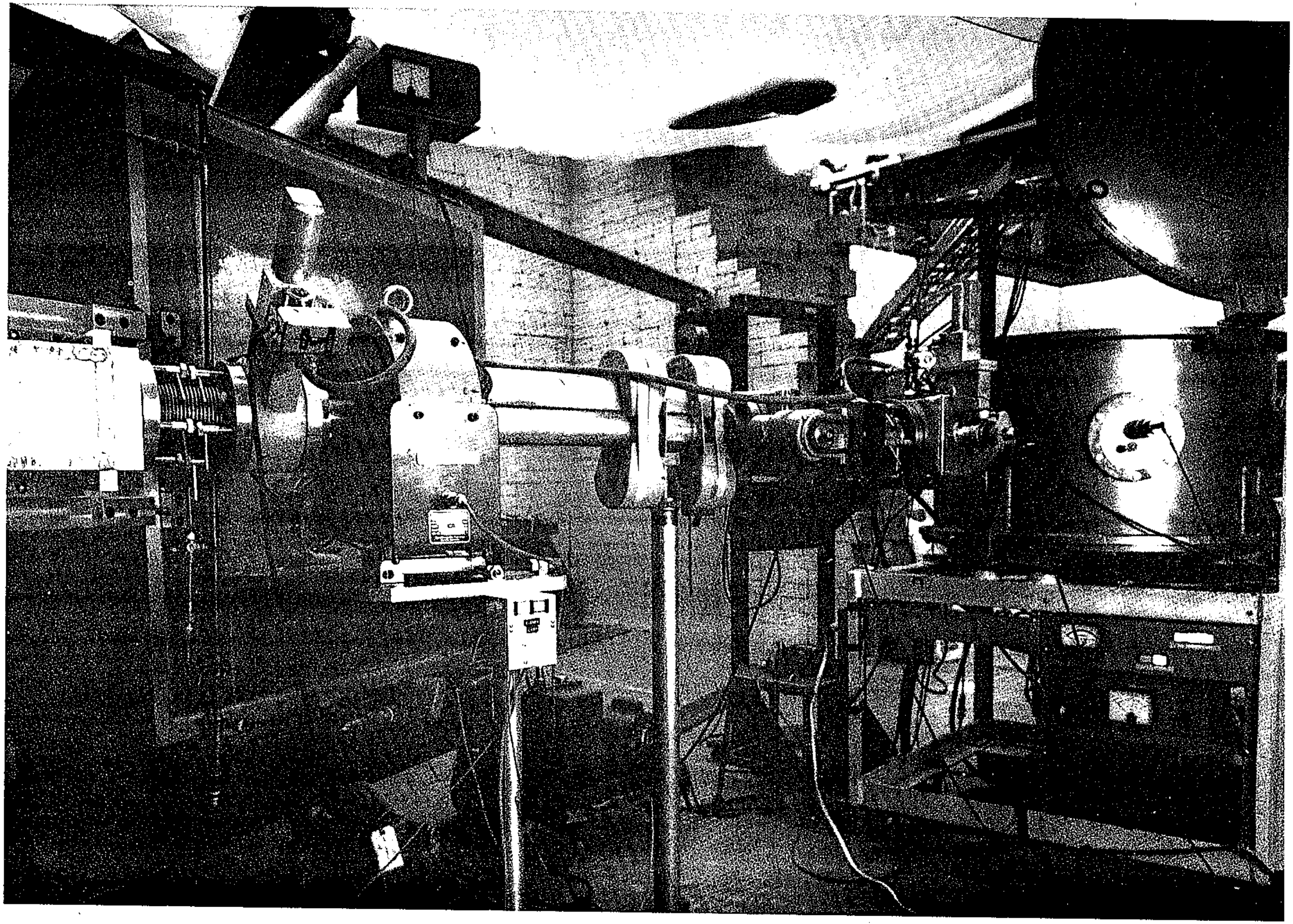


Fig. 2: View of beam pipe between cyclotron and scattering chamber. Permanent magnets on beam pipe at center of picture form a temporary quadrupole. Motor and chain drive just to right of permanent magnets are for inserting Quartz viewer in beam. Interlocking construction of shielding walls is visible in background.

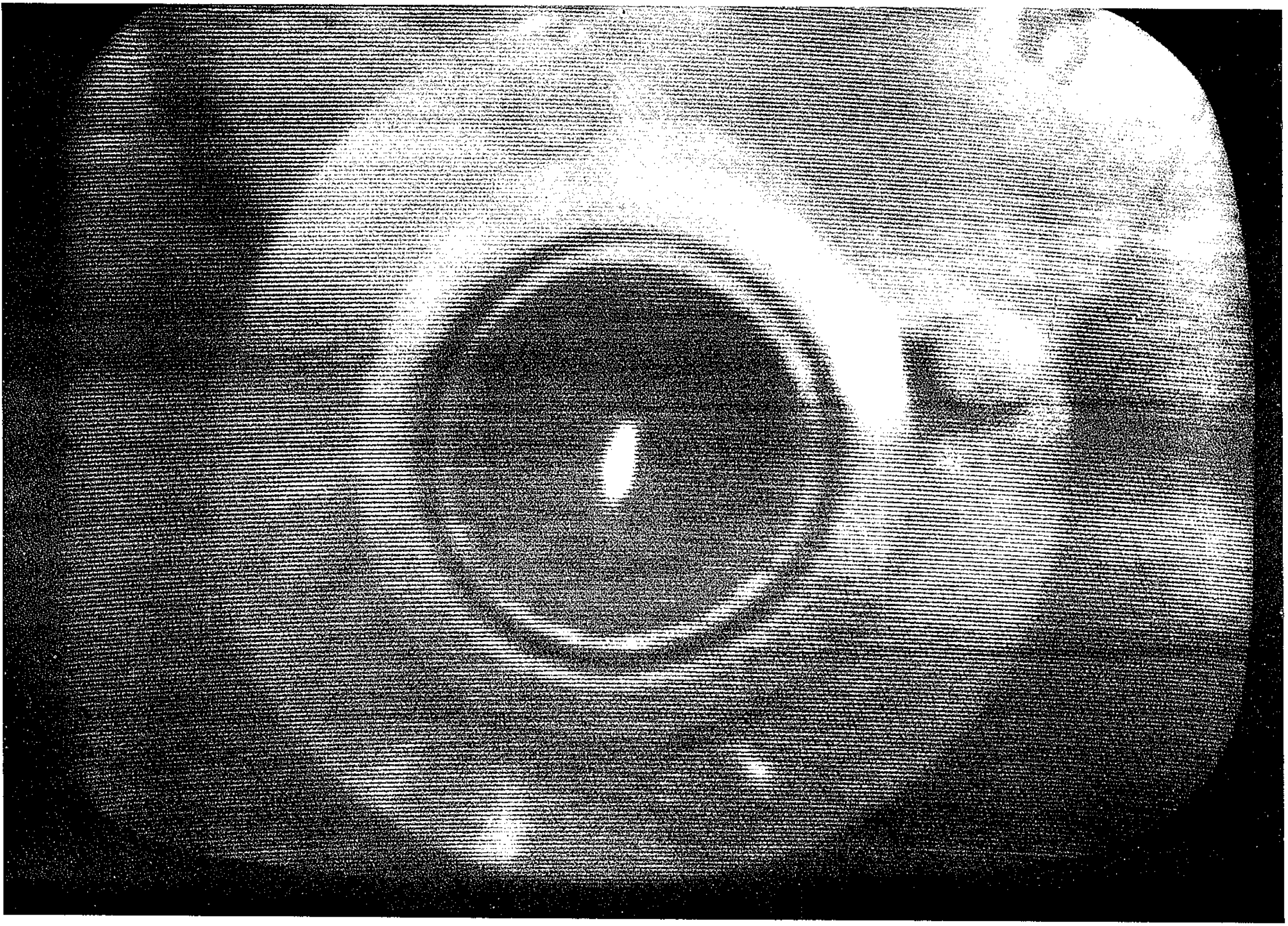


Fig. 3: View of beam pipe on Quartz viewer at far side of scattering chamber. The "O" ring (dark black circle) is 3" in diameter. The spot is focused by the quadrupole and permanent magnets shown in Fig. 2; no slits are in use.

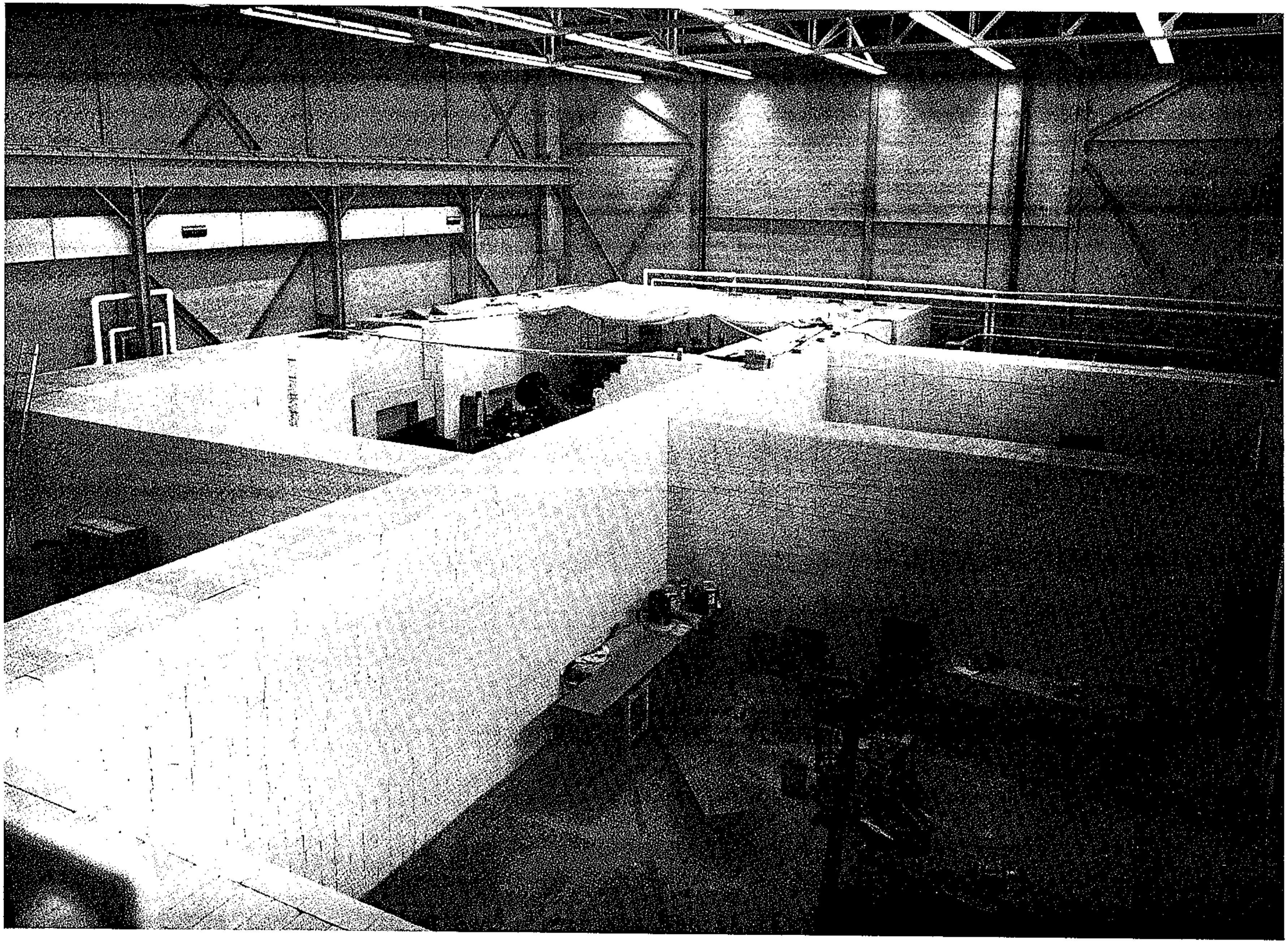


Fig. 4: View of shielding wall arrangement from north-east corner of high-bay area. Cyclotron is at center rear.

Nuclear physics activity is now centered on a basic series of experiments with the proton beam. Experiments presently in progress include elastic and inelastic scattering of protons, and studies of the (p,d) and (p,t) pickup reactions. Instrumentation is being assembled for a time-of-flight spectrometer which will be used for difficult particle identification problems and for neutron studies. The immediate objective of these programs is (a) an accumulation of accurate optical model parameters covering the 20 to 55 MeV energy range (at present only a few points are available), (b) studying the range of validity of present theories of direct reactions, and (c) using direct reactions as a spectroscopic tool to determine properties of nuclear wave functions.

Reflecting the shift in project emphasis from accelerator to nuclear physics activities, project staff expansion in the past year has again been concentrated entirely in the nuclear physics area. Dr. Sam Austin of Stanford University has been appointed Associate Professor, Dr. Richard Atneosen of Princeton University has been appointed Assistant Professor (Research), and Drs. Ram K. Bansal, Gerard M. Crawley, and G. H. MacKenzie, from Rochester, Princeton, and Birmingham respectively, have been appointed Research Associates. In addition, Dr. J. Hetherington has been appointed Assistant Professor in the nuclear theoretical group and Dr. W. C. McHarris has been appointed Assistant Professor in the nuclear chemistry group. (The activities of both these latter groups are very closely related to the cyclotron program.)

The graduate training aspect of the project program is continuing its rapid growth. Three doctoral degrees were granted in the past year—two in the beta-ray spectroscopy program and one in the accelerator development program, these being the first doctoral degrees granted by the project. In addition, five students are in position to finish doctoral programs in the coming year. A total of 21 graduate students are now associated with the project, 5 of these holding fellowships from various sources and 15 being supported as Graduate Research Assistants from the project budget. Of these 21 students 11 have joined the project within the last year. The number of Master's degrees granted now totals 21.

Proposed budgets for the five year research program are outlined on Page 85. Costs for the first year (December 15, 1965 to December 15, 1966) are itemized in detail, while costs for following years have been estimated on a per-staff-member basis plus an allowance for escalation. In making the estimates, staff growth has been presumed to slow down in the 2nd and 3rd years and terminate in the 4th and 5th years.

CYCLOTRON CONSTRUCTION

Referring to our progress report of June, 1964, we note that the cyclotron was at that time very much in the midst of construction. Magnetic measurements on the main magnet had been completed, the trimming coils were nearing completion in the factory, trial assembly was in process on the rf tuning panels, the design of the dees was just finalized, the vacuum system was partially assembled but no pumping tests had yet been made, and no high power had as yet been applied to any part of the rf drive chain. It is also interesting to note that this progress report anticipated "initial trial operation of the cyclotron in the fall (of 1964)." As usual, actual work took longer than anticipated.

Progress on the trimming coil assemblies, for example, was considerably less advanced than information from the manufacturer had led us to believe—these assemblies finally arrived in East Lansing on July 20, 1964, some six months later than the quoted delivery. Roughly three weeks after their arrival the coils were installed, connected, and a second extensive magnetic measurements program started. In this program the incremental effect of each of the eight trim coils was measured at four different main field excitations. A report containing complete results from these measurements is in press (MSUCP-22); as an example of the results, Fig. 5 shows data for four of the trimming coils at the four main magnetic excitations. The actual fields produced by the coils exceeded design estimates by 40% even in the least effective condition, (i.e., with the main magnet at

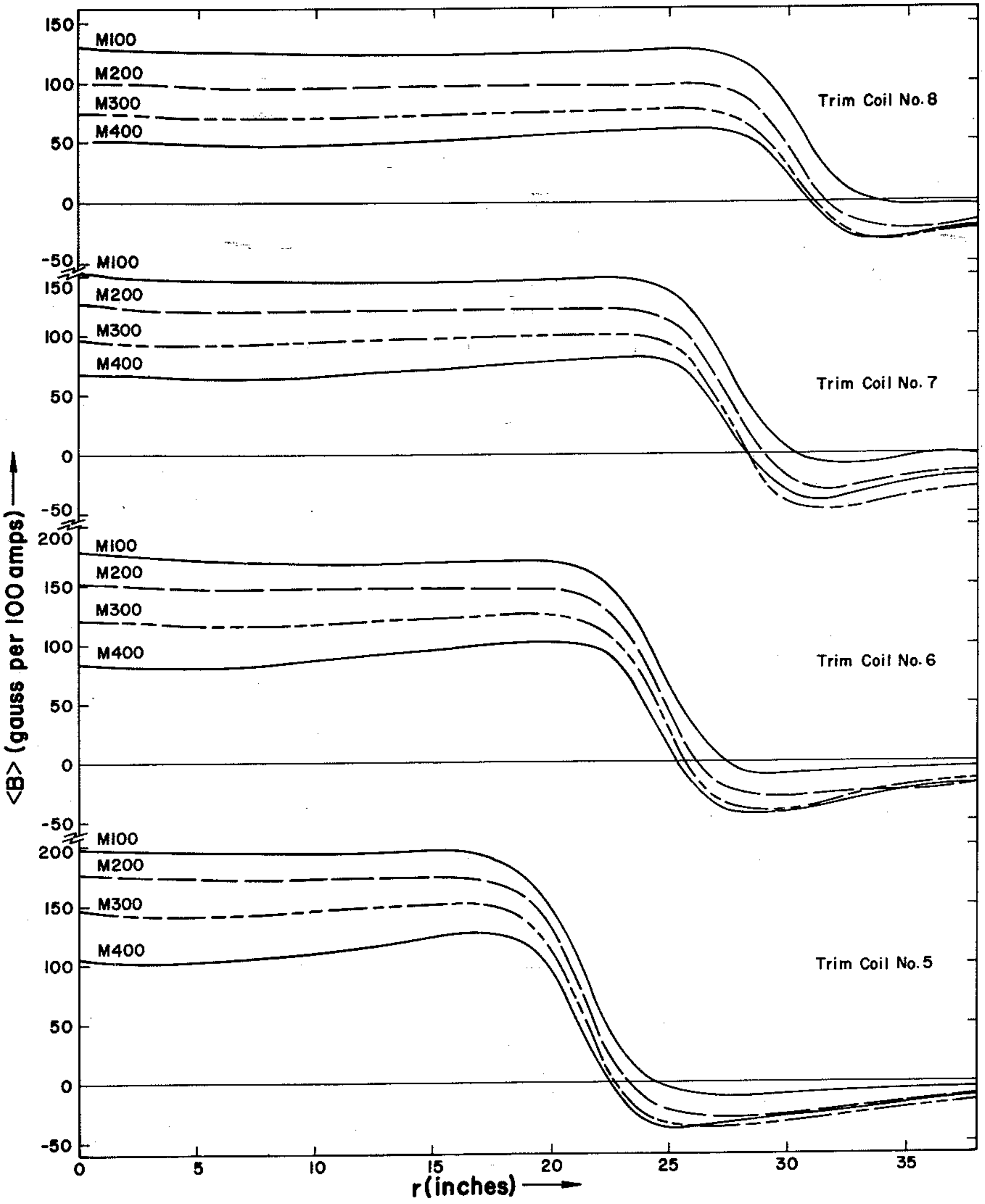


Fig. 5: Results from magnet-measurements program for the incremental average field contribution of four of the trim coils. For each coil the four curves labeled M100 to M400 are for different main-field excitations and cover the range from low field to full field.

maximum excitation). The original estimates[3] of the power required for these coils (30 kW) had already indicated the magnet design to be impressive as regards minimizing the load on these coils; the measured data imply an even lower power requirement—20 to 25 kW maximum.

After completing the profile coil magnetic measurements, attention shifted to assembly of the main vacuum tank. This tank is constructed entirely of rolled aluminum plate with no welds which means that gaskets at numerous positions come to a triple junction—usually referred to as a "T" joint. Initially the tank was assembled using molded neoprene "T" sections which were spliced to long lengths of rectangular gasket material as needed to fit the tank configuration. This technique proved unsatisfactory due to a "creep" phenomenon which very frequently shifted the molded "T" sections from their proper position before joints could be clamped. After considerable effort the molded "T"'s were abandoned and straight "butt" joints employed, one strand of rubber forming the top of the "T" and a separate strand forming the vertical member of the "T". With careful use of this technique leak-free joints are consistently obtained.

By late October, the entire tank registered leak-free on the mass spectrometer leak detector, although this was by no means the end of problems with vacuum leaks—in fact, the most

---

[3] H. G. Blosser, Proc. Inst. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

difficult leak-checking phase was to come considerably later when the rf tuning-panel system was installed with its numerous internal water-lines and flexible hoses which were sources of pressure-sensitive leaks. At present, the complete system is, however, leak tight and has been for several months—it is hoped that vacuum troubles are a problem of the past. Base pressure in the tank with source off is 1.5 x 10^{-6} Torr, typical pressure with source on is 4 x 10^{-6} Torr, and pump-down time to operating vacuum (2 x 10^{-5} Torr) is one hour.

It should be noted that the double-gasket system employed on all main gaskets has proved invaluable on a number of occasions. During the somewhat hectic final assembly of the cyclotron, for example, a gap of approximately 1/8" length was inadvertently left in one of the butt joints in a very inaccessible gasket. This leak was sufficiently large that the 50,000 liter/second diffusion pump came into equilibrium with the leak at approximately 30 microns. Applying a roughing pump to the space between the double gaskets reduced the pressure to a few x 10^{-5}, a comfortable operating pressure for positive particles, thereby saving approximately 2 to 3 days of time, and at this particular stage of the project 2 to 3 days seemed an enormously important interval to everyone concerned.

Through November and December, the rf liner, the rf tuning panels, and the ion source insertion mechanism, were successively installed in the cyclotron. Through this period, design inconsistencies between various components were discovered on almost a day-to-day basis. While the total number of such inconsistencies was probably not much different than on any project of this complexity, the importance of having an effective machine shop installation was vividly demonstrated. With splendid cooperation from the shop work-force none of the required corrections involved more than a few days of delay. If these various difficulties had been dealt with by normal procedures, i.e., preparing a drawing, requesting quotations, sending the part out for modification, etc. many months of delay would clearly have resulted.

In parallel with work on installation of the rf tuning panels, initial high-power tests on the final amplifier were conducted, the amplifier output being fed to a dummy resistive load. Parasitic oscillations unique to the amplifier proper were located and corrected. In late November, partially machined copper sheets for the dee skin were received at the Laboratory and by early January completed dees were being mounted on the stems and cooling water connections, etc. were installed. Throughout the month of January hookup work on control lines, water lines, installation of probes, ion source, remote drives for rf tuning elements, etc. proceeded at a feverish pace. Finally, in the late evening of Saturday, January 30th, all elements necessary for trial operation were in place and the tank buttoned up. The selected operating crew agreed to return that evening to make an initial try for a beam on the presumption that a Saturday evening would be a fine occasion for undisturbed concentration. The group soon learned, however, that news propagates in Cyclotron

Laboratories just as effectively as small town gossip—that evening the spacious control room was crowded almost beyond capacity by an interested throng of students, wives, children, and girl friends. In an atmosphere of considerable excitement, the magnet, trim coils, and ion source were successively turned on and an rf bake-out started. Unfortunately, these exciting events came to an abrupt halt in a matter of minutes when a severe water leak developed inside the vacuum tank. For the next ten days, this story repeated with impressive monotony, and the crowding in the control room steadily decreased. At the dinner hour of February 11, when another regular try was about to be made, not a single visitor was present.

The events of February 11 were, however, very different from previous attempts. To begin with the vacuum was relatively good and the rf voltage baked-in rapidly. When meters indicated the rf voltage to be at the correct operating value, the ion source was turned on and visual observations were made of the beam on the first turn. Since the slits and other structures in the central region of the M.S.U. cyclotron precisely prescribe the first turn trajectory, the luminescence resulting from loss of beam on slits or other structures can be used as a precision rf voltmeter—final dee voltage adjustment was made by this method. With intense expectations the cyclotron area was cleared and all attention focused on the current meter on the console. In a matter of minutes the probe was withdrawn to full radius, the current meters indicating no attenuation of beam from minimum to maximum radius and neutron monitors clicking wildly. The machine worked!

While the simple thrill of having the machine operate dominated the thinking of all present, the occasion was, in fact, considerably more significant. The machine not only worked but worked with all controls set at precomputed values, thereby establishing that a vast amount of detailed analysis and calculations had been performed without error and that all fundamental features of the design were sound. The importance of this result is difficult to overemphasize. The ability to reliably calculate beam behavior in an accelerator immediately makes possible a host of development and improvement studies which could not be considered within the framework of previous empirical development techniques due to excessive cost in both money and time. The corollary ability to undertake major accelerator projects with advance assurance on performance is also an important benefit.

In the initial operation the machine was adjusted to produce protons of 25 MeV, this energy being selected on the basis that it minimized stress on the then untested rf system. The initial grand success at 25 MeV was followed by a wave of great optimism and a schedule of operating tests was laid out calling for the energy to be raised in 8-MeV steps on successive days up to the design peak energy of 56 MeV. After patching of various vacuum leaks, the first such step to 33 MeV was made with complete ease. In addition, in this test the magnet was reversed and H^- ions successfully accelerated and extracted (via stripping). Work began on lining up the external beam pipe and hardware and shifting the scattering chamber into position. Unfortunately, after the 33-MeV run, the first of a long series of component problems came to light—in this case, a failure in the flexible hoses carrying cooling water to trimming electrodes in the rf system. Also a number of other problems had been discovered, one of the most severe being inadequate magnetic shielding of the vacuum tubes in the rf final amplifier. In fact, from mid-February to now a whole series of design changes have been made aimed at ironing out various weak spots in the mechanical design and in the rf-drive structure. Many of these changes have been quite laborious and time consuming. The rf-trimming electrodes, for example, proved so troublesome that in early March the original design was entirely abandoned—the process of designing and constructing new trimmers was assigned a high priority but by the time these electrodes were finally installed in the cyclotron, some three months had passed. In the meantime, the cyclotron could be operated at low energies, for in this frequency range the main tuning panels were sufficiently sensitive to perform both fine and coarse tuning, but operation at high frequency was forced to await installation of the new trimmers. In parallel with this work other energies were tested and at present any energy from 22 MeV to 37 MeV is available to the experimenter. Modifications to the rf drive system are now nearing completion; these revisions are expected to open the way to operation at any energy.

External proton beams are presently obtained by reversing the magnetic field of the cyclotron so that H^- ions are accelerated. At present the same source is used for both positive and negative ions; H^- currents of up to 20 μa have been obtained near the center of the cyclotron. Developmental studies of special negative sources are in progress in the source testing facility which should lead to greatly improved H^- yields. The H^- beam is extracted by using a small field bump at the $\nu_r = 1$ resonance to induce turn separation and energy selection (the previously described[4] "resonant extraction" process) after which the separated turns are deflected out of the cyclotron via stripping collisions in a thin foil located at the deflector radius.

Energy spread in the external beam is presently inferred from nuclear reaction studies and is estimated to be 0.2%. The nuclear reaction technique is unfortunately subject to considerable uncertainty due to lack of complete knowledge of other factors contributing to the spread. In one run, for example, with 25 MeV protons on Carbon the elastic peak had a full width at half maximum of 90 keV. Known factors contributing to this spread included 60 keV from kinematics and 40 keV from variations in energy loss in the target. If the detector is assumed to contribute an energy spread of 25 keV (i.e., if the detector is assumed to be as good as the best produced elsewhere) and if

---

[4] M. M. Gordon and H. G. Blosser, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

the various energy spreads are assumed to add in quadrature, a spread for the incident beam of 45 keV results. The uncertainties in this calculation are clear—if the detector resolution were appreciably worse than assumed the beam would be correspondingly better. The 0.2% result for the energy spread in the cyclotron beam is however also in reasonable accord with predictions of the cyclotron design calculations when corrected for the degree of ripple present in the rf system at the time the measurements were taken. The figure is therefore probably reliable. It also appears extremely likely that the design goal of 0.1% will be realized when the amplitude feedback loops on the rf are in full operation.

Work on the electrostatic deflector and magnetic channel, which together we refer to as the "conventional deflector" is proceeding smoothly. The 120 kilovolt power supply, which is based on a Lawrence Radiation Laboratory design[5], has been constructed and tested; the electrostatic deflector including a Philips type positioning linkage[6] has been fabricated and is ready for installation; an improved magnetic channel design featuring both minimal stray field and a built-in focusing gradient has been worked out on the computer[7] and detailed

---

[5] B. H. Smith, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

[6] H. L. Hagedoorn, private communication.

[7] R. E. Berg and H. G. Blosser, IEEE Trans. Nucl. Sec. <u>12</u>, 392 (1965).

engineering is nearing completion—the complete "conventional deflector" system should be installed and operating by late fall, thereby permitting direct extraction of any beam. (The negative ion system presently in use is for practical purposes limited to hydrogen ions since in a cyclotron only hydrogen can be accelerated to interesting energies as a singly charged ion.)

INSTRUMENTATION

Beam Transport System.

As indicated in previous proposals and publications[8], a system of beam pipes, bending and focusing magnets, and viewing equipment is being provided to transmit the beam to various target positions and to control and adjust the energy resolution and intensity of the beam on each target. For the past 18 months the transport system has been intensively studied using the linear ray tracing codes "Optik" and "Linop" (these codes are discussed in a following subsection); important design improvements have resulted. The system as presently planned is shown in Fig. 6. Principal change from previous plans is the redesign of the first 90° magnet to function as both an analyzing magnet and a switching magnet thereby eliminating the two very large switching magnets previously required. The new design has several functional advantages over the earlier system and is in addition appreciably less expensive.

The system is designed to work at resolutions of as high as 1 in 10^4 (in energy) in the spectrometer room and at resolutions of 1 in 10^3 or better at other locations. As an example of the optical arrangement, the high resolution beam path to the spectrometer room begins with quadrupoles Q_1 and Q_2 which form an image of the cyclotron effective source at

---

[8] H. G. Blosser and J. N. Butler, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

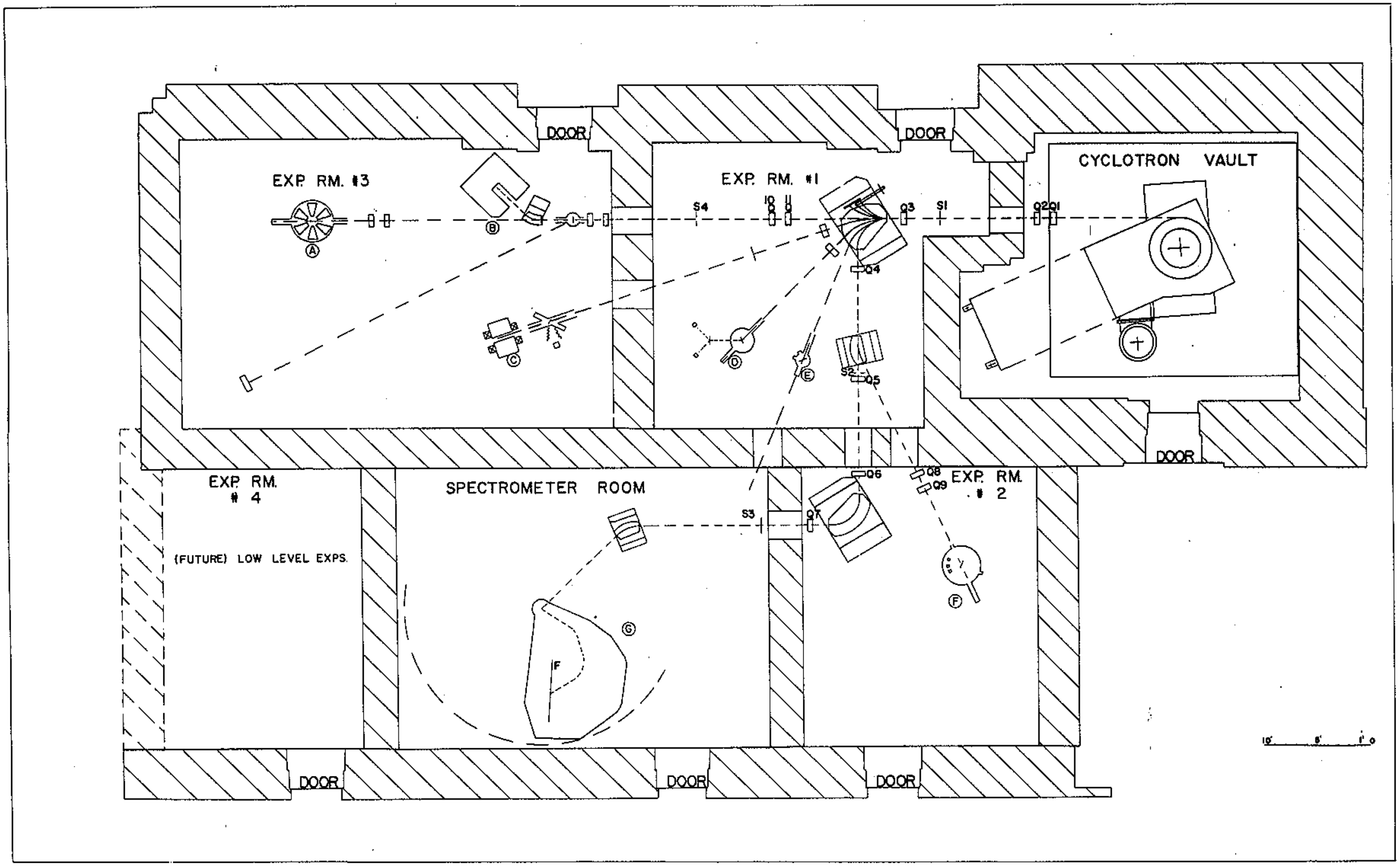


Fig. 6: A floor plan of high-bay area showing arrangement of experimental rooms and beam pipes. A-multigap electron spectrometer; B-beam stop assembly for time-of-flight program; C-gamma-ray facility with bending magnet to send beam into well in floor; D-polarization facility; E-low precision scattering chamber; F-high-precision scattering chamber; G-broad-range split-pole spectrometer.

the slits S_1. The two 90° magnets and their associated quadrupoles Q_3, Q_4, Q_6, and Q_7 form an image of S_1 at S_2 and an image of S_2 at S_3, the strengths of the quadrupoles being adjusted to produce a double focus in each case. The intermediate lens Q_5 acts to improve the vertical form factor of the system and to increase the dispersion; since this lens is located essentially at the image point S_2 it has little effect on the position of S_3. The dispersion at S_3 is 2 parts in 10^4 in energy per mm and the magnification from S_1 to S_3 is unity, as is clear from the symmetry. Energy selection of 1 in 10^4 therefore implies that S_1 must have an aperture of 0.5 mm. Such small slit openings can probably not be used with positive ion beams due to slit scattering difficulties (the range of 56-MeV protons in W is 3 mm); with external negative ion beams slit scattering is however easily eliminated by the use of thin foils for slits as has been discussed previously.[8] Finally the bending magnet in the spectrometer room images slit S_3 on the target chamber of the spectrometer.

Due to the press of other assignments essentially no work has as yet been done on the spectrometer. Plans remain the same as outlined in the previous proposal; namely, the orbit dynamics specialists on the project staff will make a careful study of present designs exploring various possible improvements. When this study is completed, engineering, procurement, and assembly will be handled in the same manner as was done on the cyclotron magnet. In the meantime for planning purposes an Enge split-pole broad-range spectrometer has been assumed and is sketched in outline in Fig. 6.

System bending magnets are all of the flat-field type; double focusing is achieved by supplementing the bending magnets with vertically focusing quadrupoles typically placed both before and after the bend. Plans for the first 90° bending and switching magnet are now complete, and bid packages for components are being prepared. The magnet should be in service by February, 1966. Design work on the second 90° magnet will begin soon. The first 90° magnet includes a facility for activation bombardments as is indicated in Fig. 6 by the beam lines bending to the right. The system puts the two-foot thick iron side yoke of the magnet directly in the path of the hard knock-on neutrons, thus greatly easing shielding requirements. Since these runs will presumably involve the most intense beams of any experiment, the extra shielding is quite important. To reduce residual activity coils in the 90° magnet will be aluminum. In view of the anticipated efficiency of the extraction system (90%) no activation bombardments will be made in the cyclotron proper.

Quadrupole magnets are presently under construction in the Laboratory machine shop using a rescaled version of the Brookhaven "Danby" design. The Danby design is superior to standard commercially available quads as regards both accuracy of the field shape and compactness. In addition, the quad is very simple to build; we estimate the Danby quads built in our shop will cost less than one-half the price of commercially available quads of corresponding strength and size. The first of these quads is now nearing completion; the full complement of twenty-four should be completed in approximately six months.

Beam tubes and related hardware will be modeled after prototype versions now in use between the cyclotron and scattering chamber. In this system aluminum construction is utilized wherever possible in order to minimize residual activity. Aluminum also, of course, has the advantage of being both light and inexpensive as compared with other frequently used materials. Sections of beam tube are fabricated with quick-disconnect flanges on each end designed for use with Marman-type clamp rings. At appropriate points along the beam pipe standard LRL beam boxes are inserted. These boxes can be interchangeably fitted with Quartz viewing screens, wire beam scanners, slits, etc. as needed. For the most part pumping stations are attached to magnets, scattering chamber, etc.; additional pumping can be applied to the beam pipe if needed through the beam boxes and through special "T" sections of beam pipe. To provide for positive radiation isolation of various experimental rooms a stopcock type beam-stopper-plug has been designed for insertion in the shield walls at each beam penetration point. These plugs will utilize a 24" diameter iron plug with axis vertical. A 3" diameter beam hole penetrates the plug horizontally; this hole is turned either parallel or at right angles to the beam for open and closed positions. A vacuum envelope surrounds the entire plug. The positive radiation isolation produced by these plugs gives, of course, a great operational advantage in that setup work can go on in some experimental rooms concurrently with experiments in others.

Scattering Chambers.

Present experiments are being performed in a 36" diameter scattering chamber obtained from the University of Rochester. This chamber, when it arrived, had not been used in seven years and considerable question existed as to its condition. After moderate reworking, the chamber has, however, proved to be an extremely valuable medium precision device, reflecting initial sturdy design and construction. Pressures of 10^{-5} Torr are, for example, routinely obtained with a 4" Freon-trapped, oil diffusion pump. The hub of the chamber, after being fitted with remote drive, achieves an overall positioning accuracy of order 0.1°. Counters are mounted on a tray via a system of precision ground bushings capable of holding five counters 7 1/2° apart, thus covering an angular range of 30°. In addition, targets can be remotely changed and rotated. Beam current is presently measured in a 1' long, 3" diameter Farraday cup. Relative yield is continuously checked in a monitor counter located at 45° in order to guard against target deterioration and related problems.

In addition to the Rochester chamber an all-purpose, high-precision scattering chamber is being designed with the objective of producing a chamber in which any charged particle experiment can be performed. Experience with the Rochester chamber has been very valuable; in addition, new chambers at a number of laboratories have been carefully studied. The precision chamber will include digital angle control and measurement using a system of encoders mounted as an integral part of the shafts of rotating assemblies. These encoders will be directly coupled to a drive mechanism which will set the shaft to any specified angle automatically. (Such systems are in use in many applications where high-precision automation is required); besides giving an absolute angle measurement they have the advantage of presenting the information directly in digital form suitable for either punching on tape or for direct computer referral.

The new chamber will be large in diameter (about 42") to provide adequate room for counter cooling systems and to facilitate precise determinations of angles. Conversely, the chamber will be rather shallow in depth to minimize volume and facilitate access. The hub of the chamber will be decoupled from the vacuum chamber so that it can be accurately positioned with respect to the beam without moving the chamber.

Detectors.

During the past year a well-equipped laboratory has been set up for fabrication of semiconductor detectors. Emphasis thus far has been on producing thick lithium drifted silicon and germanium detectors; some work has also been done on thin gold surface barrier dE/dx-detectors. The detector production laboratory has been extremely valuable for the project both as regards (a) providing the experimental program with advanced detectors considerably beyond the capability of commercially available units and, (b) the ten or so graduate students who have worked in the laboratory from time to time during the year have acquired valuable knowledge and insight into one of the major new instrumentation areas of nuclear physics. In the immediate future the laboratory program will emphasize (a) continued development of thick high resolution silicon and germanium detectors, (b) development of position sensitive detectors and (c) production of detectors with annular geometry.

Lithium Drifted Silicon Detectors. The main emphasis here has been to fabricate devices the intrinsic region of which is thicker than 3 mm (22.5 MeV protons) and whose effective area is larger than 1 cm^2. Another restriction on these detectors has been the requirement that they be useable in a transmission geometry, i.e., that thicknesses of dead layers be minimized. The fabrication techniques used include a generous admixture of many ideas and techniques found successful in other laboratories.[9,10,11,12]

The packaging of these detectors has received special attention with emphasis placed on the ability to stack and cool the detectors for optimum operation. Figure 7 shows the overall layout of a detector package used in the $^{12}C(p,p')$ experiment preliminary results from which are presented in a following section. The collimators and cooling plate are made of copper and are insulated from the detector bench with a lucite plate. The detector mount is made of aluminum. Methyl alcohol is circulated through the cooling plate after passing through a dry-ice, methyl-alcohol heat exchanger. As a result of this cooling, at normal operating voltages the leakage current of the diodes is reduced to a few nanoamperes. In Fig. 8 one of the spectra taken in the $^{12}C(p,p')$ experiment is shown. The main contributions to peak widths in this figure are kinematic broadening (60 keV), target thickness (1 mil of polystyrene), detector noise, and beam energy spread.

Lithium-Drifted Germanium Radiation Detectors. Work with germanium crystals and associated electronics has produced gamma-ray peaks typically 5 keV FWHM for the 661 keV

---

[9] F. S. Goulding and W. L. Hansen, IEEE Trans. Nucl. Sci., NS-11, 286 (1964).

[10] G. L. Miller, B. D. Pate, and S. Wagner, IEEE Trans. Nucl. Sci., NS-10, 220 (1963).

[11] R. Lothrop, U.C.L.R., private communication.

[12] K. Casper, Western Reserve University, private communication.

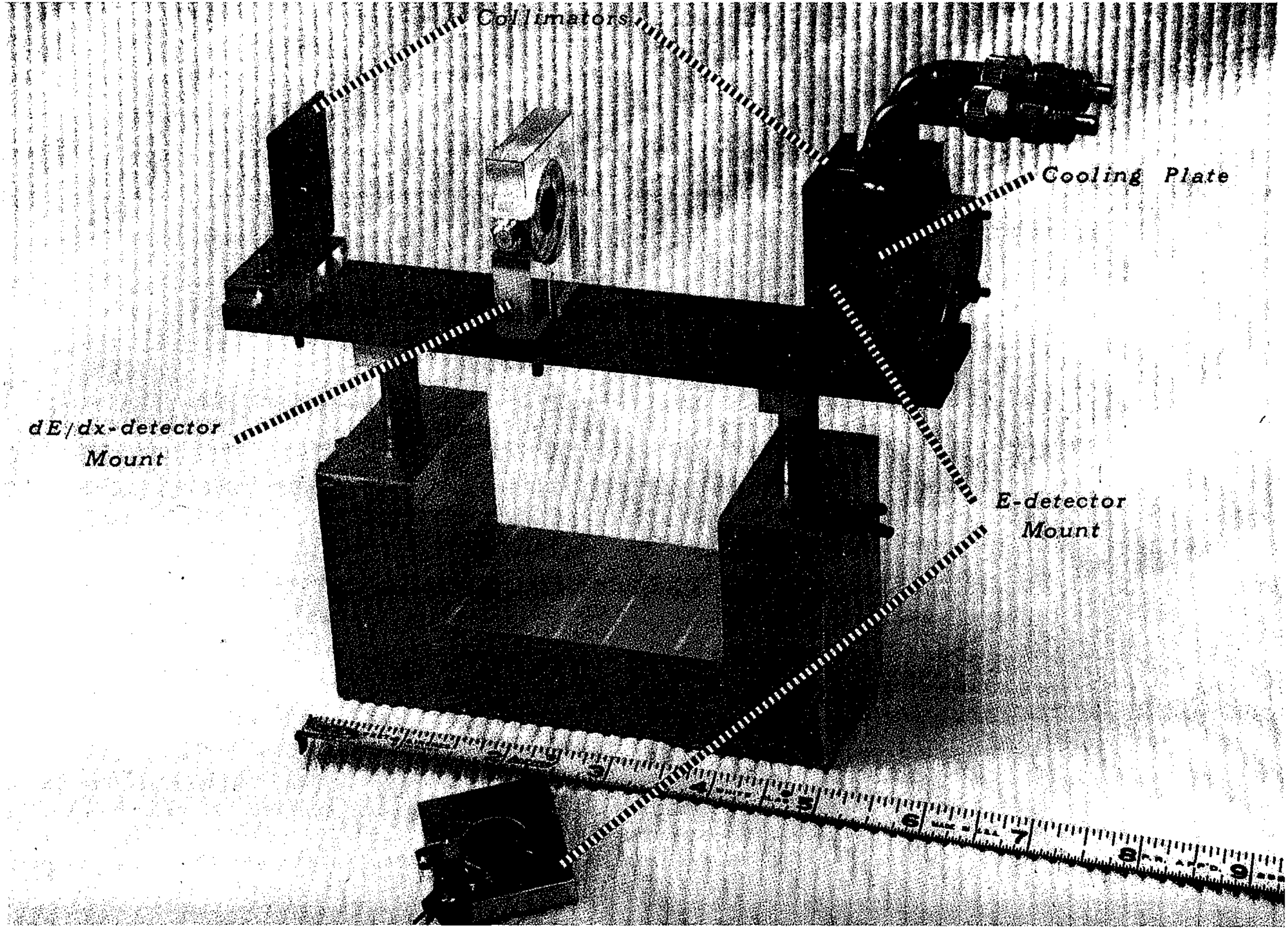


Fig. 7: View of standard detector mount. The lower "u" shaped block is an assembly stand only. Pins in the detector mount mate with precision bushings in the scattering chamber arm.

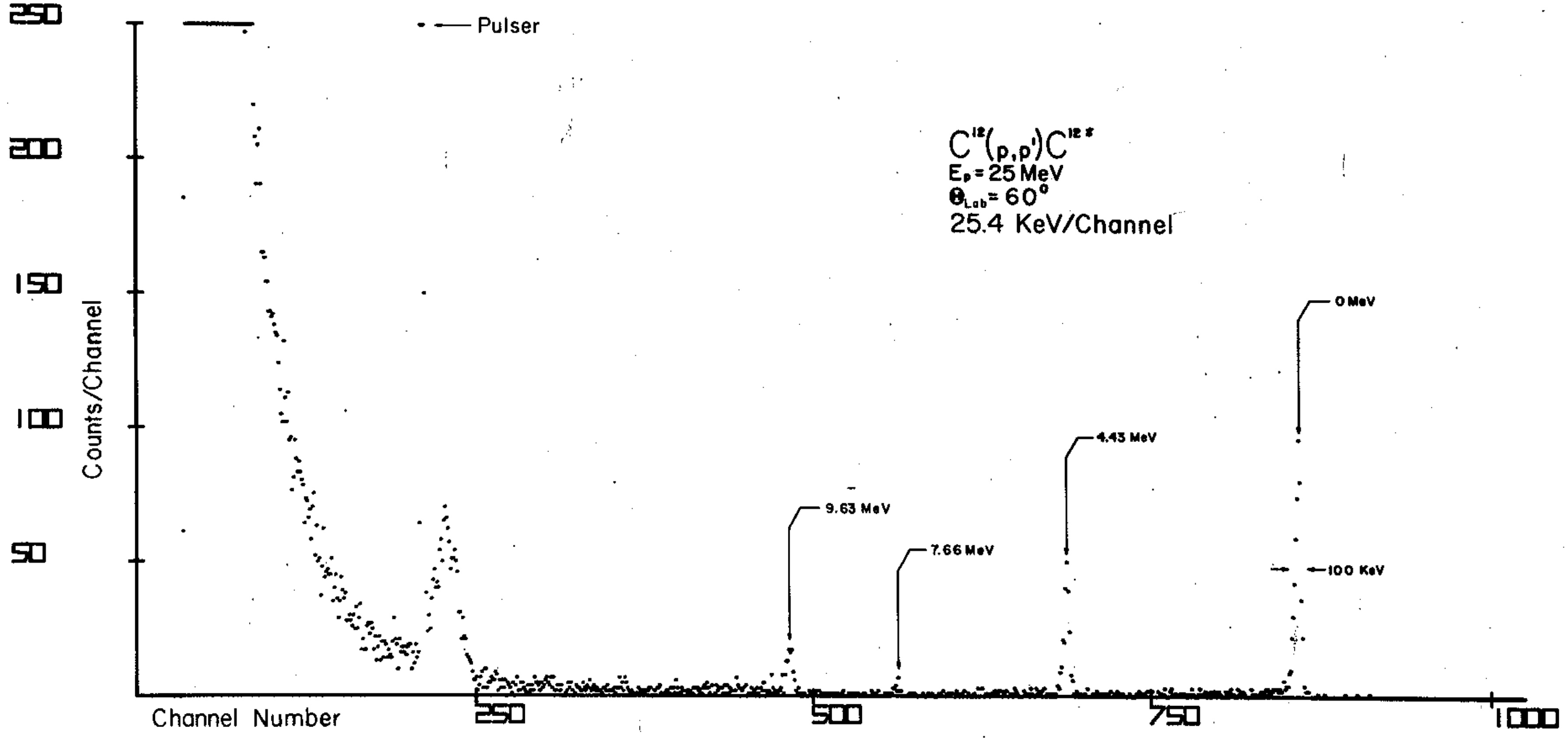


Fig. 8: Energy spectrum from protons on Carbon-12. Energy spread includes a 60 keV contribution from kinematics and an approximately 40 keV contribution from target thickness.

^{137}Cs gamma ray, with the best so far being 3.5 keV. A typical spectrum is shown in Fig. 9. Typical leakage currents at liquid-air temperature are a few nanoamps at several hundred volts, with the best so far being 0.3 nanoamps at 100 V for a 3.5 mm thick detector.

A problem we have encountered with these crystals is that in most cases the crystal loses its low leakage properties after a couple of months use. Crystals have, however, been recovered with a considerable degree of success by going through a warmup cycle and redrift of a few hours. Also in some cases recovery was obtained by etching the surfaces until good diode characteristics were regained.

To take advantage of the excellent resolution properties of the germanium detectors, a Tennelec preamplifier and amplifier system has been purchased. The germanium crystals must, of course, be cooled to liquid-nitrogen temperature for best operation. One frequently used cooling method is to place the crystal in a glass or teflon container which is lowered into a liquid-air dewar. A second cooling system utilizes a 3 liter spherical dewar with a 3-inch long, 1-inch diameter copper cold finger at the bottom. The detector is placed against the cold finger and held in place by a teflon ring and thin aluminum plate hung by springs from the top of the cold finger. Insulation is obtained by placing a glass cup with ground seal around the cold finger and evacuating the compartment. Electrical contact is furnished by a pair

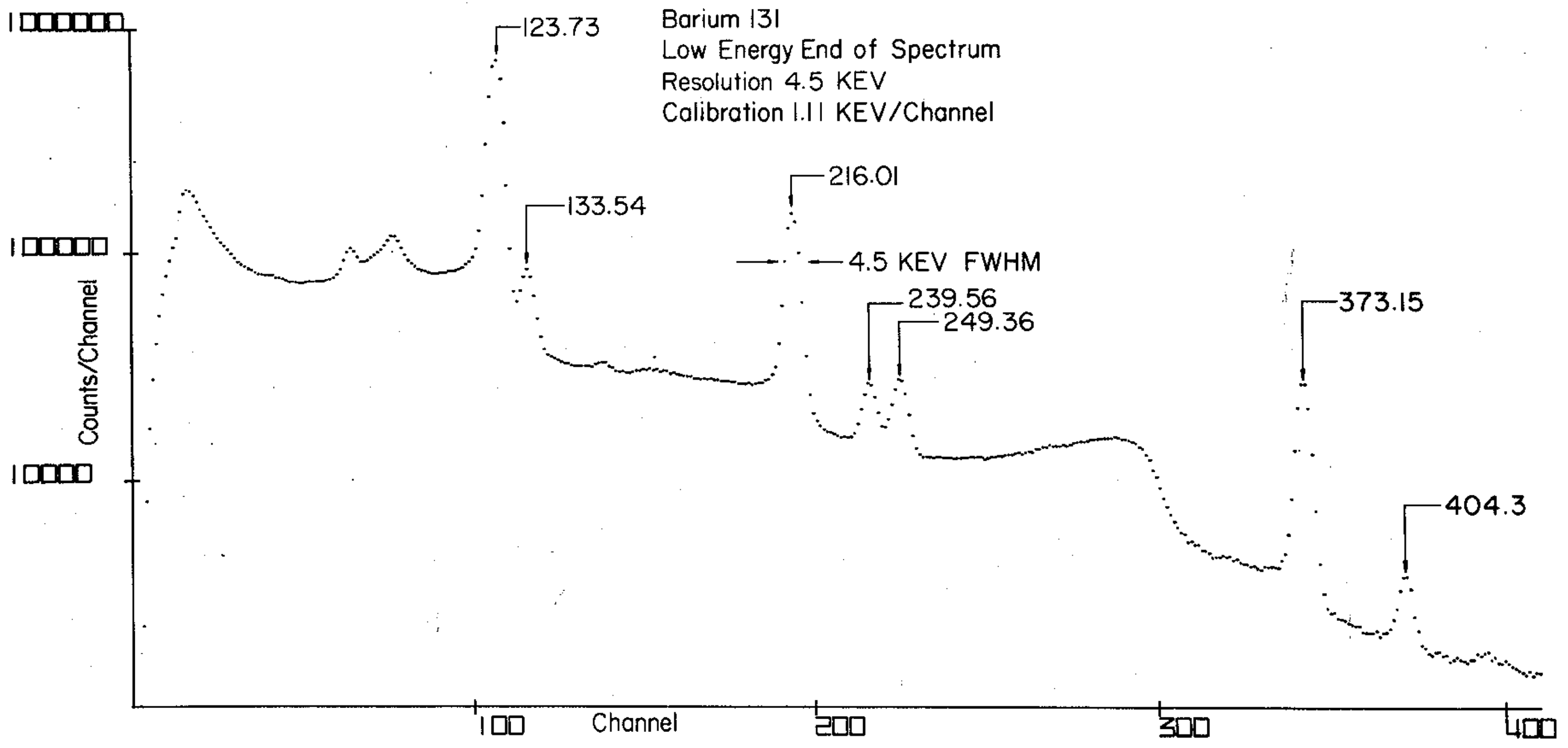


Fig. 9: Typical spectrum from one of our Ge(Li) detectors.

of tungsten wires sealed in the glass cup and oriented so that one wire fits against the cold finger and the other against the high voltage side of the crystal.

Main advantages of the cold-finger system are (1) the source can be placed very close to the crystal, (2) the short and widely separated leads minimize electrical capacitance, (3) the crystal is well isolated from foreign material, and (4) there is no need to interrupt counting when replenishing the liquid air supply. The major advantage of the immersion system is its much greater mobility.

Recently work has started on the fabrication of lithium-drifted germanium detectors of much larger size in order to increase the efficiency, especially for gamma-rays of several MeV and higher. In several spectra studied with the 3-4 mm thick detectors, it is probable that a number of weak transitions may be masked by the intense Compton distributions of higher energy and high intensity gamma rays. Impressive success has also been achieved using germanium detectors surrounded by an NaI counter in anti-coincidence. Figure 10 shows spectra taken in this arrangement.

Lithium-Drifted Germanium for Charged Particle Detection. Germanium has a number of properties which would make it advantageous for use as a medium energy (25-60 MeV) proton detector. Comparing germanium to silicon, for example, for a given energy, the range in germanium is only 55% of that in silicon. Thus the thickness of the detector need be only

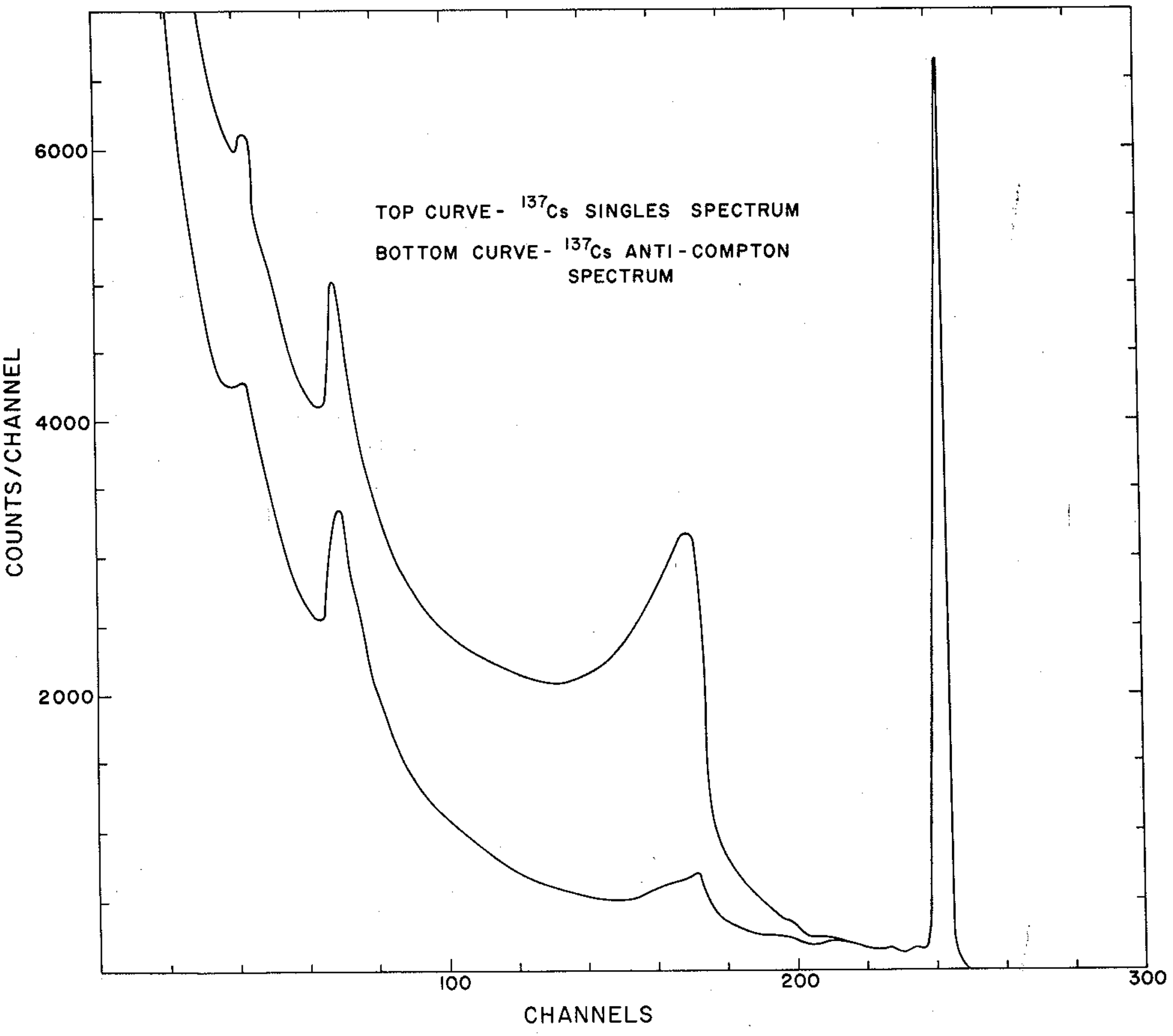


Fig. 10: Spectrum from Ge(Li) detector with and without Compton quenching via anticoincidence in surrounding NaI well.

one half as great for germanium as for silicon. Techniques are being developed which will allow us to package the germanium crystal for high resolution charged particle spectroscopy. Main difficulties in using germanium for charged particles are (a) the device must be operated at liquid-nitro-temperature and (b) it has a relatively thick dead layer on the lithium side. It is hoped that techniques can be developed which will eliminate the dead layer.

Gold-Surface Barrier dE/dx-detectors. We have purchased a number of gold-surface barrier dE/dx silicon detectors ranging in thickness between 50 and 800 microns. These detectors will be used in initial experiments with the cyclotron. While developing the lithium-drift-detector techniques we have also learned some techniques which will be useful in the fabrication of thin surface barrier detectors. For example, a planar etching technique[13] has been developed which should be quite useful for producing uniformly thin detectors down to thicknesses of about 25 microns. It is also planned to fabricate thin dE/dx-detectors using the web crystal technique.[14]

Sodium Iodide Detectors. In high-resolution spectroscopy the scintillation method of particle detection is basically

---

[13] T. C. Madden and W. M. Gibson, IEEE Trans. Nucl. Sci., NS-11, 254 (1964).

[14] E. J. Ludwig, W. M. Gibson, J. S. Hood, to be published.

inferior to the method of charge collection in a silicon or germanium diode for the fundamental reason that the conversion of particle energy into light and thence into photoelectrons is almost three orders of magnitude less efficient than the direct production of electron-hole pairs in a diode. Hence, ultimate resolution capabilities of the two detection techniques differ by a factor of 30 (in practice this factor is presently 10 to 15). Sodium Iodide is, however, still extremely useful as a result of its availability in relatively unlimited size and at low cost. (The high Z is also useful in γ-ray detection.)

Pending development of thicker solid state detectors a number of Sodium Iodide counters have been assembled, sized to stop 56-MeV protons. Also, some experiments may require still thicker counters. He^3 reactions at 75-MeV, for example, frequently produce protons in the 90-MeV range; NaI counters of appropriate thickness can be readily assembled when needed.

NaI detectors can also be made with large cross section which is very useful in minimizing slit-edge effects. Slit thickness is determined by the range of the highest-energy particle in an experiment. The range in brass of protons at 56 MeV is 0.2" and at 90 MeV, 0.5".

Present NaI detectors are cylinders 1 1/2" in diameter, 3/4" thick epoxied to 1/2" thick glass light pipes which are in turn epoxied to 2" photomultipliers. Alpha-aluminum oxide is used for light reflection. Because of the hydroscopic character of Sodium Iodide, it is packaged in a vacuum-tight container in very dry air. Particles enter the detector through a thin havar (steel) window.

With these detectors we have obtained 8.5% resolution, FWHM with 661-keV γ-rays from ^{137}Cs and 2% with 24-MeV protons. Slight improvements can be made; at 56 MeV 1% resolution is expected.

Electronics.

During the past year, we have purchased and built a number of electronic instruments for use in nuclear physics experiments. These include a Nuclear Data 4096 Channel Analyzer which can be used in various two-dimensional configurations such as 256 x 16 or 64 x 64 channels, and with the additional feature that the two analogue-to-digital converters can be used in multiplex mode, in which they operate independently of each other sharing only the 4096 memory. This makes the analyzer equivalent to four 1024 channel analyzers provided signals are mixed and routing pulses provided. Other items include a 512 channel analyzer, a number of preamplifiers and amplifiers, coincidence circuits, linear gates, particle identifiers and pulse multipliers, some of which are being constructed in our electronics shop. A high resolution time-of-flight system is being readied and will be used in a number of experiments. A workable inventory of such essential items as oscilloscopes, power supplies and pulse generators has also been assembled. In addition, two remotely controlled closed circuit TV cameras have been installed and used extensively for viewing events inside radiation areas.

Automated Data Handling.

The first experiments with the cyclotron have vividly demonstrated that data accumulates with extreme rapidity. In the recent (p,p') experiment on Carbon, for example, the average time to take a point was three minutes (this time could, moveover, be reduced considerably if it seemed desirable). The data-taking process at present involves at every point a number of routine operations such as moving the detector, outputting the data, resetting the analyzer, etc. All these operations are presently performed by the experimenter. Repeated every few minutes, such operations keep the physicist from following the course of the experiment, making decisions, and interpreting the results. One way to free the physicist from the routine tasks of data handling is to fully automate the process.

Such data handling systems can be discussed under two separate headings: data taking and data processing. (A general purpose computer could, of course, perform both these functions simultaneously, but they are nevertheless still separate, distinct operations.)

Data Taking. At present data taking is automated to some extent. Runs are started by a single switch and stopped at the end of a preset time, scaler count, or integrated charge.

Between runs, the physicist performs a series of routine operations which an automated system could perform faster and with fewer errors. For example, at present run parameters are written in a notebook whereas multi-channel spectra are punched on tape. The first step in automation would provide for the punching of all pertinent data onto the tape with the spectra. This can be achieved using relatively simple commercially available equipment. A second step in automating the data handling system would be a device which pushes buttons for the physicist actuating, for example, such devices as the mechanisms which read results to tape, reset to zero scaler integrators, clocks, etc., set new counters and target angles, change targets, erase the memory of an analyzer, and start a new run. With such an arrangement the physicist could set up all angles, targets, run duration etc. in advance and then be free for uninterrupted review and study of the progress of the experiment. Equipment for this second step in automation is also commercially available and is being procured as part of the proposed program. The automated system, it should be noted, also has the advantage of producing output in computer compatible form, ready for immediate processing.

Data Processing. Automating of data procesing has already reached a reasonably advanced state. Starting with run parameters and multi-channel spectra in digital form, the CDC-3600 has been programmed to plot and analyze the data.

The analysis begins with center-of-mass corrections, fitting of peaks in the spectra with various functions and determination of the number of counts in each peak. This number is then used with the other data to identify the peak and determine the cross section for the process it represents.

The main disadvantage of the present data handling system is the 24 to 36 hour time lag which is introduced by the 3600 scheduling system. Effectively this results in the physicist making his decisions during a run on the basis of visual scanning of raw data which is a highly imprecise procedure. Frequently when the analyzed data are returned from the computer it becomes clear that particular sections of the data are of questionable validity or some interesting effect appears which should be explored more closely—in such situations it is necessary at present to reschedule and reassemble the experiment, a laborious and time consuming process. In view, however, of the complexity of the data and the speed with which it accumulates, there appears to be no real cure for this difficulty short of an on-line computer. In view of this, a separate equipment proposal is being prepared requesting funds for such a facility.

Time-of-Flight Facility.

Cyclotrons are inherently well suited for time-of-flight work as a result of the natural beam pulsing arising from the rf acceleration process. This rf microstructure typically results in pulses 10 nanoseconds or less in length with a

50 to 80 nanosecond repetition time. The M.S.U. cyclotron is particularly adapted to such studies as a result of the phase selection system built into the cyclotron central region.[15] This system was designed to select a 7° interval of rf phase (which at 20 mH_z is 1 nanosecond) and measurements of the phase width of the cyclotron beam show the system is performing as expected. The normal 50 nanosecond repetition period of the cyclotron is unfortunately much too short for most time-of-flight studies—a sweeping-electrode system designed to make a 10-fold increase in this repetition time has, therefore, been conceptually designed and is now being engineered. This system will function in a similar manner to terminal pulsing units in a Van de Graaf, i.e., a transverse electric field will be produced between a pair of sweeping electrodes mounted inside the north dee of the cyclotron—this sweeping field will act on the beam at the 270° position of the first turn. The existing radial slit at 180° will define the object and a new slit to be installed at the 360° position (in the dummy dee) will select each tenth turn, the sweeping electrodes being driven synchronously with the cyclotron rf and 1/20 the frequency. Design calculations show that an electric field of 10 kV/cm peak, will

---

[15] H. G. Blosser, M. M. Gordon & M. Reiser, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories (CERN, April 23-26, 1963, CERN 63-19).

produce clean selection of pulses in the geometry proposed; a field of this magnitude is easy to achieve. Pulse selection in the central region has, of course, great advantages as compared with external selection since (a) the thermal load on the deflector which normally limits beam current is determined by the average current—with central pulse selection much higher currents can, therefore, be accelerated than with external pulse selection, and (b) background radiation and power dissipation problems are minimized by making the selection at low energy (~250 keV). The central selection arrangement, of course, presumes that extraction is being accomplished on a single turn; unless the stabilizing circuits on the cyclotron magnet and rf system can be considerably improved, weak (2-3%) satellite peaks will also occur. If these prove a limiting factor an added external sweeping system can easily be installed to clean up the beam. Even if this extra step is necessary the central pulsing system will still retain its advantage since more than 99% of the undesired beam will still be discarded in the center.

Figure 11 is a block diagram of the electronic components for the time-of-flight system. The pulse gate, which was discussed above, is indicated here by a single box. There are two main branches in this diagram; one which starts time measurement and one which stops it.

No more than one event from a given beam pulse can be analyzed. In order to prevent erroneous enhancement of the high energy end of the spectrum, the possibility of having

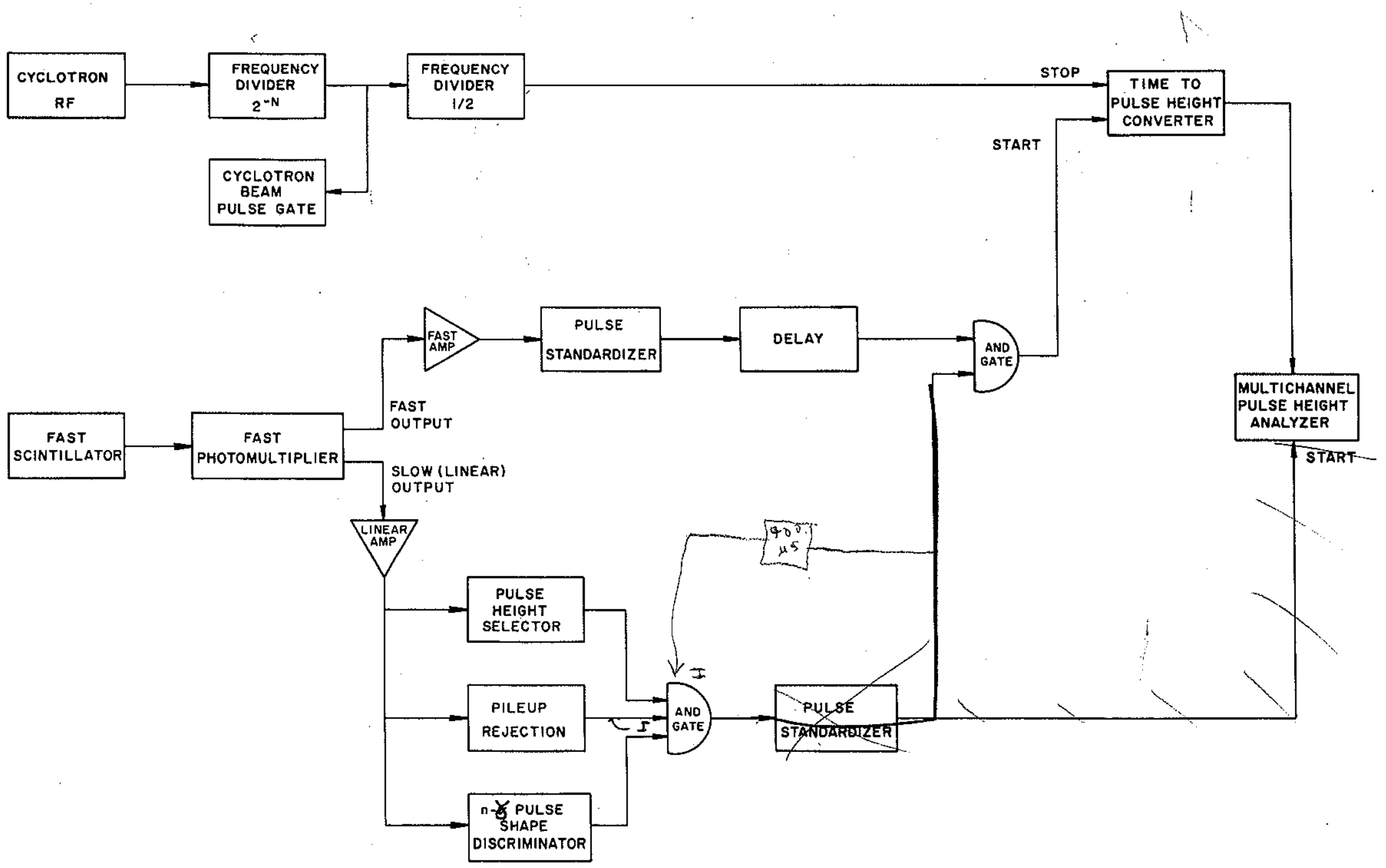


Fig. 11: Block diagram of electronics arrangement for neutron time-of-flight system.

more than one event per beam pulse must be made negligible. This can be done by maintaining the average rate much less than one per beam pulse so that from most pulses there will be no true event. The time-to-pulse-height converter (TPHC) is dead for approximately 300 μsec after each start pulse, whereas the beam pulse repetition period is of order 0.5 μsec. It is more efficient, therefore, to start the TPHC only when a true event occurs (as in Fig. 11) and stop it with the next rf beam pulse. If a divide by two block is inserted as shown in the figure the stop pulse comes only half as often as the beam pulse and the recorded events will form a double spectrum thereby providing a built-in calibration, the time between corresponding features of the spectrum being equal to the precisely known time between beam pulses.

The neutron detector will be an organic scintillator mounted on a fast-rise photomultiplier tube. Before an event is analyzed the scintillator pulse must pass inspection with respect to pulse height, pulse shape (to reject γ rays), and pileup.

The most important characteristic of a time-of-flight system is its time resolving power, or the related quantity, its energy resolution. The latter is given in terms of the time resolution dt/L by

$$\frac{dE}{E} = 2v \frac{dt}{L} ,$$

where v is the speed of a neutron of energy E, dt is the minimum resolvable time interval, and L is the length of flight path from target to detector. The quantity dt/L is obviously the quality factor of the system. We expect our system to have a dt equal to one or two nanoseconds as a result of cyclotron beam pulse spread, detector thickness, and rise time of electronic components. Background problems, which are not easy to assess in advance, make it difficult to say how large L could be made. We are planning on 10 to 20 meters as indicated in Fig. 6, location B. Hence, dt/L will be about 0.1 nsec/m. A table of energy resolution for this time resolution is given below.

E (MeV)	% dE/E	dE (keV)
10	0.86	86
20	1.2	244
30	1.5	444
40	1.7	680
50	1.9	942

Iron-Free $\pi\sqrt{2}$ Beta-Ray Spectrometer.

We have perfected what we believe to be the best post-accelerator yet developed.[16] Electrons are accelerated 5 to

---

[16] R. J. Krisciokaitis, Ph.D. thesis, Michigan State University, (1965).

6 keV just before a thin window counter (100% transmission at about 5 keV). Stray slow electrons are kept out by a repeller grid. Careful measurements show less than 1 cpm increase in normal background and less than 1% change in the counting rate on a 20 keV line. The accelerator has been used to study the L-Auger spectrum of ^{113}In and ^{113}Sn. The spectrometer has also been automated so that data can now be taken continuously without an operator present.

We shall adopt the arrangement of Bergkvist[17] to correct the spectrometer aberrations electrostatically so that larger apertures can be used. Also a segmented source assembly will be installed; by charging various subsections at appropriate potentials much broader sources can be employed without loss of resolution. With such an arrangement both conversion and Auger-electron studies can be carried out with higher resolution and better statistics. Two well regulated variable 10 kV supplies will be needed for the Bergkvist modification. Also a refrigerated baffle will be added to keep pump oil from depositing on sources.

Multi-Gap Electron Spectrometer.

A six-gap iron core electron spectrometer is presently nearing completion. The instrument is designed to have a high

---

[17] K. E. Bergkvist, Arkiv Fysik 13, 256 (1958).

transmission (≈12%) at a moderate resolution (≈1.4%). These characteristics make the instrument ideal for experiments with weak conversion electron transitions and for gamma-conversion electron coincidence measurements. The spectrometer is being set up on one of the cyclotron beam lines so that sources can be activated in situ as is needed for studies of short-lived radio isotopes and for Coulomb excitation experiments.

The iron segments are duplicates of those used in a similar instrument constructed by Bisgard[18]. The remaining portions of the spectrometer have been constructed in the Laboratory shops. The spectrometer has also recently been automated to facilitate data accumulation.

Difficulties have been encountered with the mechanical alignment of the iron segments. A temporary first order correction in the form of additional bias turns of copper wire on the appropriate coils is being used until an improved alignment system can be developed.

With the present arrangements, resolution is 1.1% and transmission approximately 4% with a source of approximately 1/8" diameter. Measurements with a single gap indicate that proper alignment should improve the resolution by approximately a factor of two.

---

[18] K. M. Bisgard, Nucl. Instr. and Methods 22, 221 (1963).

Shielding and Radiation Safety.

The shielding wall along the north side of the high-bay area and the six shielding doors consist of permanently placed, poured concrete. During the past year other shielding walls were installed. These walls are constructed of solid 4" x 8" x 16" concrete blocks commonly used in the construction industry. No bonding agent was used, the blocks being held together by friction. If desired in the future, any wall can thus be easily demounted and replacement or additional walls constructed.

Undergraduate student labor was used in the laying and painting of the walls; labor costs were one-sixth of the total cost. Approximately 80,000 blocks were placed, the bulk of the work being accomplished in a six-week period. Approximately 10,000 blocks are loaded with scrap iron or forge scale and have an average density of 165 lbs/ft^3. The remainder have a density of 140 lbs/ft^3. The high density blocks are selectively placed to attenuate the intense radiation associated with the beam plane.

Total wall volume is 730 cubic yards, and total cost is $20,000 for an average of $27/yd. For comparison, either custom-built, large concrete blocks,or poured-in-place concrete cost $75 to $100 per yard.

Figure 4 is a photograph of the high-bay area on June 17, 1965. The cyclotron and scattering chamber are at the far end. For temporary convenience the wall between the cyclotron vault and the magnet room has not been completed.

About one-half of our ultimate needs in roof shielding is on order. This shielding will be constructed of prestressed concrete beams of the pretensioned variety. The beams will span from the center wall to either the north or the south wall and will weigh approximately 10 tons each. They will, of course, be moveable with the aid of our bridge crane.

Shielding doors are interlocked with the rf accelerating system in two senses: (1) rf voltage cannot be turned on if a door is open, (2) if rf is on and a door is opened—intentionally or through electrical or mechanical failure—rf is automatically turned off. While a door is being closed (about 30 seconds) sirens sound in the radiation area. In addition, the audio output of a paraffin-embedded BF_3 counter located inside the radiation area is continuously broadcast in that area as a "beam on" warning.

A variety of beta-gamma and neutron survey meters is readily accessible on a set of open shelves between the control room and the high-bay area.

Radiation badge service is purchased from a commercial concern.

Computer Programs.

The Cyclotron Laboratory is one of the major users of the University's CDC-3600 computer. During the past year, computer use has risen steadily and now averages about 12 hours per month (not counting time on peripheral equipment).

All indications point to continued increase in the future.

As anticipated, computer programs required for the design and efficient operation of the cyclotron are now essentially complete. All these programs are written in Fortran and are readily transferable to other computers; several of them are now in use at other laboratories (Manitoba, Naval Research Lab., Washington University, and Yale). At the same time, computer programs for nuclear research applications have increased steadily in both number and variety.

Cyclotron Codes. Several Fortran programs described in the previous proposal have now been completed, namely: (1) Policy; (2) Cyclops; (3) Goblin; (4) Cartel; (5) Trimco; (6) Phinal. Additional combination programs have been written designed to streamline computation procedures; the new programs are described below. All these programs are in frequent use in the synthesis and analysis of information regarding the operation of the cyclotron.

(1) "SET-OP". For a given ion and specified final energy, this program provides all the control settings required at the console to operate the cyclotron, plus extra information for trouble-shooting. Field data for the main magnet, measured at seven excitations, are stored in the code as sets of Fourier coefficients. Along with each of these main magnet fields is stored an "ideal" average field $B_o(r)$ previously determined for each ion to produce optimum axial focusing and isochronism. The incremental field of each circular trim coil, measured at four main magnet excitations,

is also stored in the program. For a given ion and desired final energy, the program interpolates in sets of magnet data to find the appropriate main field and ideal $B_o(r)$. It then adjusts the trim coil currents, using a modified least-squares procedure, so as to fit the ideal field over a specified radius range. By this process the necessary current settings in the trim coils are determined. The program then calculates (using "Cyclops") equilibrium orbit properties for the resultant field as a function of energy and interpolates in the equilibrium orbit data to find the extraction energy (the energy at which $\nu_r = 0.8$). Next the "Phinal" program is called in to compute the rf frequency which minimizes the beam energy spread at extraction. This program also specifies the dee voltage necessary to fit the prescribed 210 revolution cyclotron orbit pattern. Other useful operating data are computed including: (a) current settings for first-harmonic "bump" coils, (b) phase-slip and energy vs. turn number, and (c) maximum and minimum values of rf frequency for 50% beam loss at a specified radius. Part of the "Set-Op" output is a direct table of instructions for the cyclotron operator; Fig. 12 shows an example of such a table.

The "Set-Op" system has proved extremely effective. The cyclotron has in every case operated successfully using "Set-Op" parameters—moderately extensive "knob-twiddling" has failed to locate better conditions.

The frequency limits for probe at 27" are a novel and extremely useful part of the operating information furnished

```
FIELD NUMBER  370,        75.561  MEV HE 3                06/16/65

MAIN FIELD DATA

     MAIN COIL CURRENT  =     742.69 AMPS
     DEUT NMR FREQUENCY =  12604.20 MC.


R. F. DATA

          R. F. FREQUENCY =  14.9859401 MC.,  1 HARMONIC
          DEE VOLTAGE =  48.18 KV.

     FREQUENCY LIMITS FOR PROBE AT 27 INCHES
          MAXIMUM FREQUENCY =  15.0013925 MC.
          MINIMUM FREQUENCY =  14.9739858 MC.


TRIM COIL DATA

         TRIM COIL        CURRENT        METER       POT
          NUMBER         (AMPERES)      NUMBERS    READING
             1             14.45        7 + 13       0.72
             2              0.00          2          0.00
             3             10.54          3          0.53
             4              0.00        8 + 14       0.00
             5            -26.79        9 + 15      -1.34
             6             19.55       10 + 16       0.98
             7            -60.91       11 + 17      -3.05
             8             14.21       12 + 18       0.71


VALLEY COIL DATA

            COIL          CURRENT        METER       POT
            I.D.         (AMPERES)      NUMBERS    READING
            WEST          -36.95          4         -1.85
            EAST           20.09          5          1.00
            NORTH          16.86          6          0.84

     CANCELLATION OF MAGNET FIRST HARMONIC AT 27 INCHES
           2.67 GAUSS AT  12.11 DEGREES

          I(WEST)  =  -36.95 AMPERES
          I(EAST)  =   20.09 AMPERES
          I(NORTH) =   16.86 AMPERES

     PRODUCTION OF DESIRED FIRST HARMONIC AT 27 INCHES
          -0.00 GAUSS AT  -0.00 DEGREES

          I(WEST)  =    0.00 AMPERES
          I(EAST)  =   -0.00 AMPERES
          I(NORTH) =    0.00 AMPERES
```

Fig. 12: Output data sheet from Set-Op program giving operator instructions for lining up cyclotron.

by "Set-Op". To use these limits the master oscillator for the rf system is tuned up and down to determine the frequencies giving 50% beam loss with the beam probe set at 27". A precision check on the energy gain per turn, accurate to approximately 1 part in 10^3 is obtained by comparing the width of the measured frequency interval with the width indicated on the operating sheet. A precision check on the magnetic field, accurate to approximately 1 part in 10^5, is obtained by comparing the centroid of the measured frequency interval with that from the operating sheet. From such data, final precision adjustments of field and voltage are determined.

(2) "Cyclone". This code combines the functions of Cartel and Goblin into one super code for the accurate determination of median plane orbits throughout the cyclotron. To optimize efficiency the first quarter turn, the next four turns, and the remainder of the cyclotron, are treated as distinct regions with successively less detailed descriptions of the electric field in accord with the decreasing importance of electric forces. For convenience families of trajectories describing a beam are tracked simultaneously with output consisting of absolute coordinates for the central ray and displacement coordinates for the satellite rays. Usual deflector overwrites are included along with complete tests for both central region and peripheral defining structures. By eliminating delays due to computer turn-around time this program accomplishes in a single run the equivalent of more than a week's time with the previous sequency of separate

programs.

(3) Beam Optics. Properties of the beam transport system are computed using a linear-optics program which is a combination of "Linop" (described in previous proposal) and "Optik" (a program developed by Devlin at Princeton). These programs provide complete linear optics information on the performance characteristics of a system of bending and focusing magnets; the Optik program includes an extremely useful search feature which, within limits, will adjust system parameters to achieve specified functional characteristics.

The "Cartax" program is used to calculate ion trajectories in measured magnetic fields and includes non-linear effects. When completed this program will be an ideal tool for detailed study of aberrations (and corrections thereof) in beam analyzing systems and spectrometer-spectrograph magnets.

Nuclear Research Codes.

(1) Optical Model. The Fortran program ABACUS (developed by E. Auerbach at B.N.L. for the IBM-7090) has been transcribed successfully to our CDC-3600 computer. For a wide choice of optical potentials this code calculates the resultant differential elastic cross section, polarization, and reaction cross section. It is equipped with an automatic search routine which finds the set of potential parameters yielding the best match between calculated and experimental angular distributions. To facilitate the adaptation of this code to our computer one section (Hauser-Feshbach over-write) was deleted;

at the same time, a routine was added which gives on-line plots of both experimental and calculated angular distributions for quick and easy comparison. All the important features of this code have been checked out, and it is expected to play an important role in proposed optical model studies.

Another (much smaller) program has been constructed which calculates elastic differential cross sections using Blair's "Smooth Cut-Off" model. This program has been used successfully to account for the elastic angular distributions of alpha particles (discussed in a following section).

(2) Direct Reactions. R. Siemssen (Argonne National Laboratory) has sent us copies of two DWBA programs used on the A.N.L.-3600 computer for the analysis of (d,p) and (d,n) angular distributions. Work is in progress aimed at adapting these codes to our computer (which has a smaller memory than the Argonne 3600). These codes, originally developed by Macefield in England, are restricted to deuteron stripping and pickup. A DWBA program which calculates inelastic scattering angular distributions assuming single-particle excitation has been sent to us by K. Amos (formerly at Davis, California now University of Pittsburgh). This program was developed for the IBM-7090; transcribing of this program for our 3600 will be started soon.

A pressing need exists for computer programs which will perform DWBA calculations on the entire spectrum of direct reaction processes. Effort will be made to manufacture

CDC-3600 programs with capabilities comparable to the SALLY and JULIE programs developed at O.R.N.L.

(3) Other Codes. A number of small programs have been (and are continually being) produced for analyzing and correlating experimental data. Examples include: (a) The kinematics of the general two-body reaction is calculated by a program using relativistic conservation laws; another kinematics program considers three-body break-up and provides the desired relationships (non-relativistic). (b) A program has been constructed which unfolds a distribution of peaks (obtained as output from a multi-channel analyzer), assuming a modified Gaussian shape for each, and provides pertinent information about each peak; this program is being extended to the calculation of actual cross sections and excitation energies. (c) A program is available which plots data (linear or log scale) with the output displayed by a Cal-Comp plotter; these plots are comparable in quality to those produced by a skilled draftsman. (d) For given target and incident particle, a program is available which calculates the Q-values of all possible reactions from stored mass tables of all known isotopes.

(4) Beta and Gamma Spectra. The following programs are used in analyzing data obtained from beta and gamma spectroscopy: (a) For γ-γ correlation experiments a program has been produced which takes analyzer output data and calculates the angular correlation coefficients; this code will be supplemented by a program which calculates angular

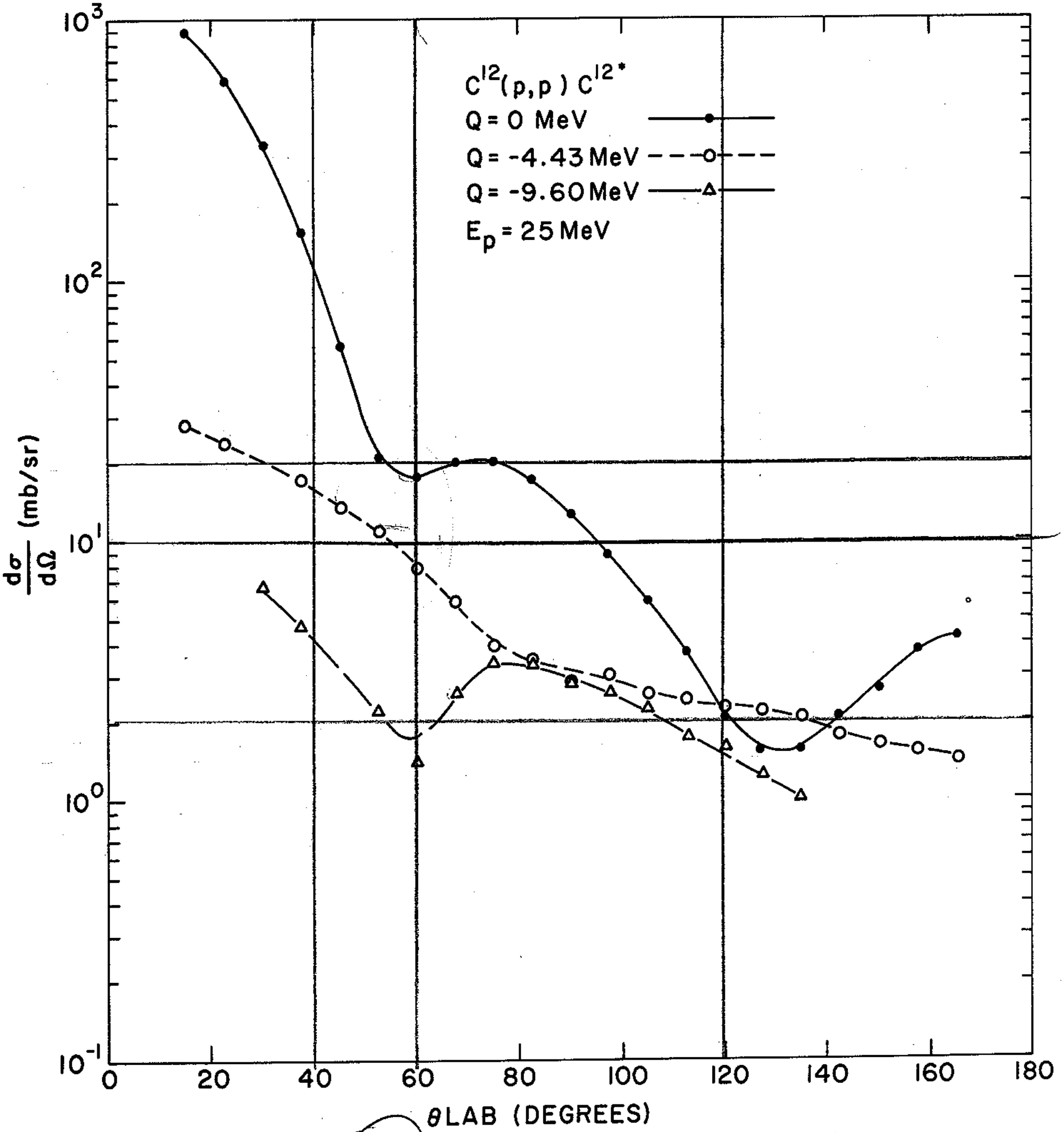
correlation coefficients for given sets of J and L values as a function of one mixing parameter. (b) Using spectral data as a function of time, a program is available for calculating the half-life of the process involved. (c) A program has been written which compares an experimental spectrum with standard calibration peaks to obtain the energies and intensities of the observed peaks; an additional program examines the γ energies and searches for sum and difference relations between them, thereby helping to reduce the γ spectrum to the desired set of energy levels. (d) A program is being developed which will calculate the functions required for a Fermi plot of a given β-spectrum.

NUCLEAR PHYSICS

Optical Model Experiments.

Analysis of reactions using the distorted wave Born approximation requires knowledge of wave functions in the entrance and exit channels. Approximations to these wave functions are normally obtained by use of the optical model; good optical-model parameters are hence fundamental to present interpretation of direct-reaction experiments. Besides providing wave functions to be used in the analysis of nuclear reactions, optical model potentials are valuable for comparison with results of many body calculations and also with shell-model predictions. Optical parameters are, of course, obtained from measurements of the angular distribution and polarization of elastically scattered particles along with determinations of the total reaction cross section. The high intensity and variable energy of the M.S.U. cyclotron are well suited to optical model experiments; in addition, data in the 25 to 55 MeV energy range are at present quite limited. A program has, therefore, been established to determine optical parameters over a wide range of nuclei and energy.

Elastic-scattering measurements with protons are now in progress. A typical spectrum obtained from scattering of protons on Carbon is shown in Fig. 9. Overall resolution is 100 keV or 0.4% of the 25 MeV bombarding energy. Figure 13 shows angular distributions for the elastic scattering and



55°

Fig. 13: Angular distribution from protons on Carbon-12.

for inelastic scattering to the 4.43 MeV and 9.63 MeV excited states.

Elastic-scattering angular-distribution measurements even when performed with high precision are, of course, not sufficient to unambiguously determine optical model parameters. Complementary polarization measurements and total reaction cross sections will, therefore, be made.

The first polarization measurements will attempt to evaluate the various methods of polarizing or analyzing 25 to 50 MeV protons. We would like to use a solid scattering material with a large separation between ground and first excited states. The data of Bassel *et.al.*[19] at 40.5 MeV indicate that ^{12}C and ^{40}Ca are good prospects. Below 30 MeV the method of Rosen *et.al.*[20] offers important advantages.

Total-reaction cross-section measurements are presently in a preliminary planning stage. An initial test run has verified that solid-state detectors can be successfully utilized in the direct beam of the cyclotron. Appropriately low intensities were easily obtained using the cyclotron central slit system; fine adjustment of the intensity (≈ 10%) could still be made even though slit openings were extremely small. Conventional transmission measurement of the reaction cross

---

[19] Bassel, Blumberg, Gross, VanderWoude, and Zucker, ORNL-3800, 1 (1965).

[20] Rosen, Brolley, Stewart, Phys. Rev. 121, 1423 (1961).

section, therefore, appears straightforward. Also an interesting charge collection technique for measuring total reaction cross sections has recently been employed at Oxford[21] and will be tested here—this technique can be used with much higher intensity and corrections for elastic scattering can be made more simply.

As indicated in a previous section, an optical model code (ABACUS) has been converted to operate on M.S.U.'s CDC-3600 computer. This code includes search routines for determination of "best-fit" sets of optical parameters.

Alpha Elastic Scattering Calculations.

Following up on experimental work performed by one of our staff (C. R. Gruhn) at another institution, a numerical analysis and interpretation of large-angle elastic alpha scattering from ^{40}Ca has been made. A modified Blair smooth-cut-off calculation successfully reproduces main features of the data. In this calculation the differential cross section is computed via a partial wave expansion of the scattering amplitude, where the scattering matrix elements are assumed to have the form:

$$\eta_\ell = [1 + \exp(-\frac{\ell - L}{\Delta})] + M(L_s)$$

The $M(L_s)$ term allows additional weight to be given to

---

[21] Bearpak, Graham, and Jones, Proc. of Paris Nucl. Phys. Conf., p. 864 (1964).

the L_sth partial wave and to build into the partial-wave expansion a resonance in a particular partial wave. In making the calculation all parameters were determined by fitting the 30.5-MeV data. Then with the parameters fixed, one parameter, L, was varied to span the energy range of the data. The results of this calculation are in qualitative agreement with experimental data for $\Delta = 0.6$, $M = 0.1$ and $L_s = 12.0$. The calculation is particularly noteworthy in that the angular position of the last oscillation remains constant as the incident energy is changed, in accord with one of the outstanding features of the data.

Direct Reactions.

Pickup Reactions. Pickup reactions such as (p,d) and (p,t) provide essential information on the structure of nuclear wave functions in addition to yielding a great deal of spectroscopic information. Thus the (p,d) reaction on even-even targets reveals the importance and types of configuration admixtures in the ground state wave functions of the targets, in most instances even when the nuclear states in the final nucleus are not well understood. As an example, significant admixtures of the 2p state have been found[22] in a number of the

---

[22] E. Kashy, and T. W. Conlon, Phys. Rev. **135**, B 389 (1964).

E. Kashy, A. Sperdato, H. A. Enge, and W. W. Buechner, Phys. Rev. **135**, B 865 (1964).

Ca and Ti isotopes including ^{40}Ca. In contrast, ^{48}Ca shows an amazingly pure ground state configuration, indicating an especially good doubly magic nucleus.

With our high-energy, well-resolved proton beam we expect to be able to carry out pickup reactions on a large number of nuclei and make systematic studies of the results. Using (p,d) reactions we will be able to reach "hole states" corresponding to most of the bound states of the nucleons in the nucleus and thus learn much about single particle energies for tightly bound nucleon states. In addition, multiparticle pick-up reactions will be studied. While these reactions are more difficult to interpret in detail, they offer an interesting and promising field of investigation.

As is now well known, the angular distributions of (p,d) and (d,p) reactions show very interesting effects associated with total angular momentum ("J dependence"); some of our effort will be directed toward investigating such effects at our higher bombarding energy. Better understanding of the interactions involved in this phenomenon will hopefully result. Similar J-dependent effects will be investigated in other reactions, such as (^{3}He, α) and (p, α), where the zero spin of the outgoing particle should simplify the interpretation.

In collaboration with C. D. Goodman and C. A. Ludemann of Oak Ridge, one of our staff (W. H. Kelly) has been engaged for the past year in a series of pickup reaction experiments. The main purpose of the experiments was to study levels arising from the $(p_{1/2})^n(g_{9/2})^m$ configurations using the ^{89}Y(p,d) and ^{90}Zr(p,d) reactions at 19.5 and 36 MeV, and the ^{89}Y(p,t) and ^{90}Zr(p,t) reactions at 36 MeV.

The target nucleus ^{89}Y has a known spin of $1/2^-$. A total of 16 states of ^{88}Y can be constructed in which the odd proton and the odd neutron holes are in either the $p_{1/2}$ or $g_{9/2}$ shell-model states. Of these only eight (two each of spins 0^+, 1^+, 4^- and 5^-) are expected to have non-zero spectroscopic factors for the (p,d) reaction.

At 19.5 MeV, seven deuteron groups were resolved corresponding to excited states in ^{88}Y at 220, 390, 740, 1228, 1535, and 1680 keV. There is evidence that the state at 1228 keV may actually be an unresolved doublet. Angular distribution measurements on these groups were characteristic of $\ell = 4$ pickup for the ground and 220 keV states (and possibly for the 1680 keV state) and of $\ell = 1$ for the 390, 740, 1228, and 1535 keV states. It is thought that the one, or possibly two, missing $\ell = 4$ levels are among the weakly populated states at higher excitation energies. These are presently undergoing further investigation. These measurements at 19.5 MeV are also being extended to the backward angles to search for J-dependent effects.

One of the 0^+ states in ^{88}Y has T = 6 and is the isobaric analogue of the ^{88}Sr ground state. Measurements using 36 MeV protons have been carried out in an attempt to excite this analogue state. An initial analysis indicates that this state is only weakly excited.

Inelastic Proton Scattering. Inelastic scattering of medium energy particles is an important means of investigating the validity of strong and weak coupling models in odd-A nuclei. Under extreme assumptions, each model makes a definite prediction for the relative excitation of various states by inelastic scattering. The strong coupling model, for example, predicts that the cross section for the excitation of a state of spin I', in the odd-A nucleus, with angular momentum transfer ℓ, is given by

$$\frac{d\sigma}{d\Omega}(\ell,\ I \rightarrow I') = (I\ell K0|I'K')^2 \frac{d\sigma}{d\Omega}(0 \rightarrow \ell)$$

where $\frac{d\sigma}{d\Omega}(0 \rightarrow \ell)$ is the cross section for the excitation of a state of spin ℓ in the neighboring even-even nucleus, K is the band number and I the ground state spin of the odd-A nucleus. Similarly, the weak coupling model predicts that the cross section for the excitation of a state of spin I' in an odd-A nucleus is given by:

$$\frac{d\sigma}{d\Omega}(\ell,\ I \rightarrow I') = \frac{2I' + 1}{(2\ell + 1)(2I + 1)} \frac{d\sigma}{d\Omega}(0 \rightarrow \ell) .$$

For illustration, inelastic alpha scattering at 42 MeV[23],

---

[23] I. M. Nagib, Ph.D. Thesis, University of Washington (1962)

inelastic deuteron scattering at 12.8 MeV[24] and inelastic proton scattering at 17.5 MeV[25] all indicate that the low lying states of Al^{27} may be described as a $d_{5/2}$ hole coupled to the first 2^+ state in Si^{28}. In addition, the observed suppression of the excitation of the 2.7 MeV $(5/2^+)$ state in Al^{27} gives a measure of the one phonon admixture in the ground state $(5/2^+)$ of Al^{27}.

The higher energy proton beam of the M.S.U. cyclotron will allow such investigations to be extended to higher energies where one is more confident that the reaction is predominently a direct process. Furthermore, coulomb barrier and angular momentum inhibition will be much less important in the outgoing channels for these higher energy protons. Thus, with good energy resolution, excited states arising from the coupling of a particle or hole to higher phonon excitations in even-even nuclei can be studied.

Isotopic Analogue States. There has been and continues to be considerable interest in analogue states in nuclei, i.e., states having the same nuclear configuration but different Z. Excited states of isotopic spin $T = T_z + 1$ can be reached by (p,d) reactions and since one has relatively good methods of calculating the spectroscopic factor for the reaction leading

---

[24] H. Niewodniczanski, J. Nurznski, A. Stozalkowski, J. Wilczynski, J. R. Rook, and P. E. Hodgson, N.P. 55, 386 (1964).

[25] G. M. Crawley, Ph.D. Thesis, Princeton University (1965).

to these states, a systematic study of a number of these states at energies above 40 MeV may help to clear up the problem which exists in choosing proper neutron bound state wave functions. In the (p,t) reaction, one can, in addition to levels with $T = T_z + 1$, reach levels where $T = T_z + 2$. Many of these levels have been investigated at Berkeley with overall resolution of 150 keV[26]. It would be of considerable interest to see if these states exhibit the "micro giant" resonant structure expected due to mixing of states of different T in the high-level-density region where these states are found. It is expected that such studies will be started as soon as the high resolution magnetic spectrograph is constructed.

Other somewhat more complex reactions can lead to states of still greater isotopic spin. For example, the $^{45}Sc(p,{}^{6}He)$ ^{40}Ca reactions can excite levels with $T = T_z + 3$, i.e., $T = 3$ for ^{40}Ca. This particular experiment is now being instrumented and will be carried out in the near future. Ge(Li) gamma-ray detectors can be used in many cases to obtain precise energies of analogue states through measurements of the deexcitation gamma-rays and apparatus for doing such measurements is being constructed.

The (He^3,t) reaction is an important reaction which will

---

[26] J. Cerny and R. H. Pehl, ANL-6848, 208 (1964).

contribute greatly to our understanding of analogue states. It is in many ways similar to the (p,n) reaction, but has the advantage that the product particles are charged. The detection problem is thus greatly simplified, and solid-state detectors will provide a powerful tool. This reaction can also be advantageously investigated using the planned broad-range magnetic spectrograph. Since typical Q-values are -5 MeV, the tritons will be the most rigid particles emitted in the reaction and can thus be observed with no competing background.

Decay Schemes of Spherical Nuclei.

Since the nuclei $^{121}_{51}$Sb, ^{123}Sb, and ^{125}Sb differ by pairs of neutrons their spectra are expected to show many similarities. Systematic trends of the known excited states of $^{127}_{53}$I, ^{129}I, and ^{131}I also show that Iodine levels may be analogous to those of Sb. Published decay schemes of most of these nuclei are subject to considerable question. A program of additional experimental investigations has therefore been undertaken to (i) verify or correct decay schemes, (ii) to determine systematic trends, and (iii) to study relationships between collective and single particle excitations.

^{121}Sb. Results of previous scintillation detector experiments[27] on the states of ^{121}Sb have been recently

---

[27] R. L. Auble, W. H. Kelly, and H. H. Bolotin, Nucl. Phys. 58, 337 (1964).

rechecked with Ge(Li) detectors with particular emphasis on the new and weak transitions that were reported earlier. These latest results were found to be in agreement with those reported previously.

Decay of ^{127}Te and ^{127m}Te. The 105-day ^{127m}Te and 9.3-hour ^{127}Te activities were produced by neutron irradiation in the Oak Ridge Research Reactor. Specific tellurium chemistry was performed on the irradiated sample to remove contaminants. Table 1 summarizes the relative intensities of the gamma rays. Coincidence experiments were performed and results are also summarized in Table 1.

Gamma-gamma directional correlation experiments were performed on the more prominent cascades. These results are given in Table 2. The A_2 and A_4 terms given here are the coefficients of the Legendre polynomials in the angular correlation function

$$W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta).$$

In these experiments a very interesting phenomenon has been observed, namely that the values of the A_2 and A_4 coefficients for the 360-57.6 keV cascade are strongly dependent upon the chemical form of the source. The values given in Table 2, for example, were obtained with dilute sources of tellurium chloride in concentrated HCl in a range of dilution where chemical effects were demonstrably small. When the solution is concentrated by evaporation, the coefficients attenuate by a factor of approximately two as the solution

TABLE I

Summary of data on photons emitted in the decay of ^{127}Te.

Transition Energy (MeV)[*]	Relative Photon Intensity[*]	Transition Rates[†]	Coincident Transitions (MeV)
0.0576±0.0005	61±1	0.89	0.145, 0.214 0.360, 0.591 0.657
0.087±0.001(I.T.)	25±1	99.2	
0.145±0.005[‡]	0.51±0.06[‡]	0.0023	0.0576, 0.214
0.203±0.001	5.4±0.2	0.018	0.214
0.214±0.001	3.9±0.2	0.013	0.0576, 0.145 0.203
0.360±0.0005	14.8±0.1	0.0465	0.0576
0.417±0.0005	100	0.313	
0.591±0.001	0.22±0.04	0.00062	0.0576
0.657±0.001	1.43±0.06	0.00434	0.0576

[*] These data, with the exception of the 0.145 MeV transition data, were obtained from the Ge(Li) runs.

[†] Number of transitions, photons plus conversion electrons, per 100 disintegrations of ^{127m}Te. Corrections for internal conversion were made using the conversion coefficients calculated by Rose assuming the lowest multipole order for the transitions consistent with the proposed decay scheme.

[‡] Energy and intensity obtained from coincidences with the 0.214 MeV transition.

TABLE II

Summary of Angular Correlation Measurements.

Cascade				Spin	Mixing Amplitude
Gamma 1	Gamma 2	A_2	A_4	Sequence	(Gamma 1)[*]
0.214	0.203	+0.224 ±0.005	-0.005 ±0.005	5/2-3/2-5/2	+0.20±0.02 or >200
0.360	0.0576	+0.32 ±0.02	0.00 ±0.02	5/2-7/2-5/2	-0.18±0.08 or -2.29±0.07
0.591	0.0576	+0.27 ±0.06	+0.15 ±0.15	7/2-7/2-5/2	-1.7±0.3
				9/2-7/2-5/2	+0.24±0.13 or +5.68±0.09
0.657	0.0576	-0.078 ±0.037	-0.033 ±0.089	7/2-7/2-5/2	-0.33±0.08 or +2.14±0.08
				9/2-7/2-5/2	-0.24±0.07 or -3.00±0.01
				11/2-7/2-5/2	

[*] Mixing amplitudes of +0.52±0.05 and -0.0803±0.0063 for the 0.203 and 0.0576 MeV transitions respectively were given by Geiger and utilized in analyzing these angular correlation data.

approaches dryness. Careful auxiliary experiments have shown that this effect is not due to changes in geometry or scattering in the source. Speculatively, the phenomenon is presently ascribed to an interaction of the quadrupole moment of the nucleus in its 57.6-keV state with electric field gradients present in the concentrated solution causing a slow random precession. This is supported, in part, by the fact that the effect did not appear in parallel correlation measurements of the 214-203 keV cascade (the half-life of the 57.6 keV state is approximately 2 nanoseconds, whereas that of the 203 keV state is known to be much shorter). The 360-57.6 keV cascade is presently being studied using the time-differential angular correlation technique to obtain more insight into the mechanism of the perturbation.

Figure 14 gives the decay scheme of ^{127}Te. The results of the directional correlation measurements were not sufficient to allow unambiguous spin assignments. However, these measurements, in conjunction with internal conversion coefficients determined by Geiger[28], do allow unique spin assignments to be made for the ground, 57.6, 203, and 417 keV states and limits the possible values of the spins for the 649 and 715 keV states. The log ft values, which are given in Fig. 14, indicate that all these states have positive parity. These

---

[28] J. S. Geiger, Phys. Rev. Letters 7, 48 (1963).

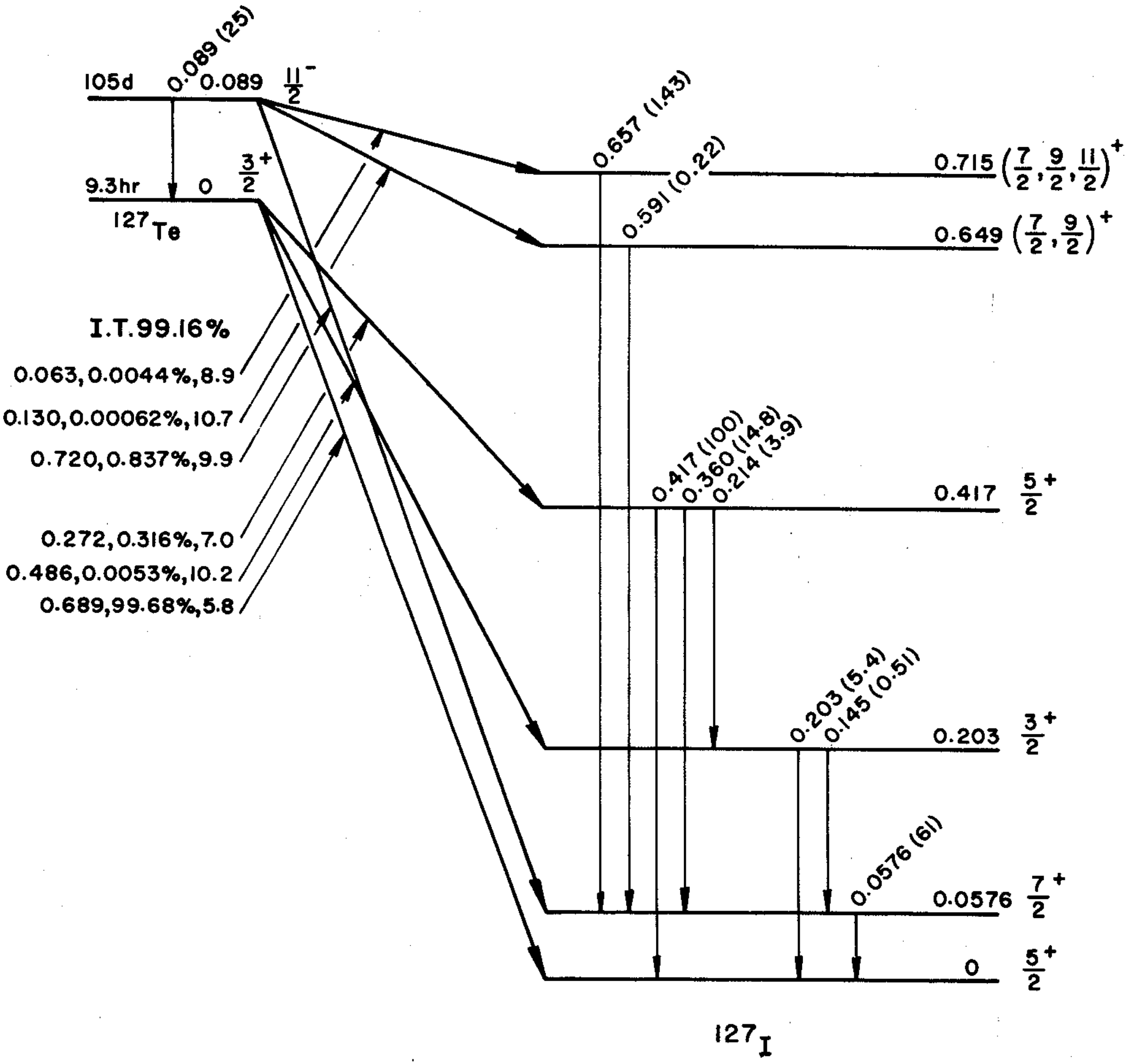


Fig. 14: Level diagram and decay modes for ^{127}Te and ^{127}I.

results have recently been accepted for publication.

The Decay of ^{123}Sn to ^{123}Sb. The 125-day ^{123}Sn activity was produced by neutron irradiation in the Oak Ridge Research Reactor. Chemical separations of the tin were performed to remove contaminants. Previously published data indicate only one excited state at 1080 keV[29]. Using scintillation and Ge(Li) detectors, we have shown that three states in ^{123}Sb are populated by the beta decay of ^{123}Sn. These states have energies of 1032, 1090, and 1187 keV. The log ft values of the beta transitions indicate that the spins of these states are between 7/2 and 15/2 with positive parity, assuming that the spin and parity of the ^{123}Sn parent is $11/2^-$. The proposed decay scheme is shown in Fig. 15(a).

Excited States of ^{125}Sb. Several authors[30] have studied the decay of 9.4-day ^{125}Sn to ^{125}Sb. Levels at 0, 1075, 1410, 1885, 1985, and 2230 keV were reported. Preliminary results obtained using scintillation and Ge(Li) detectors show gamma-rays having energies 159, 330, 350, 391, 469, 801, 823, 892, 916, 937, 981, 1018, 1069, 1090, 1151, 1173, 1221, 1254, 1348, 1419, 1491, 1808, 1890, 2002, 2201, and 2276 keV. From scintillation-scintillation and from Ge(Li)-scintillation

---

[29] H. A. Grench, S. B. Benson, L. C. Schmid, Bull. Am. Phys. Soc. 3, 207 (1958).

[30] S. H. Devare and H. G. Devare, Phys. Rev. 133, B568 (1964) and references cited therein.

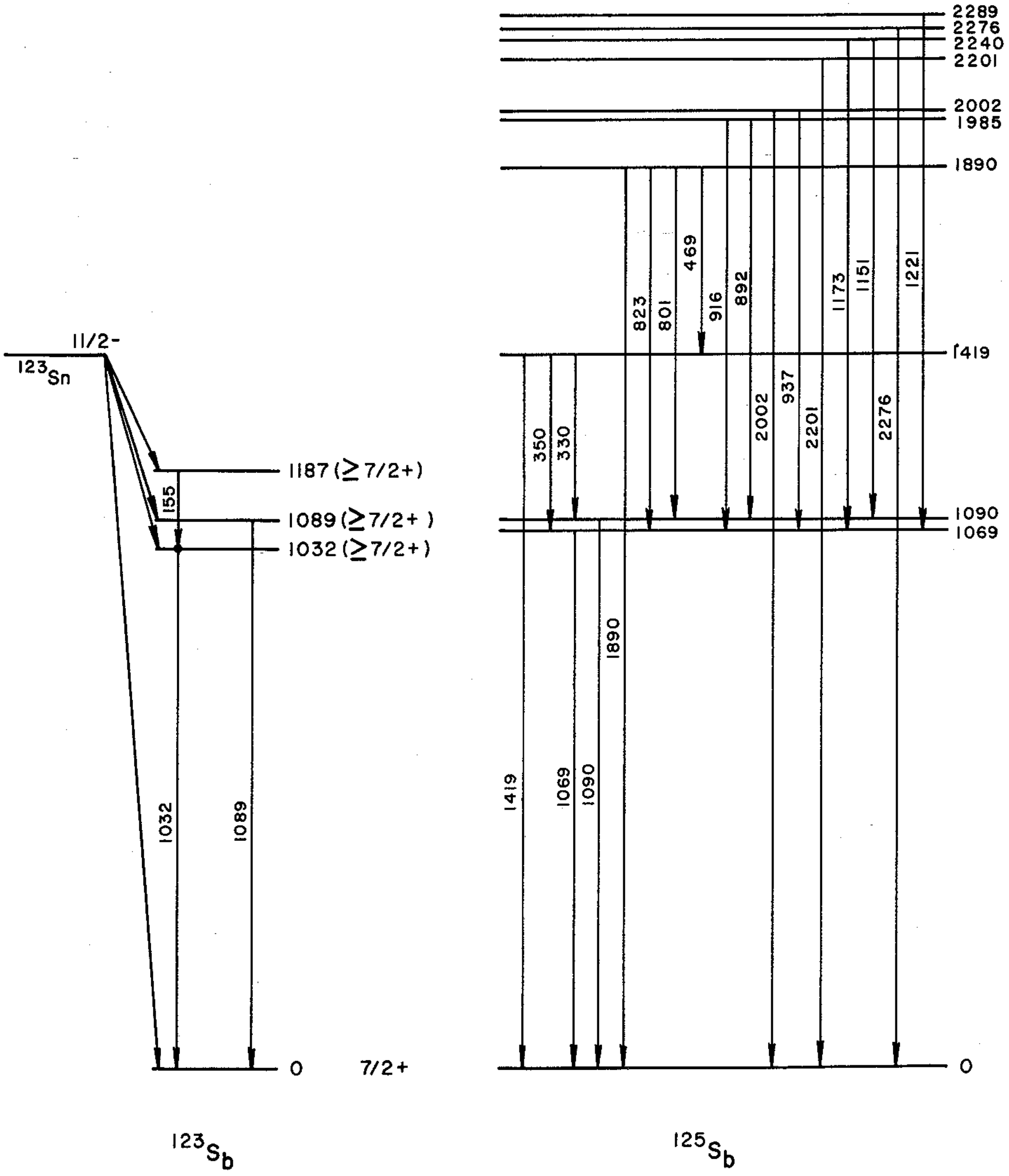


Fig. 15: Level diagrams and decay modes for ^{123}Sn and ^{123}Sb and level diagram for ^{125}Sb.

coincidence experiments using a multi-parameter multi-channel analyzer, it was possible to construct the tentative energy-level diagram shown in Fig. 15(b). Spin assignments are awaiting the results of the analysis of gamma-gamma angular correlation experiments.

Decay of ^{129m}Te and ^{131m}Te. Investigation of these activities has just begun. The use of the Ge(Li) detectors has already enabled us to observe approximately twice as many transitions as had previously been reported. Coincidence experiments using solid-state detectors are presently being performed to determine details of the decay scheme.

Measurement of High Energy Gamma Rays.

A precision method for determining the energy of high energy gamma rays using Ge(Li) detectors has been developed. The essence of the technique is the use of parallel input capacitors to "divide" the energy of a high-energy peak such that it will correspond approximately with the energy of well-known lower energy gamma rays. The division ratio of the parallel capacitors is calibrated using a pair of known gamma rays (such as the 662 keV Cesium transition and the 1332 keV transition in Cobalt).

The first measurement using this technique checked the linearity of the Ge(Li) detectors by applying the technique to the known 2514 keV transition in Sodium 22. Linearity of ±0.03% was indicated which compares with the previously published value of ±0.3%[31]. The method has also been applied to the de-excitation gamma ray of the first 3^- level of ^{16}O; an energy of 6127.8 ± 1.2 keV was measured which gives, after correcting for recoil, 6129.1 ± 1.2 keV as the excitation energy for the level. This value is in good agreement with and improves upon the previous values of 6131 ± 10 keV[32] and 6138 ± 11 keV[33] obtained from $^{19}F(p,\alpha)^{16}O$ experiments. A paper reporting this work has been submitted for publication.

Lifetimes of Excited Nuclear States.

A program of lifetime measurements has been initiated using the Doppler shift attenuation method. When an excited nucleus is produced in a nuclear reaction, it has a recoil velocity which Doppler shifts the energy of the de-excitation gamma ray. If the nucleus is recoiling in the target or backing, its velocity decreases expoentially with a slowing-down time characteristic of the material. This slowing down attenuates the Doppler shift by an amount which depends on the relative magnitudes of the slowing-down time and the

---

[31] G. T. Ewan and A. J. Tavendale; Can. J. Phys. 42, 2286 (1964).

[32] G. L. Squires, C. K. Bockelman, and W. W. Buechner, Phys. Rev. 104, 413 (1956).

[33] T. E. Young, G. C. Phillips, and R. R. Spencer, Phys. Rev. 108, 72 (1957).

lifetime. It is not hard to show that the attenuation of the Doppler shift, F, is given to first order by $F = \alpha/(\tau + \alpha)$, where α = slowing-down time, τ = lifetime.

The high-energy particles available from the M.S.U. cyclotron can produce Doppler broadening of gamma-ray peaks many times greater than the resolution of Germanium counters. Hence the width of a peak is related to the attenuation of the Doppler shift. The method of measurement consists of adjusting the slowing-down time of the recoiling nucleus until the attenuation is 0.5, i.e., where $\alpha \simeq \tau$. The slowing-down time can be adjusted by changing the chemical composition of the target or the pressure if a gas is used. One can also use a thin target and change backing material.

The most interesting range of lifetimes for this technique is from 10^{-11} to 10^{-14} sec where direct measurements are not possible. In the range from 10^{-9} to 10^{-11} sec, both direct and Doppler measurements are possible and comparison of the two provides a convenient calibration check. Levels in ^{16}O, ^{19}F, and ^{32}S are presently being studied.

Low-Energy Beta-Ray Spectroscopy.

The $\pi\sqrt{2}$ air-core spectrometer is engaged in a continuing program of conversion and Auger-electron studies. The research has important implications in both atomic and nuclear physics.

With respect to the latter, high resolution conversion electron studies are of great value in (a) determining multipolarities of γ-ray transitions, (b) resolving very closely spaced nuclear states, and (c) obtaining properties of nuclear levels such as E_x, J, and π. Auger electron measurements complement conversion studies in that they can be used to obtain γ-ray multipolarities for very low energy γ-rays and, since many KLL Lines are known to high precision, they provide a tool for the calibration of conversion lines thus yielding accurate measurement of excitation energies. Auger measurements can also be used to determine Q-values where the electron capture process is the only decay mode. The Auger process is also, of course, a very interesting problem in atomic physics.

At present considerable effort is being directed to improving our understanding of the mechanism of the Auger process (the special low energy detection equipment described in a previous section gives the instrument unique capability in this area) with the objective of developing more effective nuclear spectroscopy techniques; in addition, a continuing program of conversion electron studies of nuclear transitions is in progress.

The conversion spectrum of ^{137}Cs → ^{137}Ba has been studied with a resolution of 0.047%. While the spectrometer is capable of substantially higher resolution, the specific activity of ^{137}Cs is not high enough to make possible the use of 0.1 mm wide sources in our spectrometer. The results for the K- and L-subshell ratios for ^{137}Ba agree with those at Chalk

River[34], and the M/L_1 ratio is in agreement with predictions by Chu and Perlman[35]. This experiment also yielded a value of 0.009 ± 0.003 for the $\sum N,O/L_1$ ratio which represents the first measurement of this ratio.

The conversion and L-Auger spectra of $^{210}Pb \rightarrow {}^{210}Bi$ have been investigated with a much higher resolution (≃0.15%) than in any previous study. The ^{210}Bi L-subshell ratios agree well with predictions of Sliv and Band[36] in one of the few cases where no mixing is present and where the radiation is known to be pure M1. However, the L_2/L_1 ratio does not agree well with the predictions of Rose[37]. The M_1, M_2, M_3, N_1, N_2, N_3, and O + P conversion intensities were determined with greatly increased accuracy. The M_i/L_1 and $\sum M_i/L_1$ fall 10% below Chu and Perlman's predictions. These results in conjunction with those on ^{205}Pb (26 keV) seem to indicate that the Chu and Perlman empirical screening correction for heavy elements is increasingly in error as the energy of the

---

[34] J. S. Geiger, R. L. Graham, and F. Brown, Can. J. Phys. 40, 1258 (1962).

[35] Y. Y. Chu and M. L. Perlman, Phys. Rev. 135, B319 (1964).

[36] L. A. Sliv and I. M. Band, "α-β-γ-ray Spectroscopy", edited by Kai Siegbahn, (North-Holland Publishing Co., 1965).

[37] M. F. Rose, "Internal Conversion Coefficients," (North-Holland Publishing Co., 1958).

transition drops below 75 keV.

The ratio of the L_1-M_4M_5 Auger line to the L_1 conversion line in ^{210}Bi has been accurately determined. Hence for any isotope of Bi, a measurement of the intensity of this Auger line can henceforth be used to directly infer the number of L_1 vacancies, and at least for Bi, the L_1/K as opposed to the L/K capture ratios can be measured.

Intensities and energies of 65 L-Auger lines of ^{210}Bi have been measured and most of these lines have been identified. Comparison with the results of Sujkowski and Slätis[38] for ^{212}Bi show excellent agreement wherever similarities are expected. Because ^{210}Pb → ^{210}Bi yields a ratio of $L_1/L_2/L_3$ vacancies of about 90/9/1, the L_1 lines in our spectrum are much stronger than in ^{212}Pb → ^{212}Bi and comparison of the two spectra was very helpful. Also virtually all of the L_3 vacancies observed here are the result of the L_1-$L_3M_{4,5}$ Coster-Kronig process.

We have determined the energies of the $L_{1,2}$-M_iM_j Auger lines with accuracies of 5 to 25 eV and have found an approximate empirical relationship for predicting them. We have demonstrated <u>for the first time</u> the existence of Auger-vacancy-satellites which are the Auger analogue of X-ray satellites. The whole L_3-MM spectrum is shifted about 40 eV down from its normal position. The L_3-MN spectrum is not displaced much

---

[38] Z. Sujkowski and H. Slätis, Arkiv Fysik 14, 101 (1958).

and the L_3-NN spectrum is displaced upward by about 50 eV. These displacements agree with predictions from X-ray satellites. An accurate value of the Coster-Kronig coefficient f_{13} for Bi has been obtained from the relative intensity of the L_3 spectrum to the L_1 conversion line.

The L-Auger spectrum of $^{113}Sn \rightarrow {}^{113}In$ (2-4 keV) has been studied using the post-accelerator. Exhaustive data have also been taken on the K-Auger spectrum and conversion line structure of this nuclide.

The ^{113}Sn source was especially difficult to prepare because of the low β-energy. Nevertheless, energies and relative intensities of 47 lines and groups of lines were measured. An approximate empirical relationship similar to that for ^{210}Bi but showing less relative energy dependence has been found. Since this is the first L-Auger spectrum with high resolution in this part of the periodic table, this relationship will be extremely useful in investigating other spectra. L-Auger satellite lines which follow the K-LL Auger process (the initial state consists of two L vacancies) have also been found with energies and intensities consistent with expectations.

Neutron Studies.

Neutron Spectroscopy.

Two-body reactions in which a neutron is emitted can provide important information on nuclear structure. A well-known example is the (d,n) stripping reaction in which parity, and possibly spin, of a residual state is obtained from the angular distribution of the corresponding neutron group.

Another example is the (p,n) reaction in which isobaric states are observed in the neutron spectra, this situation being an example of the "isobaric configuration selection" process whereby states composed of the same shell-model configuration as the initial state are strongly and preferentially excited. Thus far, only ground-state analogues have been well studied and these only for light and medium weight nuclei. The relatively high energy of the M.S.U. cyclotron and its good energy resolution will enable work of this type to be carried much further. At 50 MeV the compound nucleus contribution to (p,n) reactions will be much smaller than in the work of the Livermore group at 14.8 and 18.5 MeV. In addition, self-supporting targets of thickness 100 keV (Livermore targets ~300 keV) can easily be made for 50-MeV protons so that spectral peaks corresponding to isobaric states should be much more prominent. Also, at 50 MeV adequate energy is available to overcome the high coulomb displacement energies in heavy nuclei, therefore allowing observation of both ground and excited isobaric analogue states throughout the periodic table.

Neutron-producing reactions initiated by ^{3}He will also be studied. Nuclear structure effects should be displayed from capture of a pair of protons in (^{3}He,n) reactions. In all neutron observations the basic requirements are that the neutron energies and fluxes be measured. The time-of-flight system discussed in a previous section will be ideal for this purpose; a recoil-telescope system is also being set up and will be used for initial surveys.

Neutron-Induced Reactions. The T(d,n)^{4}He reaction will be used as a neutron source; effectively mono-energetic neutrons variable in energy up to about 45 MeV are produced as the deuteron energy is varied to its maximum of 28 MeV.

Recoil-telescope type neutron spectrometers are easily adapted to the study of (n,charged particle) reactions by substitution of a target foil for the usual hydrogenous radiator. In this application a larger angular acceptance is permissible in the telescope than when used as a neutron spectrometer because of the greatly reduced variation of recoil energy with angle as compared to n-p scattering. This is an important compensation for the reduced cross section. By using high-resolution solid-state detectors in the telescope, and a particle-identifier circuit, angular and energy distributions can be studied depending upon the competing requirements of efficiency and resolution. The (n,d) pickup reaction should be particularly interesting for obtaining nuclear spectroscopic information.

n-p Scattering. The three pieces of neutron equipment already mentioned: time-of-flight system, recoil telescope and T(d,n)He^4 neutron source, are the basic ingredients in experiments on n-p scattering. In the energy region around 45 MeV it appears possible to achieve a significant increase in the accuracy of n-p scattering data[39]; this is true of both angular distribution and polarization data. The $T(d,n)^4He$ reaction is known to produce neutrons with a high degree of polarization for deuteron energies up to 10 MeV[40], and the trend indicates even higher polarization with increasing deuteron energy.

The 45 MeV range is also a good energy for determination of the $^1P_1$ phase shift and of the coupling parameter, ε_1, between $^3S_1$ and $^3D_1$ states. The $^1P_1$ phase shift has been found to be important in applying two-body forces to heavy nuclei[41], i.e., to nuclear matter. The tensor force, which is important in light nuclei, is dependent on ε_1[42].

Ternary Fission Studies.

Studies have been made at several laboratories of fission accompanied by emission of a long-range alpha particle [43].

---

[39] The Nucleon-Nucleon Interaction by Richard Wilson, Interscience Publishing, 1963.

[40] Data summarized by W. Haeberli in Progress in Fast Neutron Physics, ed. Phillips, Marion and Risser (U. Chicago Press, 1963).

[41] N. Azziz and P. Signell, Nucl. Phys. 59, 444 (1964).

[42] Derrick, Nustard and Blatt, Phys. Rev. Letters 6, 69 (1961).

[43] J. A. Coleman, A. W. Fairhall, and I. Halpern, Phys. Rev. 133, B724 (1964).

The data indicate that the ratio of fission events of this type to those in which ordinary binary fission occurs goes through a minimum at an excitation energy of the fissioning nucleus of about 19 MeV. The few data points taken beyond this minimum show a rapid increase in the ratio with excitation energy. Such an increase is of interest since the alpha particle is emitted from the neck region between the fragments in what appears to be otherwise a normal binary fission mode[44]. Hence the alpha particle can be used as a probe to study fission at the instant when nuclear matter is stretched to its utmost limit.

It is planned to extend the measurements of the excitation function for this process to higher energies by inducing fission of ^{238}U with incident protons of energy 20 MeV and greater. Using a time-to-height coincidence unit in conjunction with a two-dimensional analyzer, both true and chance events will be measured simultaneously for all alpha-particle energies. The mass distribution of the fission fragments associated with alpha particles will be measured by feeding the output of a divider circuit into another analyzer gated by a triple-coincidence requirement.

Transverse Doppler Shift Measurement.

An experiment[45] which has become a textbook illustration[46]

---

[44] R. A. Atneosen, T. D. Thomas, and G. T. Garvey, to be published in Phys. Rev. (1965).

of the special theory of relativity is the measurement of the Doppler shift in the H_α lines of hydrogen. Moving canal rays with $\beta = 0.005$ were the sources of light in this experiment. The low velocity and other conditions of the experiment did not allow a direct measurement of the Doppler shift of sufficient accuracy to show that the relativisitic, rather than the classical, formula applied. Instead, a shift was measured in the center of gravity of the spectroscopic lines emitted by canal rays moving toward and away from the observer.

A direct measurement of the transverse Doppler shift, which is a strictly relativistic effect, is possible. If ν_o is the frequency of the radiation emitted by a stationary source, the frequency observed at 90° to a source moving with velocity βc is $\nu_o(1 - \beta^2)^{1/2}$. We intend to measure this shift on the gamma-ray emitted by the 3.560-MeV state of ^{6}Li when excited by inelastic scattering of 75 MeV ^{3}He nuclei; the excited ^{6}Li will have $\beta \approx 0.15$. Both the magnitude and direction of the source velocity will be defined by coincident observation of the scattered ^{3}He. The transverse shift of 40 keV will be measured in a Ge(Li) detector with 10 keV resolution. Both the angular distribution and the dependence on β will be checked to insure freedom from alignment errors, etc.

---

[45] H. E. Ives and G. R. Stilwell, "An Experimental Study of the Rate of a Moving Atomic Clock," J. Opt. Soc. Am. 28, 215 (1938).

[46] David Halliday and Robert Resnick, Physics for Students of Science and Engineering (John Wiley & Sons, Inc., 1962), pp. 914-917.

RESEARCH STAFF

In recent years M.S.U., like many universities, has undergone a period of rapid expansion (student population is expected to reach 36,500 in the fall of 1965). One of the striking features of this expansion has been the rapid development of a very substantial nuclear research group at the University. Of the total physics department regular faculty of 35, 13 are now actively involved in nuclear research, 9 of these 13 having joined the staff in the past five years.

During the past year new faculty appointments in nuclear physics and related areas were: S. M. Austin as Associate Professor working with the cyclotron experimental group, J. H. Hetherington as Assistant Professor working with the nuclear-theoretical group, and W. C. McHarris, Assistant Professor, working in the nuclear-chemistry area. In addition, four new research staff members have joined the Cyclotron staff, namely: R. A. Atneosen as Assistant Professor (Research) and R. K. Bansal, G. M. Crawley, and G. H. MacKenzie as Research Associates. A career summary and lists of publications are given below for Austin, Atneosen, Bansal, Crawley, and MacKenzie. Dr.'s Hetherington and McHarris are not included since their research, although directly related, is separately supported.

Eleven regular faculty members will participate in the research program herein proposed, namely, Professors Blosser, Gordon and Haynes, Associate Professors Austin, Galonsky, Kashy, and Kelly and Assistant Professors Arnette, Benenson, Gruhn, and Johnson. (For all of this group the cyclotron program is the sole research activity.) The group also works in close collaboration with the nuclear theoretical group headed by Professors H. McManus and P. S. Signell. Curriculum vitae and lists of publications for the present staff have appeared in one or another of our previous proposals and are not repeated here. Brief summaries of experience and achievements of our newly appointed staff follow.

Sam M. Austin, Associate Professor.

Dr. Austin received his Ph.D. in 1960 at the University of Wisconsin where he worked on fast neutron cross sections and polarizations. With the assistance of an N.S.F. postdoctoral fellowship, the year 1960-61 was spent at the Clarendon Lab, Oxford, where he worked on nuclear reactions in ^{12}C produced by 120-150 MeV protons. From 1961 to 1965 he was an Assistant Professor at Stanford University and worked in the Van de Graaff Laboratory on a number of nuclear reaction studies. Dr. Austin has been a Sloan Research Fellow since 1963, and this fellowship has been renewed for the coming academic year. Publications by Dr. Austin include:

Fast Neutron Capture Cross Sections, S. M. Austin, M. G. Silbert, D. B. Fossan, and W. E. Wilson, Bull. Am. Phys. Soc. Ser. II. 4, 43 (1959).

The Polarization of Neutrons from the $^7Li(p,n)^7Be$ Reaction (II), S. M. Austin, S. E. Darden, A. Okazaki and Z. Wilhelmi, Nucl. Phys. 22, 451 (1961).

The $^{12}C(n,np)^{11}B$, $^{12}C(p,pn)^{11}C$ and $^{12}C(p,2p)^{11}B$ Reactions Induced by Nucleons of 120-150 MeV, S. M. Austin, G. L. Salmon, D. J. Rowe, A. B. Clegg, and K. J. Foley, Proc. of the Rutherford Jubilee Int. Conf., J. B. Birks, ed. (Heywood & Co., Ltd., London, 1961), p. 139.

Scattering of Neutrons by Particles, S. M. Austin, H. H. Barschall and R. E. Shamu, Phys. Rev. 126, 1532 (1962).

Reactions Induced in ^{12}C by Nucleons of Energy 120-150 MeV, S. M. Austin, G. L. Salmon, A. B. Clegg, K. J. Foley, and D. Newton, Proc. Phys. Soc. (London) 80, 383 (1962).

Angular Distribution of the $^{7}Li(p,n)^{7}Be$ Neutrons, S. M. Austin, Bull. Am. Phys. Soc. Ser. II. 7, 269 (1962).

Ericson Fluctuations in the $^{20}Ne(n,\alpha)^{17}O$ Reaction, S. M. Austin, Bull. Am. Phys. Soc. Ser. II. 7, 605 (1962).

Radiative Capture of ^{3}He by ^{3}H, D. Kohler and S. M. Austin, Bull. Am. Phys. Soc. Ser. II. 8, 290 (1963).

Richard A. Atneosen, Assistant Professor (Research).

Dr. Atneosen received his Ph.D. in 1963 at Indiana University; his thesis research consisted of a study of alpha induced reactions using the Indiana cyclotron. For the past two years he has held a post-doctoral appointment at Princeton University working on properties of proton induced fission. Publications by Dr. Atneosen include:

Energy Dependence of Elastic and Inelastic Scattering of Alpha Particles by ^{12}C and the $^{12}C(\alpha,p)^{15}N$ Reaction, R. A. Atneosen, H. L. Wilson, M. B. Sampson, and D. W. Miller, Phys. Rev. 135B, 660 (Aug., 1964).

Emission of Long-Range Alpha Particles in the Fission of ^{238}U with 17.5-MeV Protons, R. A. Atneosen, T. D. Thomas and G. T. Garvey, (submitted to Phys. Rev.).

X-rays Emitted in Coincidence with the Fission of ^{252}Cf, T. D. Thomas, R. A. Atneosen, W. G. Gibson, and M. L. Perlman, Int. Atomic Energy Agency Symposium of Physics & Chemistry, Salzburg, SM-60/57 (March, 1965).

Ram K. Bansal, Research Associate.

Dr. Bansal received his Ph.D. in 1965 from the University of Rochester where he worked with J. B. French on theoretical problems in nuclear structure. Dr. Bansal is on leave from the Indian Atomic Energy Establishment in Bombay where he worked from 1955 to 1959. Publications by Dr. Bansal include:

Reduction of Cartesian Tensors and Its Application to Stochastic Dynamics, R. K. Bansal and E. C. G. Sudarshan, Nuovo Cimento 25, 1270 (1962).

Even Parity States in f 7/2 Shell Nuclei, Phys. Letters 11, 145 (1964).

Isobaric Spin Polarization Effects in Single-Particle Transfer Reactions, R. K. Bansal, Bull. Am. Phys. Soc. 9, 465 (1964).

Calculation of M_2 Life Times of $d_{3/2}$-Hole States in Scandium Isotopes (submitted to Phys. Rev. Letters).

Gerard M. Crawley, Research Associate.

Dr. Crawley received his Ph.D. in 1965 from Princeton University; his doctoral thesis was on inelastic proton reactions in the 1d-2s shell. Before going to Princeton, Dr. Crawley received an M.S. degree from the University of Melbourne (Australia) where he worked on photo-neutron reactions. Publications by Dr. Crawley include:

Emission of Photo-neutrons from Natural Lithium, F. R. Allun, G. M. Crawley, and B. M. Spicer, Nucl. Phys. 51, 177 (1963).

Inelastic Proton Scattering in the 2s-1d Shell, G. M. Crawley and G. T. Garvey, Bull. Am. Phys. Soc. 9, 665 (1964).

George H. MacKenzie, Research Associate.

Dr. MacKenzie received his Ph.D. degree in 1965 from the University of Birmingham; his experience at Birmingham includes a variety of both accelerator work and nuclear physics. (Due to a filing error a list of Dr. MacKenzie's publications is not presently available.)

DEGREE RECIPIENTS AND THESIS TITLES

Doctoral.

J. W. Beal, Ph.D., Aug., 1964, Studies of Beam Deflection from a Three Sector Cyclotron.

R. J. Krisciokaitis, Ph.D., June, 1965, The L-Auger Spectrum of ^{113}In as Derived from the Electron Capture Decay of ^{113}Sn.

L. J. Velinsky, Ph.D., Dec., 1964, Iron-Free Double Focusing Beta-Ray Spectrometer.

Masters.

J. E. Stover, M.S., Sept., 1960, Rapid Transversal of 3/3 Radial Resonance Near the Center of a Sector-Focused Cyclotron.

B. T. Smith, M.S., Dec., 1960, Magnetic Field Due to a Circular Current.

M. L. Mallory, M.S., Sept., 1961, Temperature Dependent Luminescence in $CaWO_4$ and $CdWO_4$ Crystals.

W. S. Hudec, M.S., Sept., 1961, Effects of Field Imperfections on Radial Stability in a Three-Sectored Cyclotron.

David Goss, M.S., 1961, Correction for Electron Escape from Self-Scintillating Crystals with Applications to the Beta-Decay of ^{40}K.

Rasool Javahery, M.S., 1961, A Study of a Parallel Plate Ionization Chamber.

Delmar G. Parker, M.S., 1961, An Experimental Investigation of the Mean Lifetime of the 1.114 MeV Excited State of ^{65}Cu.

J. W. Beal, M.S., June, 1962, The Electric Field of an Idealized Dee Geometry and Its Effects on Cyclotron Orbit Properties.

Ronald L. Auble, M.S., 1962, A Survey of Angular Correlation Theory with an Application to ^{121}Te.

Ricardo S. Pascual, Jr., M.S., 1962, The Search for the Weak 1.14 MeV Gamma Ray of ^{115m}Cd and a Literature Research on ^{96}Tc, ^{119}Te and ^{121}Te.

J. A. Futhey, M.S., Aug., 1963, A Thermoelectrically Cooled Hall-Effect Magnetic Field Probe.

R. E. Berg, M.S., Aug., 1963, Magnetic Coil Design for a Superconducting Air-Cored 40-MeV Cyclotron.

M. A. Dalverny, M.S., Oct., 1963, Investigations of Central Region Orbits in an Isochronous Three-Sectored Cyclotron with 180° Dee Geometry Using SILAX Orbit Program.

Daniel A. Gollnick, M.S., 1963, An Experimental Determination of the Decay Energy of ^{131}Ba and ^{121}Te.

Louis M. Beyer, M.S., Dec., 1963, no thesis.

K. Kosaka, M.S., Dec., 1964, First Order Study of Some Beam Analyzing Systems for a Medium-Energy Cyclotron.

John M. Gonser, M.S., 1964, Measurements of Nuclear Resonance Fluorescence on the 1.27-MeV Level of ^{116}Sn.

Raymond L. Kozub, M.S., March, 1964, no thesis.

Han Ki Sup, M.S., June, 1964, no thesis.

Marilyn A. Velinsky, M.S., Dec., 1964, no thesis.

Kenneth M. Thompson, M.S., June, 1965, no thesis.

PUBLICATIONS (1964-65)

The publications and reports listed below are by project personnel and include those that have appeared in print or that have been submitted for publication since the last progress report (June, 1964). APS abstracts are cited only for cases where formal reports or publications have not yet been prepared. (Publications based on work performed by staff members while at other institutions are included marked with an asterisk and with names of M.S.U. staff members underlined.)

Publications of Drs. Atneosen, Austin, Bansal, Crawley, and MacKenzie have been listed in a previous section and are, therefore, not included here.

Articles.

*Scattering of Polarized d-T Neutrons from Helium, R. L. Walter, W. Benenson, T. H. May and C. A. Kelsey, Nucl. Phys. 59, 235 (1964).

Sectored Cyclotrons, H. G. Blosser, IEEE Transactions, June, 1965.

Focusing Air-Core Magnetic Channel for the M.S.U. 55-MeV Cyclotron, R. E. Berg and H. G. Blosser, IEEE Transactions, June, 1965.

*Thresholds for (p,n) Reactions on 26 Intermediate Weight Nuclei, C. H. Johnson, C. C. Trail, and A. Galonsky, Phys. Rev. 136, B1719 (1964).

*Shell Model States and Configuration Mixing in the Ti Isotopes by the (p,d) Reaction, E. Kashy, and T. W. Conlon, Phys. Rev. 135, B389 (1964).

*Shell Model States in ^{49}Ca, E. Kashy, A. Sperduto, H. A. Enge and W. W. Buechner, Phys. Rev. 135, B865 (1964).

*The Reactions ^{103}Rh(p,d)^{102}Rn and ^{103}Rh(p,t)^{101}Rh at 16.8 MeV, K. S. Thorn and E. Kashy, Nucl. Phys. 60, 35 (1964).

*Preparation of Germanium Detectors, E. Kashy and M. E. Rickey, Rev. Sci. Instr. 35, 1364 (1964).

*Levels in ^{101}Rh Populated by the Decay of ^{101}Pd, J. S. Evans, E. Kashy, R. A. Naumann and R. F. Petry, Phys. Rev. 138, B9 (1965).

A Study of the Excited States of ^{127}I Populated in the Decay of ^{127}Te and ^{127m}Te, R. L. Auble and W. H. Kelly, Nucl. Phys., to be published (1965).

Cyclotron Ion Source Testing Facility, M. L. Mallory and M. Reiser, IEEE Transactions, June, 1965.

*Study of the ^{40}Ca(α,2α) Reactions, R. W. Bauer, G. Heymann, W. Kossler, N. S. Wall, and C. R. Gruhn, Rev. Mod. Phys. 37 No. 3, 369 (1965).

Papers Presented at Meetings.

Invited Paper.

Sectored Cyclotrons, H. G. Blosser, 1965 Washington, D.C. Particle Accelerator Conference.

Contributed Papers.

*Study of the ^{40}Ca(α,2α) Reactions, R. W. Bauer, G. Heymann, N. S. Wall, and C. R. Gruhn, Proc. Conf. on Nucl. Structure, Gatlinburg (Oct., 1964), to be published.

Relative Intensities of Internal Conversion Lines in ^{137m}Ba and ^{210}Bi, L. J. Velinsky, M. A. Velinsky, and S. K. Haynes, Proc. U.U.P.A.P. Conf. on Internal Conversion Process, Vanderbilt University, (1965), to be published.

The M.S.U. $\pi\sqrt{2}$ Iron Free Beta-Ray Spectrometer and the ^{137}Cs Internal Conversion Lines, L. Velinsky and S. K. Haynes, Michigan Physics Teachers Association Meeting, (1964).

Postfocusing Acceleration Cell for $\pi\sqrt{2}$ β-Ray Spectrometer, R. J. Krisciokaitis and S. K. Haynes, Bull. Am. Phys. Soc. 10, 53 (1965).

*J-Dependence in the ^{56}Fe(p,d)^{55}Fe Reaction, C. A. Whitten, E. Kashy and J. P. Schiffer, Bull. Am. Phys. Soc. 9, 650 (1964).

*Angular Distribution Measurements from ^{20}Ne(d,p)^{21}Na and ^{22}Ne(d,p)^{23}Ne, D. J. Pullen, A. Sperduto and E. Kashy, Bu-l. Am. Phys. Soc. 10, 39 (1965).

*1 $d_{3/2}$ and 2 $s_{1/2}$ Hole States in ^{47}Ca, E. Kashy, T. W. Conlon and B. F. Bayman, Bull. Am. Phys. Soc. 10, 70 (1965).

*Energies of T = 1 States of ^{24}Mg, ^{28}Si, ^{32}S and ^{40}Ca, M. E. Rickey, E. Kashy, and D. Knudsen, Bull. Am. Phys. Soc. 10, 550 (1965).

*Collective Features in ^{131}Cs, D. J. Horen, W. H. Kelly, J. M. Hollander and R. L. Graham (Comptes Rendus du Congrès International de Physique Nucleaire, Paris, 2-8 July, 1964) Vol. II, Paper 3b(I)/C154, (1964).

*The ^{12}C(p,d)^{11}C Reaction at 36 MeV, W. H. Kelly, C. A. Ludemann and C. D. Goodman, Bull. Am. Phys. Soc. 10, 121 (1965).

*States in ^{87}Y and ^{88}Zr, C. D. Goodman, C. A. Ludemann, W. H. Kelly, Bull. Am. Phys. Soc. 10, 27 (1965).

*Levels in ^{88}Y, C. A. Ludemann, C. D. Goodman, and W. H. Kelly, Bull. Am. Phys. Soc. 10, 122 (1965).

Reports.

*Neutrino Fluxes without Focusing and with "Ideal" Focusing, A. Galonsky, MURA-698 (Sept. 3, 1964).

MSUCP-20, Central Geometry and Initial Orbits in the M.S.U. Cyclotron, M. Reiser (June, 1964).

MSUCP-21, Studies of Beam Deflection from a Three-Sector Cyclotron, J. W. Beal (Aug., 1964).

MSUCP-22, Magnetic Field Measurements on the M.S.U. Cyclotron Main Magnet, R. E. Berg (in press).

COST ESTIMATES

For the year December 15, 1965 to December 15, 1966, the National Science Foundation is requested to grant $550,000 in support of the proposed program of research; Michigan State University for this period will provide program support estimated at $369,000. An itemization of estimated costs for the year is given in Table III.

Some explanation of the various items in Table III is perhaps useful. First of all it should be noted that all project personnel, including faculty, are on twelve-month appointments. (Faculty duties do, however, follow the normal academic pattern, i.e., combined research and teaching in the academic year and full-time research in the summer; teaching loads are on a one course per faculty member basis.) With the exception of Professor Haynes who is paid entirely from University funds, all faculty are paid 40% from the N.S.F. grant and 60% from University budgets throughout the year. For comparison with conventional academic salary arrangements 2/11 (or 18%) of the twelve-month salary could be considered as a summer salary; if this is considered as paid entirely by N.S.F., an N.S.F. academic year contribution of 22% of the twelve-month salary or 27% of the ten-month salary results.

The "Research" item in Table III represents the four Research Associates presently on the staff plus one vacant position. The Administrative-Professional item represents the project Chief Engineer and Administrative Assistant.

TABLE III

Proposed budget for year December 15, 1965 to December 15, 1966.

		NSF	MSU
A.	Wages & Salaries - Full Time Personnel		
	Faculty	64,870	119,705
	Research	45,540	——
	Administrative-Professional	8,840	13,900
	Clerical-Technical	25,595	2,425
	Regular Labor	81,660	16,920
		226,505	152,950
B.	Fringe Benefits		
	TIAA	7,371	13,360
	Social Security	4,681	1,931
	Retirement	5,363	967
		17,415	16,258
C.	Wages & Salaries - Students		
	Graduate	72,000	——
	Undergraduate	32,000	——
D.	Electricity (Cyclotron)	20,000	——
E.	Supplies	37,500	6,000
F.	Travel	7,500	——
G.	Publications	3,500	——
H.	Equipment	22,000	6,000
I.	Computer: 100 hours @ $400/hour	20,000	20,000
J.	Overhead (53.72% of A + C, NSF 20% of subtotal)	91,667	168,045
	TOTAL (Rounded)	550,000	369,000

The Clerical-Technical item includes the project secretary, a computer programmer, and an assistant engineer. The Regular Labor item covers machine shop, electronics shop, drafting room and operating personnel (14 persons total).

Considerable question has been raised in past discussions of project budgets as to whether the labor force was too large. In response to N.S.F. suggestions this force was reduced in early 1965 from 15 persons to 12 persons (one machinist, one draftsman, and one cyclotron operator cut) on a trial basis. Most of the reduction proved an illusory economy. The 50% cut in the drafting room staff, for example, resulted in faculty and graduate students spending considerable time on drafting. In addition, lab operation was noticeably less efficient (much more arm-waving and back-of-the-envelope designing with according increase in errors). The machine shop cut produced a rapid increase in the shop backlog and as a result it was necessary to increase outside procurement. Unfortunately, outside machine work is seldom an economy—for most items the special experience and facilities accumulated in the Laboratory during the construction of the cyclotron make internal fabrication much more efficient. Quadrupoles are a prime example—internal fabrication costs including all labor are running at approximately 50% of the cost of less-good commercially available units. As a result of these facts and after discussion with N.S.F. the machine shop and drafting room were recently restored to their previous size, bringing the labor force to its present level of fourteen.

Particularly in view of the results of this trial, for this Laboratory, the present staff distribution (faculty, labor, graduate assistants, etc.) is believed to be well optimized as regards maximizing scientific progress from given resources; budget estimates have, therefore, been made on the basis of maintaining this distribution. It should though be specifically noted that we intend on a continuing basis to maintain very close monitoring on this question—if at any time a redistribution of staff appears reasonably likely to improve overall efficiency appropriate adjustments will be made.

Approximately 30 graduate students are expected to work with the project. Graduate Assistantships are estimated on a basis of twenty students, each holding a half-time assistantship for the academic year and a full-time assistantship for the summer. The remaining ten students hold fellowships of various kinds. Undergraduate assistance is estimated on the basis of 20,000 hours at an average cost of $1.60 per hour.

The electricity item is for the cyclotron only and is listed as a direct charge in accord with established regulations on "unusual expense" overhead-type items.

Budget items for supplies, travel, publications and computer are based on present cost experience. Equipment items include aberration correction power supplies and a refrigerated baffle both for the $\pi\sqrt{2}$ spectrometer, an additional one parameter pulse height analyzer for counter testing, setup work, etc. and additional amplifiers, preamps, and coincidence circuitry for the main data room.

For the four-year period from December 15, 1966 to December 15, 1970, annual N.S.F. grants of \$640,000, \$700,000, \$730,000 and \$760,000 are requested, the estimates anticipating two additional faculty members in 1966-67, one in 1967-68 and none thereafter. Detailed budgets for these years will be submitted on an annual basis with revisions and updating to conform to program developments.