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PROPOSAL

FOR

SUPPORT

OF THE

NUCLEAR PHYSICS PROGRAM

OF THE

MICHIGAN STATE UNIVERSITY
CYCLOTRON

AUGUST, 1970

PROPOSAL
to the
NATIONAL SCIENCE FOUNDATION

for

SUPPORT
OF THE
NUCLEAR PHYSICS PROGRAM

of the

MICHIGAN STATE UNIVERSITY CYCLOTRON

from

January 1, 1971
to
December 31, 1975

by
Project Staff

Department of Physics
Michigan State University
East Lansing, Michigan

August, 1970

ENDORSEMENT

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

Henry G. Blosser
Professor of Physics
Director, Cyclotron Laboratory

Roger E. Wilkinson
Vice President for
Business and Finance

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INTRODUCTION

INTRODUCTION

This proposal requests funds for support of the nuclear physics program of the Michigan State University Cyclotron Laboratory for the period January 1971 through December 1975. We expect in this period to make important basic contributions to fundamental understanding of the nucleus and also in a lesser way to contribute to other areas of research and to the application of nuclear techniques to applied problems.

Since most details and even some broad outlines of the research projects which we will conduct over this extended time period can not be accurately anticipated, the justification for our request for support must rest primarily on an assessment of the quality of our staff and of our complex of facilities. In our view, immediate past performance is the soundest and most objective evidence of this quality, and an extensive part of this proposal is therefore devoted to a review of the accomplishments of the laboratory in the five year operating period now being completed. This review, we feel, emphatically evidences both the skill and the energy of our research staff. Discussion of our future plans to the extent we now know them is included in the review of various research topics. We feel this improves the continuity and coherence of the presentation as compared to the alternate arrangement of reviewing future plans in a separate major section.

The merits of our nuclear research facilities are also relevant to an evaluation of the likely productivity of the laboratory in the coming five years. Our facilities as they now exist have a number of capabilities presently unmatched elsewhere (as far as we are aware), particularly in the area of high precision study of nuclear reactions. These capabilities and further improvements to the instrumentation which are under study should make it possible for our staff to be even more productive in the coming years. We feel it noteworthy that the special capabilities of our research facilities are very substantially the result of our own work and that the capital construction of the facilities has been accomplished at a cost which is low in comparison with typical costs of comparable facilities. (Cyclotron $960,000, computer $630,000, beam transport and shielding $380,000, other experimental equipment $535,000.) Our facilities should also allow us to further expand the substantial number of collaborative experiments conducted jointly with scientists from other universities.

Since the research review sections of this document are, in our view, the primary attestation of the quality of our staff, we have omitted the usual scientific resumes for all of the staff except Dr. Jerry Nolen who will be joining us as of next month and has hence not participated in the preparation of this document. (Dr. Nolen will be filling a position provided by an NSF Science Development Grant to the University.)

As in the past a detailed budget is included only for the first year of the five year period. The budget is based on maintaining the group at its present level, the addition of Dr. Nolen being more than offset by reductions in research associates and graduate assistants. Nevertheless the total sum requested for 1971 ($819,500) is 9% higher than our 1970 budget. Most of this increase is due to changes in overhead regulations which give a 1971 overhead charge which is 20% above 1970 even though the 1971 salary total is slightly lower. Estimates of our needs in the years 1971-75 are based on maintaining our staff at its present size, presuming that costs will continue to increase at a rate of approximately 8% per year.

We hope very much that funds will be available to allow us to maintain our present program level. In the last four years our supporting staff has been reduced by about one-third even though our total operating grant for this year is nearly the same as that of four years ago. The large reduction in supporting staff was forced by the combined effect of (a) cost escalation, (b) the change in NSF overhead policy which in practice has increased the overhead charge to the grant by 66% in four years, and (c) the fact that many budget items are fixed commitments and cuts therefore tend to fall preferentially on the supporting staff. If funds are not available to cover our full request, cuts will again necessarily fall predominantly on the supporting staff and lead, we fear, to a significant reduction of overall efficiency.

RESEARCH PROGRAM

RESEARCH PROGRAM

In the following sections of this proposal we summarize the advances in understanding of the structure of atomic nuclei that have resulted from research performed in the Michigan State University Cyclotron Laboratory in the previous five years. We also discuss current research programs and their motivations and goals, and, to the extent that our foresight allows, describe the probable paths of investigation that will be pursued in the coming years.

It is a central feature of nuclear physics that an understanding of one of its special branches is intimately tied to understanding in other areas of the discipline. For this reason, the decomposition and segmentation of the science into topics of specialization is almost as inimicable to its essence as it is necessary to a presentation such as we are attempting here. With this caveat, we proceed with a topical outline of our research. It will fail, necessarily, to mention all of our activities, let alone to establish all of the vital interactions between past research and present, between theory and experiment, between complementary but independent studies of the same basic phenomena, and between technical innovation and the discovery of new basic phenomena, which together give a coherent amplification to the productivity of our laboratory beyond the sum of the various individual contributions.

We shall discuss the fundamental research in nuclear physics which is carried out in the laboratory in two large sections entitled "Reaction Studies" and "Decay Studies" and in two shorter sections entitled "Nuclear Structure Calculations" and "Astrophysical Studies". Research directed towards areas outside nuclear physics that has been carried out in the laboratory with the aid of techniques and equipment developed for nuclear studies is discussed in a section called "Applications of Nuclear Techniques". Finally, our extensive and vital program of research designed to keep our laboratory in the vanguard of technical expertise is described in a section entitled "Research Facilities".

I. REACTION STUDIES

In this section we discuss our work with those nuclear processes which are investigated simultaneously with the bombardment of the target nuclei by the cyclotron beam. Primary interest in these studies can be directed to the particular reaction process itself or to the residual nuclear systems that are formed by the beam-induced reaction. The section is subdivided under the topical headings of "Transfer Reactions", "Inelastic Scattering Reactions", and "Isospin Studies and Charge Exchange Reactions".

The research to be discussed is, of course, primarily experimental in nature. In general, however, the experiments were conceived in relation to specific or general theoretical questions in nuclear physics and must be discussed in those terms. Our laboratory staff has enjoyed close collaborative relationships with members of the MSU Nuclear Theory Group (who have their offices in a wing of the Cyclotron building), as well as with a diverse group of theorists from all over the world, and these interactions have contributed vitally to progress in both experiment and theory. Also, the cyclotron staff has itself been quite active in that ill-defined but vital no-mans-land which lies between the energies and cross-sections measured by the experimentalist and the reduced matrix elements, nuclear potentials, and wave functions calculated by the theorist.

In this intermediate area fall, for example, the problems covering the analysis of angular distributions of reaction intensities with the distorted wave Born approximation (DWBA) theory, this job typically being allocated to the experimentalist's domain. An example from the theorist's side is the calculation from nuclear model wave functions of spectroscopic factors for comparison with the intrinsic transition strengths obtained from DWBA analysis of nuclear data. Active research in these "transition" areas aids in cross-fertilization between theory and experiment and is highly beneficial to the basic growth of both areas.

The central dilema facing the physicist studying nuclear reactions is that in order to straightforwardly attack the question of "the structure of nuclear energy levels as revealed by nuclear reactions" he must first have a complete theory describing the interactions of high-velocity nuclei of hydrogen or helium isotopes with more complex nuclei. But, in order to construct definitive reaction theories, he must first know the "frame work" of the reaction, namely the quantitative descriptions of the initial and final nuclear states involved in the process.

This basic quandary can be viewed as illustrating Niels Bohr's philosophical proposition that a generalized version of the principle of complementarity is to be found manifested in all well-articulated fields of knowledge. This complementarity between "reaction process" and "nuclear structure" is, in fact, a key source of creative tension in the study of nuclear physics. Some of the individual research programs to be discussed in this section have been principally directed towards elucidating the problem of the reaction mechanism, others, in so far as possible, towards the goal of extracting knowledge about nuclear wave functions from the reaction data. The two aspects of the problem can never be completely divorced, however.

I.A. Transfer Reactions

Direct reactions, in which from one to four nucleons are transferred between the initial and final nuclear states, constitute one of the most important sources of information from which we presently derive our knowledge of nuclear structure. The word "direct" refers to the essential feature of this class of processes, namely that the transfer of the nucleon(s) takes place without disturbing the arrangement of the remaining nuclear configuration. Thus, if a theory is available which adequately accounts for the "mechanism" aspects of the reaction data, the appropriately analyzed data provide experimental values for the matrix elements of one-body (or two-body, etc.) creation or annihilation operators, taken between the target wave function and those of the various residual states. Not only do such data relate the structure of specific nuclear states to one another, and thus serve as a test of theoretical predictions for the wave functions of these states, but, taken in the aggregate, they also provide fundamental information about the occupation probabilities of the quantum orbits of individual nucleons which constitute the target state.

I.A.1. The (p,d) Reaction—The transfer reaction that has been utilized most extensively by investigators in our laboratory is the (p,d) neutron pickup process. Starting with a target of ${}^{Z}_{N}(A)$, the reaction populates various eigenstates of the system ${}^{Z}_{N-1}(A-1)$. The shapes of the angular distributions of the intensities of the deuterons emitted in populating the various residual levels provide indices for identifying the angular momenta "ℓ" of the neutrons which are transferred between the initial and the final states. And, as mentioned, the transition intensities are dependent upon the structural relationships between initial and final states. Strong transitions indicate that the wave functions of the residual states resemble wave functions obtained by applying one-body annihilation operators of the appropriate quantum numbers to the target state. The analysis of both the shapes of the (p,d) distributions and their intensities involve the DWBA theory of direct reactions.[a]

The (p,d) studies which we will discuss can be grouped according to the energy resolution which was achieved in measuring the deuteron spectra. The initial experiments were made before the installation of the H^+ beam extraction system by using single-turn stripping extraction of the H^- beam. Resolutions obtained in this era were ∿100-150 keV FWHM and with this capability, the typically widely-spaced level structures of 1p-shell nuclei and of some 1d,2s-shell nuclei (using the standard nomenclature of the nuclear shell model) were amenable to investigation.

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a. R. H. Bassel, R. M. Drisko and G. R. Satchler, Oak Ridge National Laboractry Report No. ORNL-3240 (unpublished).

In the 1p-shell, targets of ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{14}N, ^{15}N, and ^{16}O were bombarded and the level structures of the various residual nuclei formed by (p,d) were studied.[42,55,80,106,107] The theory of the nuclear structure of the 1p-shell is well developed, with the work of Cohen and Kurath[a] a prototype of a successful, comprehensive shell-model calculation. The relative values of the (p,d) spectroscopic factors extracted from the 1p-shell data via DWBA analysis were in generally good agreement with the theoretical predictions, thus contributing a strong affirmation of the approach used in calculating the model wave functions. Only in the case of the 2^+ and 3^+ doublets of ^{8}Be were there serious differences between calculation and experiment. These are the well known cases where the isospin of the levels involved have large T=0 and T=1 mixings. Another general conclusion of these studies was that no evidence existed of significant 1d,2s-shell admixtures into the ground states of ^{6}Li, ^{7}Li, and ^{9}Be.

The fact that reactions such as (p,d) selectively populate a few states quite strongly makes it possible to identify previously unassigned levels in experimental spectra with model states which have been predicted to have the appropriate energies and spectroscopic factors. For example, the $3/2^-$ state in ^{13}N predicted by Cohen and Kurath to occur at 10.6 MeV with a large spectroscopic factor of 1.2 is identified beyond reasonable doubt as the strong (S=0.7) ℓ=1 level observed in the ^{14}N(p,d)^{13}N spectrum at 11.80 MeV.[42]

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[a] S. Cohen and D. Kurath, Nucl. Phys. 73(1965)1.

The original orientation of the p-shell studies emphasized the extraction of information about the structure of the initial and final nuclear states. During the course of the work it became apparent that the standard DWBA calculations did not adequately account for the observed shapes of the angular distributions. This problem reduces confidence in absolute values of the extracted spectroscopic factors, although the relative values are presumably still reliable. These difficulties led to a reaction-mechanism oriented study[106] of the $^{16}O(p,d)^{15}O$ reaction at bombarding energies from 21 to 45 MeV. This study indicated that indeed the standard (local, zero-range) DWBA theory has difficulty in correctly predicting the behavior of those (p,d) transitions in light nuclei which are characterized by large negative Q-values. Much of the trouble seems to arise from excessive contributions to the theoretical cross-sections which arise from the nuclear interior. Analysis has shown[134] that corrections for non-locality and finite range, together with a smooth damping of the contributions from the nuclear interior which is consistent with a density-dependence of the nuclear interaction, strikingly improve both the internal consistency of the calculated reaction cross-sections and their agreement with experiment. The changes which result in the shapes of the calculated angular distributions from these modification are shown in Fig. I-1, and in Table I-1 we list the spectroscopic factors extracted from the data to show how the modifications of the analysis yield values much more consistent with our basic understanding of the nuclear shell model.

Our study[107] of the $^{15}N(p,d)^{14}N$ reaction provides a good example of the kind of information that can be obtained from this sort of investigation, and of its importance. In this experiment the results of the $^{16}O(p,d)$ study were used as a guide to the selection of both the bombarding energy and the parameters used in the DWBA analysis. In addition, a precise study[309] of the $^{14}N(d,d)$ process was executed to assure that the deuteron optical model potential needed for the DWBA calculations could be fixed with the same reliability as the proton potential. Fig. I-2 shows the deuteron spectrum measured at 19.9° aligned with the energy level diagram of ^{14}N. The experimental spectrum, with the relatively few levels strongly excited, again illustrates the selectivity of the (p,d) reaction. The levels populated have positive parity and configurations of the type $(1s)^4(1p)^{10}$. These states can be easily reached by removing a neutron from the ground state of ^{15}N, as is indicated in the simple diagram shown in Fig. I-3. A comparison between theoretical and experimental spectroscopic factors is shown in Fig. I-4. There is rather good agreement except that there are seven strong transitions seen experimentally while only six are predicted from the 1p-shell-model. The extra populated level arises from the mixing of the $(1s)^4(1p)^{10}$ $J=2^+$, $T=1$ state with the $(1s)^4(1p)^8(1d)^1(2s)^1$ state of the same (J,T,π) which lies nearby.

In this same "100 keV" generation of (p,d) experiments, the "alpha-particle" nuclei of the 1d,2s shell, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, and ^{40}Ca, and also, ^{22}Ne, were studied.[83,300] From this work emerged the patterns of how the $1d_{5/2}$, $2s_{1/2}$, and

$1d_{3/2}$ orbits of the 1d,2s shell are filled as the nuclear mass increases. Also, much information about the detailed level structures of the residual nuclear system was obtained, from which the relevant predictions from theoretical structure studies could be tested. For example, the results of the $^{28}Si(p,d)^{27}Si$ experiment, when compared to simple shell model[91] and simple rotational model[90] predictions as in Table I-2, illustrate the advantages in this situation of the shell model representation, with its six active 1d,2s-shell neutrons, over the two-particle space of the rotational representation.

With the advent of positive ion extraction and with a general improvement in instrumentation, the typical resolutions obtained in (p,d) experiments approached 50 keV FWHM. With this improvement in technique, more densely packed energy-level systems could be investigated. In the 1d,2s shell, the target nuclei ^{34}S, ^{35}Cl, and ^{37}Cl have been studied[302] in an experimental project designed to complement and test the recent comprehensive and (to date) apparently successful shell-model theory developed for this region in a collaboration between physicists from our laboratory and from Oak Ridge National Laboratory.[95,153] The comparison of experimentally extracted and theoretically predicted spectroscopic factors shown in Table I-3 indicates that the model wave functions seem well grounded to experimental reality, but further detailed study of the dense spectrum of higher excited states is needed to thoroughly delimit the range of validity of the model.

The 1f,2p shell was also represented in this "50 keV" generation of experiments. A thorough "mechanism' and "structure" study[148] of the (p,d) reaction on the titanium isotopes ^{46}Ti, ^{48}Ti, and ^{50}Ti was carried out at bombarding energies from 25 to 45 MeV. It was found that corrections for finite range and non-locality in the DWBA analysis made possible the extraction of consistent spectroscopic factors independent of bombarding energy. Remaining problems in satisfying sum-rule requirements with respect to groups of levels with $T=T_z$ and $T=T_z+1$ seem definitely attributable to the problem of correctly handling the Q-value dependence of the DWBA form-factor.

In our latest generation of (p,d) experiments we make use of either the ultimate capabilities of solid-state detector technology or of our new Enge split-pole spectrograph to achieve resolutions in the range 5 to 25 keV FWHM for 30 MeV bombarding energies. With these advanced capabilities, a systematic study[308] has been made of neutron pickup from the N=82 nuclei ^{138}Ba, ^{140}Ce, ^{142}Nd, and ^{144}Sm. Analysis of these experiments indicates that the nucleon orbits above N=82 are effectively unoccupied, i.e., the shell closure at neutron number 82 is quite good. The details of the results give a comprehensive picture of how the hole strength for the orbits of the N=50-82 major shell are distributed and fragmented as a function of the proton excess above Z=50.

The multiple attributes of the Enge magnet make it an ideal instrument for pursuing future ultra-high resolution, precision (p,d) experiments. The ultimate in energy resolution is necessary for studying the closely spaced energy-level spectra of most heavy nuclei and of odd-odd nuclei in general. Odd-odd nuclei will occupy much of our attention because it has become apparent that the most critical and sensitive predictions of nuclear structure theories occur in these systems. In addition to the typically dense spectra of odd-odd nuclei, the non-zero spins of the target nuclei involved in their formation via (p,d) allow the possibility for many final states to be formed by more than one ℓ-value for the transferred neutron, thus yielding angular distributions which are mixtures of the shapes for single ℓ-values and which are consequently much more difficult to analyze. Accurate data at small angles is vital to resolve such problems, and the Enge magnet, by virtue of the fact that forward angle transfer data can be recorded without undue interference from high counting rates from the elastically scattered beam particles, again is ideally suited for such investigations. Initial use of the capability has been to further investigate the details (very forward angles and possible doublets) of the ^{35}Cl and ^{37}Cl reactions. These preliminary studies should serve as prototypes for future investigations of other odd-odd nuclei.

II.A.2. <u>The (p,t), (p,^{3}He), and (p,α) Reactions</u>—The same alpha-particle nuclei of the 1d,2s shell which were studied with the (p,d) reaction were subsequently made the object of an investigation[264] utilizing the unique spectroscopic properties of the (p,t) reaction. The requirement that the pair of neutrons transferred in this process occupy a J=0, T=1 configuration leads to a one-to-one relationships between the orbital angular momenta L transferred with the neutron pairs and the spins of the residual levels formed by bombardment of J=0 targets. Since the angular distributions of this reaction are sensitive functions of L, this series of experiments yielded a number of unambiguous spin-parity assignments for energy levels of the relatively unexplored nuclei ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, and ^{38}Ca.

Detailed calculations to obtain spectroscopic factors from measured (p,t) differential cross-sections are difficult and highly sensitive to the parameters of the optical model and bound-state potentials. In addition, the transition intensities, unlike those of single-nucleon transfer, are sensitive to small configuration admixtures in the nuclear wave functions. For these reasons, considerable effort must be expended to obtain meaningful information about spectroscopic factors and hence about the nuclear structure of the levels involved in the reaction. With the new availability of sophisticated nuclear model wave functions (see Sec. III) and improvements in the DWBA theory for this sort of process, the (p,t) reaction should, in the future, enable us to probe the makeup of nuclei in a new, different, and more demanding way. From the experimental aspect, the availability of the split-pole spectrograph will, for the same reasons mentioned in the (p,d) discussion, provide data of higher quality and greater range than we have previously been able to obtain.

In contrast to the difficulties of detailed DWBA analysis of (p,t) data, simple comparisons of (p,t) and (p,^{3}He) spectra and distributions from the same target can often yield extremely interesting information. We have employed this technique, in colloboration with scientists from Princeton University, to study the T=1 and T=2 levels of ^{56}Ni and ^{56}Co through the (p,t) and (p,^{3}He) reactions on ^{58}Ni at E_p=34 MeV. (Obviously, this work could have been appropriately included in the subsection on Isospin Studies.) The items of interest in this study are the isobaric analogs of the T=2, $J^\pi=0^+$ ground state of ^{56}Fe (T_z=2). As has been seen[a] in ^{56}Fe(^{3}He,t)^{56}Co, the analog state appears in ^{56}Co (T_z=1) as a doublet spaced 70 keV apart, due to isospin mixing between it and an adjacent $J^\pi=0^+$, T=1 level. From the extent of the mixing, one can attempt to evaluate the strength of the off-diagonal matrix element of the isospin-nonconserving part of the nuclear interaction. The magnitude of this matrix element can then in turn be related to model wave functions for the states involved.[b]

To investigate this matter further, we undertook to find the analogue of this doublet in ^{56}Ni (T_z=0), where because of the different T_z, the net matrix element effecting the splitting is a different combination of vector and tensor terms. In addition we reinvestigated the ^{56}Co system, with the (p,^{3}He) instead of the (^{3}He,t) reaction.

The experiments are difficult because of the small cross sections ($\lesssim$20 μb/ster) and the high density of states in the regions of interest. In one of our first real experiments with the Enge spectrograph, the system worked beautifully in surmounting these problems. Spectra of the (p,t) and (p,^{3}He)

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a. T. G. Dzubay, R. Sherr, F. D. Becchetti, Jr., and D. Dehnhard, Nucl. Physics A142(1970)488.

b. G. Bertch, Nucl. Phys. A142(1970)499.

reactions products are shown in Figs. I-5 and I-6. The energy resolution in the triton spectrum approaches 10 keV FWHM.

Angular distribution measurements show that the states of the ^{56}Co doublet and ^{56}Ni states at 9.915, 9.991, and 10.021 <u>all</u> have L=0 shapes. Thus the expected T=2 doublet in ^{56}Ni appears to have been further fragmented by mixing with a $J^{\pi}=0^{+}$, T=0 state. Our experimental refinements have in this case led us out of the realm of the supposedly straightforward theoretical situation we originally thought to examine, and back into that uncomfortable state of uncertainty from which the next advance in our understanding must arise.

Other current (p,t) investigations in our laboratory have extended to the rare earth region. Comparisons of (p,t) excitations, with their enhancements for correlated neutron pairs, to the predictions of α-decay theories are being studied. Data have been obtained for a ^{141}Pr target and plans are to continue with targets of ^{159}Tb, ^{165}Ho and ^{169}Tm.

Among other transfer reactions which have been used to study the properties of nuclear states in our laboratory has been the (p,α) transfer process on ^{24}Mg and ^{26}Mg.[310] These experiments were prompted by the discovery[a] that the (p,α) reaction on a target of $^{Z}_{N+2}(A+2)$ yields results for the residual $^{Z-1}_{N}(A-1)$ system that are in many respects similar to what are (or would be) obtained from observation of the (d,^{3}He) reaction leading to the same $^{Z-1}_{N}(A-1)$ nucleus from a target of $^{Z}_{N}(A)$, if such were available. This work has been carried out in

[a] J. A. Nolen, Thesis, Princeton University, 1965.

collaboration with visiting scientists from Argonne National Laboratory. Pairs of states in ^{21}Na and ^{23}Na whose wave functions can be characterized as proton holes in the 1p shell coupled to the ground states of ^{22}Mg and ^{24}Mg, respectively, have been found to be strongly populated in these experiments. The j-dependence of the (p,α) angular distributions has enabled spins of $1/2^-$ to be assigned to the lower energy members of each pair, and $3/2^-$ to the higher energy members. These results are consistent with predictions of both rotational and shell-model theories and help clear up considerable experimental confusion that has clouded the nature of these states for some time.

New problems are also suggested by these experiments, in that there are some striking differences in average cross sections between the ^{24}Mg and ^{26}Mg targets. Further higher resolution study of the Mg targets and similar studies of ^{28}Si and ^{30}Si and ^{32}S and ^{34}S are planned in an attempt to isolate the source of these anomalies.

Taking advantage of the multi-particle, variable-energy capabilities of our accelerator, the (α,t), (α,^{3}He), (p,t), (p,^{3}He), (d,p), (^{3}He,d), and (p,α) reactions[254] on various targets, all leading to either ^{17}F or ^{17}O, have been measured. This study, which is almost completed, has yielded very extensive and interesting spectroscopic information on the single particle structure of the mass-17 mirror pair, and it is hoped that further analysis of the data will shed some light on core polarization effects in the mass-16 core due to the addition of the 17th nucleon. Detailed comparisons with the microscopic theory of the nuclear structure in this region will be undertaken in conjunction with the shell model studies discussed in Sec. III.

Other programs of transfer reaction studies in the laboratory include the (^{3}He,^{6}He) reaction on light nuclei, where the main interest, as is discussed in Sec. I.C.1, lies in the measurement of the masses of the T_z=-3/2 members of isospin quartets. In addition to this information, the angular distribution of ^{12}C(^{3}He,^{6}He)^{9}C at 68.5 MeV has been obtained. It shows strong evidence for the direct nature of the reaction.

I.B. Inelastic Scattering of Protons

The study of the inelastic scattering of protons from atomic nuclei has been another important area of research in our laboratory during the past five years. The investigations in this area may be classified either as "mechanism" oriented or "structure" oriented but, as in the case of transfer reactions, there is often strong mixing between the two directions of emphasis. An extended series of experiments and analyses has pursued the determination of the basic effective interaction, V_{eff}, which mediates (p,p') inelastic scattering and other fundamental nucleon-nucleus processes. These studies, together with some specific tests of particular aspects of reaction theories, will be discussed under the heading "The Effective Interaction". Investigations of the properties of a variety of nuclear energy levels via the (p,p') process will be discussed under the heading of "Nuclear Structure". The dominant theme of this series of studies has been the ambition to obtain descriptions of the experimental observations in terms of microscopic structure theories.

I.B.1. The Effective Interaction—In the microscopic model of inelastic proton scattering, the nuclear matrix elements $<\Psi_f|V_{eff}|\Psi_i>$ depend, of course, upon both V_{eff} and the wave functions of the initial and final nuclear states. In order to empirically investigate the properties of the V_{eff} we have therefore attempted to choose experimental situations in which there is good reason to believe that the nuclear wave functions are both simple and reasonably well established. In this way we hope to be able to isolate characteristics of V_{eff} and fix some properties of this very important aspect of nuclear reaction physics.

The following reactions have been studied in this program: ^{6}Li (p,p')^{6}Li(3.56 MeV) in the energy range E_p=24-46 MeV,[75,77] ^{7}Li(p,p')^{7}Li(0.478 MeV) and ^{7}Li(p,n)^{7}Be(0.431 MeV) in the energy range E_p=23-52 MeV,[53] ^{14}N(p,p')^{14}N(2.31 MeV), at E_p=24-40 MeV,[133] and ^{16}O(p,p')^{16}O at E_p=27-46 MeV.[165] The results have been used both to test theoretical values for V_{eff} predicted by the MSU Theoretical Nuclear Physics Group and, by assuming simple Yukawa shapes and standard ranges, to determine empirically the strengths of the V_{11}, V_{00}, and V_{10} parts of V_{eff}. It appears that the spin-isospin dependent interaction, V_{11}, does not vary significantly with proton energy in the range studied, and has a strength consistent with that obtained in other experiments and with theoretical expectations. The value of the central term, V_{00}, appears to decrease with increasing energy. Analysis of the ^{14}N data has also indicated the need for tensor contributions to V_{eff}.[133] Future (p,n) experiments are planned with our new time-of-flight system to attempt to settle the question of the energy dependence of V_{01}, a matter of some controversy at present.

That specific portion of the inelastic proton scattering process which involves the "flipping" of the spin of the proton can be studied in a model-independent theoretical framework by measurement of the correlation between scattered protons and the gamma rays emitted from a given $J^{\pi}=2^{+}$ excited state in a direction perpendicular to the (p,p') reaction plane. Such measurments, at $E_p=26$ and 40 MeV for the first excited state of ^{12}C, have been carried out and analyzed.[105] As has been observed at lower energies, the spin-flip probability peaks for large proton scattering angles. The observed data can be largely accounted for in the DWBA Theory by introducing deformations into the spin-orbit parts of the entrance and exit optical model channels. No definite conclusions regarding the spin-dependent part of the inelastic interaction could be reached from the ^{12}C data, possibly because of the inadequacies in the assumptions of the optical model for such light nuclei. It appears that meaningful information regarding the spin-dependence of the reaction mechanism producing the excited states can be obtained from spin-flip data only for those nuclei having well-determined optical model parameters. Accordingly work has been been undertaken[280] and is near completion on ^{120}Sn and ^{124}Sn.

Preliminary analyses indicate a general improvement in the ability of the DWBA approach to fit the observed data, but there are interesting differences between the two isotopes which are as yet unexplainable.

I.B.2. Nuclear Structure—A major concern of the nuclear structure investigations carried out in the inelastic scattering program has been the question of the extent to which core-polarizations contributions need to be included in the calculations of the theoretical cross sections in order to obtain agreement with experiment. Examinations[85,131] of ^{89}Y and ^{209}Bi, and a comprehensive[291,136,260] study of nuclei in the 1f,2p shell, specifically ^{40}Ca, ^{48}Ca, ^{50}Ti, ^{51}V, ^{52}Cr, ^{58}Ni, ^{60}Ni, ^{62}Ni, and ^{64}Ni, have provided a wealth of information on this topic. In collaboration with the MSU Nuclear Theory Group, it has been definitively established that with the use of (a) simple but reasonable wave functions for the nuclear states involved, (b) realistic values for V_{eff} and (c) core polarization corrections, the observed (p,p') phenomena can be theoretically accounted for. However, without the core polarization corrections, calculated cross sections are much too small. Dramatic evidence of the importance of the core can be seen from the results, presented in Fig. I-7, of the (p,p') reactions on ^{48}Ca and ^{50}Ti leading to the 2^+ first excited states. The striking similarity of the differential cross sections shows that the transition strength observed for ^{50}Ti can be accounted for almost entirely in terms of its ^{48}Ca core, with the contributions from the two extra protons outside this core being insignificant.

In most of these (p,p') investigations, particular aspects of the residual level structures were studied in addition to the general question of core polarization. We mention only the calcium data as an example. The ^{40}Ca results are being analyzed microscopically in collaboration with members of the Nuclear Theory Group in a fashion such that different effective interactions (Kallio-Kolltveit[a.] and Yukawa) and different sets of eigenvectors (T.T.S. Kuo[b.] and Gerace-Green[c.]) are tested. The selectivity of the reaction, evidenced by the sample spectrum shown in Fig. I-8, promises to provide distinctive criteria for choosing among the alternate nuclear models. The excited 0^+ state of ^{40}Ca at 3.35 MeV is being studied in particular detail because its angular distribution is expected to be especially sensitive to the form factor used in the DWBA calcuations[d.]. Finally a comparative optical model analysis of the ^{40}Ca and ^{48}Ca elastic scattering data has provided new information about the surface of these nuclei.[172]

As was the case for the transfer reaction experiments, the (p,p') experiments can be classified according to the experimental energy resolution with which they were executed. In the earliest studies, such as the Li(p,p') reactions, the final state particles were sometimes not observed directly at all, but rather de-excitation gamma rays from the excited states were detected. Resolutions of the order of 100 keV FWHM were achieved for the intermediate generation of experiments,

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a. A. Kallio and K. Kolltveit, Nucl. Phys. 53(87)1964.
b. T.T.S. Kuo, private communication.
c. W. J. Gerace and A. M. Green, Nucl. Phys. A113(1968)641.
d. G. R. Satchler, Nucl. Phys. A100(1967)481.

such as ^{89}Y(p,p'), these data being obtained by detecting the scattered protons in Si(Li) solid state detectors. A major breakthrough in solid state detector physics, accomplished in our laboratory[78] and described in more detail in Sec. VI.D., enabled the latest generation of experiments, those on the 1f,2p shell nuclei, to be performed with Ge(Li) detectors at resolutions in the range 30-40 keV FWHM. Under development at present, and sure to be a major factor in our future research, is an ultra-high resolution technique we have conceived[170] to take advantage of the unique attributes of the cyclotron itself and of the Enge magnet. With this system, described in Sec. VI.A., energy resolutions of the order of 5 keV FWHM, out of the 30 MeV, have been achieved, both for heavy (^{209}Bi) and light (^{27}Al) nuclei (see Fig. VI-1).

I.C. Isospin Studies and Charge Exchange Reactions

The concept of nuclear isospin has been exploited in a variety of experiments since the first observations of isobaric analogue states in medium weight nuclei by Anderson and Wong[a.] in the (p,n) reaction, and shortly after as resonances in proton elastic scattering by Fox, Moore and Robson[b.] A number of different experiments in this general area of nuclear physics have been and are being carried out at MSU and a summary of the important features are presented below.

[a] J. D. Anderson, C. Wong and J. W. McClure, Phys. Rev. 126(1962)2170.

[b] J. D. Fox, C. F. Moore and D. Robson, Phys. Rev. Lett. 12(1964)198.

I.C.1. Mass Measurements of Isospin Multiplets—A number of precise mass measurements have been directed at experimentally verifying the validity of the isobaric multiplet mass equation

$$M(T_z)=a+bT_z+cT_z^2.$$

This equation is predicted from a first order perturbation treatment of Coulomb interactions in the nuclear Hamiltonian. Its derivation is independent of nuclear model wave functions and requires only the assumption of a two-body charge-dependent force. Thus the necessity for a cubic term in the equation would imply a breakdown of the two-body assumption or of the perturbation treatment. Information on the charge symmetry and charge independence of nuclear forces may be obtained from the precise values of the coefficients a, b and c for a range of nuclei.

An experimental check of the mass equation requires knowledge of the masses of at least four members of an isospin multiplet; most information is available for the T=3/2 quartets in the 1p and 1d,2s shells. In most of these quartets the ground state T_z=-3/2 levels are least well known. A series of experiments, designed to measure these T_z=-3/2 masses with significantly greater precision than has hitherto been possible, is in progress.[150]

The nuclei of interest are formed with the (^{3}He,^{6}He) reaction. The experiments employ the Enge split-pole magnetic spectrograph which has a large solid angle for acceptance of reaction products but yet preserves good energy resolution in the detected spectra by virtue of the way in which it allows for compensation of the energy spread resulting from reaction kinematics. The ^{6}He particles are detected with position-sensitive solid state detectors in the focal plane of the magnet. Use of both the position and energy signal from these detectors permits unambiguous particle identification. An example of the identification of ^{6}He is shown in Fig. I-9. Both a large solid angle and good particle discrimination are crucial to the success of this experiment because of the very small cross sections for these multiple-particle transfer reactions.

The experiments involve calibration of the effective spectrograph field (at a particular radius of curvature) with respect to its NMR-monitored flat-field value, and calibration of the beam analysis system. Both of these calibrations are obtained simultaneously to an absolute accuracy of a few keV by a momentum matching method[149] (discussed in Sec. VI.A.2). This calibration of the spectrograph field and the beam analysis sytem then allows the ^{3}He beam energy and outgoing ^{6}He energies to be determined very accurately. After allowing for target thickness effects, the Q-values of the (^{3}He,^{6}He) reactions and hence the unknown masses can be determined.

Table I-4 lists the reactions studied so far, their measured Q-values and the resulting mass excesses, as well as the latest values published for these masses from other sources for comparison. A principal source of error in the data is the uncertainty in the energy loss in the targets.

Other contributions to the uncertainties arise from calibration of the spectrograph, statistical uncertainty in the centroids, scattering angle determination, etc.

Table I-5 displays the coefficients a (β,T), b(β,T) and c(β,T) of the quadratic mass equation obtained from a weighted-least-squares fit to the mass 9, 13, and 21 quartets. Adding a term d(β,T) T_Z^3 to the quadratic equation above and fitting the data as before, one obtains the values of "d" presented in this Table. Only the A=9 quartet shows any justification for a cubic term. In order to pursue this subject to a definite conclusion, additional measurements, of $T_z=-3/2$ masses from ^{25}Si to ^{37}Ca, are in progress.

I.C.2. (p,n$\bar{p}$) Reactions near A=208—The proton decays of the isobaric analogue states in the lead region are being studied[158,306] by the (p,n$\bar{p}$) reaction on targets of ^{209}Bi, ^{206}Pb, ^{207}Pb, and ^{208}Pb. The analogue states are formed by direct (p,n) charge exchange, and the subsequent proton decays ($\bar{p}$) are observed with solid state detectors. The work on bismuth has been completed and preliminary reports have been made on the lead measurements. One aim of this project is to measure the relative partial decay widths for all proton channels from the analogue states and to relate this data to the shell structure of the neutron orbits in the parent states.

An example of the data obtained in this type of experiment is shown in Fig. I-10. The spectra result from bombarding a ^{208}Pb target with protons (E_p=22.8 MeV) and observing emitted protons at two different angles relative to the beam direction. The three peaks labelled "$\bar{p}$" in the upper spectrum are the groups from the decay of the ^{208}Pb analogue state to the first three levels in ^{207}Pb. The same peaks appear at practically the same laboratory energy in the lower spectrum, although there they are partially obscured by contaminant peaks which shift in energy with changes in angle. Several prominent peaks from the (p,p') reaction on carbon and oxygen contaminants in the target are indicated in each spectrum.

These data are analyzed under the assumption that each observed decay channel (corresponding to a particular level in the residual nucleus) contributes to the spectrum a Lorentzian line shape with a total width proportional to the analogue state and an intensity proportional to its partial proton decay width. The (p,n$\bar{p}$) results for ^{208}Pb and ^{209}Bi are consistent with each other, as the independent particle model would predict, but differ significantly in some respects (the extracted width of the $f_{5/2}$ channel) from resonance-type experiments designed to extract the same information.

The Coulomb displacement energy for each nucleus can also be extracted from the measured decay energies. New values have been obtained for ^{206}Pb and ^{209}Bi. (The resonance-scattering method for obtaining these numbers would require the unstable targets ^{205}Pb and ^{208}Bi.) The Coulomb energy for ^{209}Bi is found to be 18.92±.03 MeV and the preliminary results for ^{206}Pb is 18.98±.07 MeV.

I.C.3. An Isospin Forbidden Analogue Resonance in the Compound Nucleus ^{210}Po—For several years, many experimental groups, particularly those at laboratories with Van de Graaff accelerators, have studied unbound analogue states as compound nucleus resonances in proton scattering. With the exception of some work in light nuclei, all of these resonances are characterized by the isotopic spin quantum number $T=T_z+1$. Such resonances in nuclei with a neutron excess always have one or more open proton decay channels which are called "isospin-allowed" channels because the total isotopic spin can be conserved in the decay. In one of the recently initiated projects in our laboratory we have undertaken a search for the lowest $T=T_z+2$ analogue state in the compound nucleus ^{210}Po ($T_z=21$) formed by bombarding ^{209}Bi with protons. The resonance would be the analogue of the $J^{\pi}=0^{+}$ ground state of ^{210}Pb, having $T=23$. One can calculate from Coulomb energy systematics that it should occur at an excitation energy of 37.63 MeV, corresponding to a center-of-mass energy for the incoming protons of 32.65 MeV. The formation of the resonance is isospin-forbidden if all levels have pure isosopin, but the Coulomb potential is expected to mix the analogue state with other 0^{+} levels in its immediate vicinity. These background states come from $T=22$ configurations, and presumable the resonance could be formed via the isospin impurity that results from the mixing.

There are many isospin-allowed proton channels open which corresond to decay to various excited states in ^{209}Bi with T=45/2, i.e. analogues of low-lying levels in ^{209}Pb. Proton decay to states in ^{209}Bi below the ^{209}Pb ground state analogue (E_x=18.75 MeV) are isospin-forbidden and so presumably should be weak. Thus, we are searching for resonances in the (p,p') reaction leading to final states with an excitation energy around 18.75 MeV and above. These states themselves undergo proton decay, and these $\bar{p}$ proton groups should be identifiable from their energy, which is independent of the beam energy.

Preliminary data indicates a resonant effect at about the expected energy. The only proton groups observed to resonate were a decay proton group ($\bar{p}$) and the elastic group. It has not yet been possible to positively identify the intermediate state whose proton decay is observed; the energy is consistent with that calculated for the decay, in ^{209}Po*, of the analogue of the ^{209}Bi octupole multiplet at 2.6 MeV. The excitation function is shown in Fig. I-11. Comparison with a spectrum from a mylar target indicated no detectable carbon or oxygen proton peaks in the bismuth target spectra.

There is a weak indication of a resonance in the elastic channel. The elastic excitation function is plotted with a suppressed zero in the lower part of Fig. I-12. The anomaly which occurs between 32.2 and 32.9 MeV is absent from the inelastic excitation function leading to a group of states at about 2.6 MeV, plotted in the upper part of the figure.

The elastic anomaly has some features of an interference pattern familiar from elastic proton resonances. Further measurements are in progress.

I.C.4. Studies with the Low-Energy Proton Beam—Among the many exceptional design and operating attributes of the MSU Cyclotron is the availablility of a 5-10 MeV proton beam with an energy spread $\Delta E/E$ of less than 1 in 6000. Using such beams, isobaric analogue states in ^{29}P and ^{91}Nb have been studied. In ^{29}P, a level believed to be the lowest lying T=3/2 state has been observed by the $^{28}Si(p,p)$ elastic scattering reaction at E_p=5.84 MeV. The resonance is narrow because the only energetically allowed particle decay, that is, proton decay, is isospin forbidden. Since previous measurement[a.] of the width of this resonance was somewhat limited by experimental resolution a measurement was attempted at MSU with 1 keV resolution. Results are shown in Figs. I-13 and I-14. The detailed line shape of the E_p=5.193 MeV resonance which has a width of 3.5 keV was measured as a check, and then not one, but two resonances, of width 1 keV, were observed in the region of the reported T=3/2 level. The questions raised by the appearance of the additional resonance will hopefully be resolved by a measurement of the energy of the delayed protons emitted from the T=3/2 state of ^{29}P as formed by the β^+ decay of the T=3/2 ^{29}S ground state.

The low energy proton facility is also being employed in a series of investigations of the levels of ^{64}Ga and ^{66}Ga. The technique employed is that of recording Ge(Li) gamma

a. B. Teitelman and G.M. Temmer, Phys. Rev. 177(1969)1657.

ray spectra at a succession of increasing bombarding energies and observing the appearance of new gamma rays in the spectra as the successive thresholds for (p,n) population of the various energy levels are exceeded.

I.C.5. Charge-Exchange Reactions—In the past few years charge exchange reactions have been used to study isobaric analogue states in both (p,n) and (^{3}He,t) reactions. The former studies have yielded accurate Coulomb energies and have been analysed in terms of a macroscopic or quasi-elastic scattering process to obtain information on the isospin term $V(r)T\cdot\tau$ of the optical model potential. More recently, interest has also focussed on the transitions to states of lower isospin in the final nucleus as a means of learning about the reaction mechanism and the nucleon-nucleon force, as well as obtaining detailed spectroscopic information. Both (p,n) and (^{3}He,t) experiments have been carried out on a number of nuclei. Detailed compar~~i~~ative studies of these reactions on a series of target nuclei are planned.

The (^{3}He,t) reaction can proceed to $T=T_z+1$ (analog) and $T=T_z$ states that have the same configuration, the latter states being denoted as anti-analog states (AAS). Starting from a $J^\pi=0^+$ target, the 0^+ AAS can be excited only if: i) there is more than one subshell of the target not fully closed and, ii) the effective interaction $\omega(r)T\cdot\tau$

is different for each of the non-filled orbitals, that is, if the interaction can be written in the form $(\omega_1 T_1 + \omega_2 T_2)\cdot\tau$ for orbits 1 and 2. A measure of the strength of the transition to the AAS provides a measure of the orbit dependance of the interaction. A study of such transitions has been made[169] on the nuclei ^{40}Ar, ^{64}Zn and ^{66}Zn, as the positions of the 0^+ AAS are known in the residual nuclei. The strengths of these states was about 10% that of the analogue state. The interesting feature of the angular distributions is that they are characterized by L=1 transitions, which are not allowed if the usual effective interaction is employed. Figure I-15 illustrates these results for the case of ^{66}Zn(^{3}He,t), where the transitions to the 0^+ AAS (ground state) and 0^+ IAS (3.85 MeV) are shown with macroscopic calculation for L=0 and L=1 transfers. On a microscopic level, no variation in the parameters for the form factors of the two orbits involved could produce a good fit. An L=1 transfer is allowed if a spin-orbit term is included in the effective interaction. Such calculations are being attempted.

The charge exchange reaction to the lower-lying $T=T_z$ states is also important in yielding nuclear structure information on states not strongly excited in other reactions. Excitation of configurations corresponding to the coupling of a neutron hole to a proton is highly selective in this reaction. We have studied the nuclei ^{34}Cl and ^{9}B via the (^{3}He,t) reaction at 35 MeV. Angular distributions of the tritons leading to many states in these nuclei have been made using both a detector-telescope system and the spectrograph. From the shape of the angular distributions, one can assign the spins of final states unknown from other reactions. Both of these nuclei are of interest to theoretical collaborations in which staff members are involved, and the spectroscopic results are important with respect to evaluating such issues as the details of the wave functions of the $J^{\pi}=1^{+}$ states in ^{34}Cl. Similar experiments are under way on ^{30}Si, ^{32}S, and ^{35}Cl.

As a first attempt using the neutron time-of-flight facility (see instrumentation section) the ^{27}Al(p,n) reaction is being studied. Angular distributions have been measured from 10° to 100° with a resolution of about 180 keV (see Fig. VI-7). A number of the low-lying states of ^{27}Si are resolved. Comparisons with (^{3}He,t) data on this same nucleus will be made. This program will be extended to obtain both (^{3}He,t) and (p,n) data on ^{39}K, ^{54}Fe and ^{91}Zr, in order to "calibrate" the experimentally more tractable (^{3}He,t) process in terms of the theoretically simpler (p,n) reaction.

II. DECAY STUDIES

In this section we discuss results of experiments in which, typically, β-unstable nuclei are formed by bombardment of appropriate targets in the cyclotron beam and the β-decay and ensuing γ-ray cascade decays are then studied at locations removed from the immediate vicinity of the cyclotron. We also include here discussion of other kinds of experiments which have grown out of the basic decay studies program. The material is arranged more or less according to the mass region involved.

II.A. Odd Proton Nuclei Above Tin ($Z \geq 50$, $N \leq 82$)

A significant portion of our program of decay scheme studies have concentrated on the systematic behavior of states of the odd-mass, odd-proton spherical nuclei in the region above Z=50. This is the first stage of a more comprehensive program of examining the n-p interaction in odd-odd nuclei after studying the properties of odd-mass, odd-proton and odd-neutron nuclei. In this mass region, typically, one can study large numbers of adjacent isotopes of the same element with relative ease. Most of the odd-neutron radioactive parents have beta decaying isomers of both high and low spin which between them populate many states of widely different spins in the daughters.

Ge(Li), Si(Li) and NaI(Tl) gamma-ray and electron detectors have been used in various singles, coincidence and anticoincidence configurations in our experiments. Some internal conversion electron work has also been performed with the MSU six-gap orange and $\pi\sqrt{2}$ iron-free electron spectrometers. Angular correlation measurements have been made on a number of the gamma cascades in some of the less complex decays to determine level spins and multipolarities of the gamma decays. Relative transition probabilities (gamma and beta) have been used in other cases to assign spins and parities. Where possible, the information thus obtained is correlated with the results of scattering experiments [eg. (^{3}He,d), (p,p'), etc.] in order to obtain further insight into the nature of the nuclear wave functions.

The radioactive parents for these studies have been produced in the MSU cyclotron by (^{3}He,xn) and (p,xn) reactions where $1 \leq x \leq 5$, and with thermal neutrons in reactors at MSU, Oak Ridge National Laboratory and the University of Michigan. Excitation functions, cross bombardments and chemical separations are used in addition to genetic relationships and characteristic x-rays to establish the mass numbers and elements of the activities. The β^{-}-decaying odd-neutron parents for which studies are completed (and in most cases published[3,23,44-50,88,113,114,117,154,163,166]) are: $^{117m+g}\mathrm{Te}$, $^{119m+g}\mathrm{Te}$, $^{121m+g}\mathrm{Te}$, $^{123}\mathrm{Sn}$, $^{125m+g}\mathrm{Sn}$, $^{127m+g}\mathrm{Te}$, $^{129m+g}\mathrm{Te}$, $^{131m+g}\mathrm{Te}$, $^{131m+g}\mathrm{Ba}$, $^{133m+g}\mathrm{Ba}$, $^{137m+g}\mathrm{Ce}$, $^{139}\mathrm{Ce}$, $^{149m+g}\mathrm{Nd}$, and $^{141m+g}\mathrm{Nd}$. Studies of $^{141m+g}\mathrm{Sm}$, $^{143m+g}\mathrm{Sm}$, $^{145m+g}\mathrm{Gd}$, and $^{149}\mathrm{Gd}$ are in progress. As a part of this general program we have also studied some odd-neutron nuclei in this region. These, so far, occurred via contaminants in the primary odd-proton data, and hence the investigations are not so extensive. Results obtained for the daughter systems

^{117}Sn and ^{139}Ce have been completed and published.[116,117] In addition, a comprehensive study has been made of the decay chain ^{140}Nd→^{140}Pr→^{140}Ce.[283] The states found in ^{140}Ce are in excellent agreement with the predictions[120] obtained in the shell model calculation program described in Sec. III.

In most of these cases, reaction data are not available— either because the nuclide is too far from the line of beta stability and not near enough to stable target nuclides and/or simply because no one has yet studied the nucleus via a reaction process. It has become increasingly clear that although large numbers of states are populated in the β-decays there are many states that are not populated significantly because of the β-decay selection rules and the decay energies involved. Alternate modes of populating states are hence important and, to this end, we have begun to perform scattering experiments in some of the more interesting cases [e.g. ^{141}Pr(p,t)^{139}Pr]. The value of our flexible and adaptable organization, which facilitates and indeed encourages such diversifications in which a research project "follows its head", cannot be overestimated.

In addition to the (p,t) studies, we have begun a series of in-beam gamma ray experiments using the (p,nγ), (p,2nγ), (^{3}He,3nγ) and (^{3}He,4nγ) reactions. The (p,nγ) results, coupled with (^{3}He,d) reaction experiments, will enable us to carefully examine states of many odd-odd nuclei in this region. Heavy ion beams, when they become available, will allow an even more thorough examination of the nuclides in this region.

In the following subsections we have elected to concentrate on a review of our studies of one of the most interesting nuclear systems of this region. We thus hope to convey an idea of the techniques, goals and accomplishments of the program without the burden of detail which a full account of all of the activies would entail.

II.A.1. <u>The Decay Schemes of $^{139m+g}$Nd</u>—Our studies[113,144] of states of ^{139}Pr excited in the decay of ^{139m}Nd have revealed a number of novel features and therefore constitute an interesting example to review in detail. The region just below N=82 is first of all a very interesting region of the nuclidic chart for study because of the many systematic examples of rather extreme isomerism which can be observed. $^{139}_{60}$Nd$_{79}$ is thrice removed from stable ^{139}La and has a rather large amount of energy available for β-decay (Q=2.8 MeV). As in other N=79 odd-mass isotones, the $h_{11/2}$-$d_{3/2}$ (metastable-ground state) separation is fairly small, which makes the M4 isomeric transition quite slow. This means that we are presented with two dissimilar isomers decaying almost independently, and because each can populate reasonably high-lying states in ^{139}Pr, much information about many quite different states in this daughter nucleus can be obtained.

The decay schemes that we have obtained for ^{139m}Nd and ^{139g}Nd are given in Fig. II-1. These are based upon extensive gamma ray measurements with Ge(Li) and NaI(Tl) detectors and upon internal conversion electron data.

The decay scheme of ^{139g}Nd turns out to be unexceptional, having much in parallel with the decay scheme[88] of ^{141}Nd and some other nuclei in this region below N=82. The low-spin states that it populates in ^{139}Pr can be characterized reasonably well and follow expected systematics. On the other hand, the decay scheme of ^{139m}Nd is anything but standard. This high-spin isomer decays only 12.7% by the 231.2-keV isomeric transition, the rest being by β^+ or electron capture (ε) to mostly high-spin high-lying states in ^{139}Pr. Six of these, between 1624.5 and 2196.7 keV, are populated by decay that is less hindered (log ft's between 5.5 and 6.3) than the decay to an $h_{11/2}$ isomeric state at 821.9 keV in ^{139}Pr (log ft = 7.0), which is almost certainly an allowed transition. This would imply that the transitions to these six states are also allowed, which mean they are odd-parity states.

A total of 23 states in ^{139}Pr, practically none of which had been reported before, were observed from the combined decays of ^{139m}Nd and ^{139g}Nd. These states apparently can be classified in three quite distinct categories: (1) single-quasiparticle states, (2) single-quasiparticle state coupled to various vibrational configurations, and (3) three-quasiparticle states. Although quantitative theoretical studies of this nucleus are unavailable, the experimental results are quite consistent with empirical trends of the region in so far as the single-quasiparticle and vibrational phenomena are concerned. Our attention here is directed toward the third group of states, those six levels fed with low log ft values in the decay of ^{139m}Nd.

These states, at 1624.5, 1834.1, 1927.1, 2048.8, 2174.3, and 2196.7 keV, appear to be high-spin odd-parity ($9/2^-$ or

$11/2^-$) states. The only straightforward explanation we have found that will explain their enhanced ε population relative to the 821.9-keV state plus the many low-energy γ-transitions among them and the dearth of transitions to the ground or 113.8-keV states is that these six states are part of a three-quasiparticle multiplet having the configuration $(\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$. The particle transitions that we postulate are outlined in stylized form in Fig. II-2.

In the extreme single-particle approximation, $^{139g}_{70}\mathrm{Nd}_{79}$ can be represented as three $d_{3/2}$ neutron holes in the N=82 shell (i.e., a single neutron in the $d_{3/2}$ orbit) and eight $g_{7/2}$ (closed subshell) and two $d_{5/2}$ protons above Z=50. ^{139m}Nd ought to differ only in the promotion of an $h_{11/2}$ neutron into the $d_{3/2}$ level, resulting in eleven $h_{11/2}$ and two $d_{3/2}$ neutrons. Now, there is nothing untoward about the decay of ^{139g}Nd to the ground state of ^{139}Pr, for the only change is the conversion of a $d_{5/2}$ proton into a $d_{3/2}$ neutron. This accounts for the low log ft value of 5.1 for this transition.

The analogous transition from ^{139m}Nd, i.e., $\pi d_{5/2} \rightarrow \nu d_{3/2}$, however, results in the three-particle configuration $(\pi d_{5/2})(\nu d_{3/2})^{-1}(\nu h_{11/2})^{-1}$. Hence, the apparent abnormally large population to these states is, in fact, the expected mode of decay. The 821.9-keV $11/2^-$ state, on the other hand, should have the configuration $(\nu h_{11/2})(\nu d_{3/2})^2$, so decay to it would require converting one $d_{5/2}$ proton into an $h_{11/2}$ neutron, either in one step or perhaps through an intermediate

$d_{3/2}$ neutron state, and a simultaneous promotion of the remaining $d_{3/2}$ proton to the $h_{11/2}$ state. The resulting relatively large log ft of 7.0 is thus reasonable.

Relatively few three-quasiparticle states are known and these few are customarily produced by brute-force techniques (i.e., bombardments). Their recognition has hinged on isomeric states having a long half-life because of high spin; as for example, the nearby $19/2^-$ isomer[a] at 1621 keV in ^{135}Cs that could have either the same or a similar configuration as the states in ^{139}Pr. It is worth noting that here we have a somewhat unique mechanism for populating three-quasiparticle multiplets in a number of nuclei. The requirement is a high-spin nucleus, such as the $h_{11/2}$ isomers, which has sufficient decay energy to populate states above the pairing energy gap in its daughter nucleus. Additionally, the parent nucleus must be inhibited with respect to decay by other modes; for example, an isomeric transition, if present must be of sufficiently low energy to allow the ε decay to compete. Finally, the nucleus must have a relatively unique intrinsic configuration that forces the preferred decay path to be into the three-quasiparticle states. Such arrangements would appear to be present only for β^+/ε decay—further, they are likely to occur only below N=82. (Below N=50 the correct configuration occurs at ^{83}Kr and ^{85}Sr, but these are too close to β-stability for populating high-lying states. Below N=126 the configuration is projected

[a] L. B. Haller and B. Jung, Nucl. Phys. <u>52</u>(1964)524.

to occur around ^{211}Pu, a region that is not even particle stable.)

Below N=82 the appropriate configurations can be found only at N=79 and N=77. On the neutron-rich side of N=79 there are, to be sure, some peculiar and complex decays of $h_{11/2}$-isomers—e.g., ^{131m}Te decays primarily to high-spin states at 1899 and 1980 keV[45]—but these cannot be pinned down as decay to three-particle states. On the neutron-deficient side, ^{137m}Ce has a possible configuration, although it lacks the $d_{5/2}$ protons, so decay would be ℓ-forbidden ($\pi g_{7/2}$ $\nu d_{3/2}$); however, its Q_ε is small enough to preclude such decay. This leaves ^{139m}Nd as the nucleus closest to β-stability with the requisite properties. Other possible candidates in this region among currently known ε-decaying nuclei are $^{141(m)}$Sm and $^{137(m)}$Nd. We are now investigating these and have just recently found similar states to exist in ^{141}Pm.

The states in this proposed three-quasiparticle multiplet are important not only because of the peculiar decay itself, but primarily because they afford a wealth of information about specific, well-defined states in a nucleus near 2 MeV that normally would be available only for states near the ground state. For example, the states decay by the emission of many apparently enhanced γ-ray transitions to other states in the multiplet, but the transitions out of the multiplet appear to be very highly hindered—there are many instances where M1 or E2 transitions in the neighborhood of 100 keV are much faster than E1's of several MeV. Thus, the γ decay itself should give much information about the major components of the wave functions of these states. Once the states are properly characterized, the retarded transitions to states lower in ^{139}Pr should enable us to learn something about small admixtures in the states.

II.A.2. <u>^{141}Pr(p,t) Reaction and Szilard-Chalmers Chemical Reaction for Studying ^{139}Pr</u>—The ^{141}Pr(p,t) reaction at 40 MeV is being used to study the excited states of ^{139}Pr so as to supplement the investigations just described. An angular distribution has been taken from 15° to 75° in 5° intervals using an E+ΔE counter telescope. Preliminary DWBA analysis of the angular distributions of the various states populated reveals a strong tendency to populate what appear to be collective vibrational states based on the ground and first excited states of ^{139}Pr by $\ell=2$ momentum transfers. It should be possible to assign spins and parities unambiguously to some of the states that were characterized as having a possible range of spins by our earlier gamma ray work. A number of higher energy states have been seen with the (p,t) reaction that were not excited in beta and gamma decay.

The very strong beta decay of the 5.5 hr ^{139m}Nd leads to high energy gamma rays that mask the lower energy gamma rays from the weaker 30 min ^{139g}Nd decay. The aim here is to get rid of the ^{139m}Nd background through the use of the Szilard-Chalmers chemical reaction.

The results to date have shown some enhancement of the ratio of ground to metastable activity over that obtained through the conventional counting techniques described earlier but not as much as had been expected. The presence of the metastable species in the aqueous extract has been found to result, in part, from radiation damage suffered by the organometallic complexes as a result of too high a specific activity. Larger volumes of organic solvent and the addition of carrier have increased the total ground state yield, but it still remains significantly below the enhancement level desired.

Since the Szilard-Chalmers reactions are generally very specific as to the conditions under which they work well, a systematic search will be directed toward determining the destabilizing conditions responsible for limiting the desired level of separation in the above chemical system. Paralleling this approach, an investigation of new systems involving inorganic metallic complexes will be conducted.

II.B. Studies above A=150

A systematic study of the gamma-ray decays of states in the neutron-deficient bismuth, lead, and thallium isotopes is being made with Ge(Li) detectors. These nuclei lie close to doubly magic ^{208}Pb, so the shell-model should provide a good characterization of their energy level structure. Studies of the odd-odd thallium isotopes should give information on the p-n residual interaction in this region.

Many of the decay schemes of these nuclei have been studied previously with NaI(Tl) scintillation detectors and electron spectrometers but since most of the decay schemes in this region are very complex, NaI(Tl) investigations must generally be viewed as preliminary surveys. Where possible, we have used the internal conversion electron data of other investigations to aid in establishing multipolarities. We have made extensive use of Ge(Li)-Ge(Li) multiparameter coincidence experiments and have found them to be especially powerful for the determination of these very complex decay schemes. In this region, we are now working[304,305] on the decays: $^{205}\mathrm{Bi}\rightarrow{}^{205}\mathrm{Pb}$, $^{204}\mathrm{Bi}\rightarrow{}^{204}\mathrm{Pb}$, $^{203}\mathrm{Bi}\rightarrow{}^{203}\mathrm{Pb}$, $^{201}\mathrm{Pb}\rightarrow{}^{201}\mathrm{Tl}$, $^{199}\mathrm{Pb}\rightarrow{}^{199}\mathrm{Tl}$ and $^{198}\mathrm{Pb}\rightarrow{}^{198}\mathrm{Tl}$. Investigations on the decays $^{203m}\mathrm{Pb}\rightarrow{}^{203}\mathrm{Pb}$ and $^{200}\mathrm{Pb}\rightarrow{}^{200}\mathrm{Tl}$ decays have been completed.[87,167]

For some time an anomaly was known to exist in the M4 isomeric transition probability of 6.1 sec $^{203m}\mathrm{Pb}$. By using fast chemical separation techniques and a Ge(Li) detector we discovered a competing 5.1 keV M2 transition from the isomeric state. Correcting for this, one now finds that the matrix elements for the M4 transitions in the lead isotopes are all nicely constant. (Our success here has encouraged us to study carefully other M4 isomeric transitions in other regions of the periodic table—in particular in N=79 and 81 nuclei. In these cases one finds, interestingly enough, that the matrix elements are not constant for these nuclei. The question as to why is now being investigated.)

The studies of the $^{200}\mathrm{Pb}$ decay to odd-odd $^{200}\mathrm{T\ell}$ enable us to characterize the seven excited states that we found below 650 keV in terms of couplings of the single particle states observed in adjacent odd-A nuclei.

Perhaps the most complex decay scheme that we have worked on to date is that of ^{204}Bi→^{204}Pb. We have found well over 200 gamma rays as compared with the 67 that had been reported previously. Ge(Li)-Ge(Li) multiparameter coincidence data are being combined with results of a ^{206}Pb(p,t)^{204}Pb scattering experiment to construct the decay scheme. We are using a DWBA analysis of the (p,t) reaction data[268] in conjunction with internal conversion electron data and log ft values to assign spins and parities to several of the more prominent states in ^{204}Pb and to provide insight into the characters of the states.

The first excited state of ^{205}Pb has been shown indirectly to be at 2.3 keV. We are now using the high resolution $\pi\sqrt{2}$ iron-free electron spectrometer to examine its internal conversion in the N-shell.

II.C. Other Projects

II.C.1. Beta-Delayed Alphas and the Decay Schemes of the Light Zinc and Gallium Isotopes—Several nuclei in this region have been observed to undergo alpha emission after beta decay. The heaviest of these is ^{32}Cl. According to the Myers and Swiatecki mass tables[a], sufficient energy is available for this to occur for ^{63}Ga and ^{62}Ga. Nurmia and Fink have unsuccessfully searched[b] for this phenomena in the case of ^{63}Ga. The nucleus ^{62}Ga should constitute a more favorable situation, according to the mass tables, so we have decided to look there for delayed α-emission. The estimated half-life is a few seconds, and one can therefore do the experiment off-line with our fast

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[a] W.D. Myers and W.J. Swiatecki, UCRL Report 11980(1965).
[b] M. Nurmia and R. Fink, Phys. Letters 14(1965)136.

rabbit system. In the experiment we are using a helium gas thermalizer and laminar flow through a capillary to transport the recoils from the reaction producing the ^{62}Ga. Such a system has been used recently with great success by other workers in this field.[a] In conjunction with the delayed alpha experiment we are also studying the decay schemes of ^{62}Zn, ^{63}Zn, ^{62}Ga and ^{63}Ga.

II.C.2 The Electron Capture and Positron Decay of ^{40}Sc— Two differerent investigations on the decay of ^{40}Sc, with two different motivations, have been performed. The first investigation, the results of which have been published,[19,82] was directed at precisely determining the energies of the lowest 3^- state at 3737.1±0.3 keV and the ^{40}Ca T=1 analog of the ^{40}Sc ground state at 7658.9±0.5 keV. The data from this investigation were valuable in understanding the small deviations of the Coulomb energies and their implications in terms of nuclear strucutre effects and average properties of nuclei.

The second investigation on ^{40}Sc is a study of the log ft values in the ^{40}Sc decay and the mechanisms of the β decay. The states of ^{40}Ca have been studied in a variety of ways and much is known about the structures of the excited states. On the other hand, little is known about the beta decay of ^{40}Sc to ^{40}Ca. It is thought that, with the large amount of information available about ^{40}Ca states, a careful study of the ^{40}Sc decay scheme might lead to more insight

a. R. D. MacFarlane, R. A. Gouch, N. S. Oakey and D. F. Torgerson, Nucl. Instr. and Metho., to be published; K. Valli and E. Hyde, Phys. Rev. 176(1968)1377.

into the log ft values. Therefore, the 0.18 sec ^{40}Sc beta decay to states in ^{40}Ca is being studied using the pulsed beam of the cyclotron. These investigations have just started and preliminary data have been obtained.

II.C.3 <u>Decay Schemes in the Iron-Cobalt Region</u>—During an investigation[a.] of the decay scheme $^{53}_{26}$Fe$_{27}$, a 2.5 minute isomeric state was observed and was subsequently placed at 3.0406 MeV in ^{53}Fe. This $19/2^-$ state decays via an E4 isomeric transition to an $11/2^-$ state at 2.3396 MeV. This state, in turn, decays to the $7/2^-$ ground state and to a $9/2^-$ state at 1.3281 MeV. Because of the large energy difference between the $19/2^-$ isomeric state and the $7/2^-$ ground state, and the relatively small energy between the isomeric state and the $11/2^-$ state, the E6 and M5 gamma transitions can compete favorably with the E4 transition. It is of interest to compare the M5 and E6 transition probabilities with the calculated values. To our knowledge, an E6 gamma ray transition has never been seen before. We have preliminary evidence that these transitions exist and we are in the process of carefully measuring their transition probabilities. A similar isomer is possible in the mirror nucleus $^{53}_{27}$Co$_{26}$. The energy, half-life and structure are expected to be similar and we are also planning to study this isomer. It will be interesting to see if this isomer undergoes beta decay to the corresponding isomer in ^{53}Fe as this will give considerable information about these unusual mirror isomeric states.

a. K. Eskola, Ann. Acad. Sci. Fenn AVI. No. 261, p. 45 (1967) and J. Black, unpublished data.

Shortly after the introduction of the Ge(Li) gamma ray detectors, the pressing need for a convenient calibration standard covering a wide range of gamma energies and relative intensities became apparent. The 77 day decay of ^{56}Co was known to have gamma rays with energies ranging from $\sim$800 keV to $\sim$3500 keV. We therefore undertook careful energy, relative intensity, and coincidence measurements, using (1966) state of the art detectors. For the sake of completeness, the decay of ^{56}Mn to ^{56}Fe was also studied. The data and decay schemes thus determined were compared with published reaction and conversion electron data and spin assignments were made to the states.[54]

In a study of analogue and anti-analogue states in the iron-nickel region[a], Sherr has noted that the generally accepted 0^+ spin assignment of the 1.45 MeV state may be in error. Internal conversion data, reaction data and gamma-gamma angular correlation data are all somewhat ambiguous and allow any of the spins 0, 1, or 2. It has been suggested that this state may be a doublet. We are studying this state via ^{56}Ni decay and the (p,nγ) reaction in order to resolve this difficulty. Angular distribution experiments on the gamma rays following the (p,n) reaction will be performed, and should the anisotropy of the distribution be sufficiently large, it may be possible to determine the magnetic moment from the shift and attenuation of the angular distribution when the iron foil target is magnetized.

[a] R. Sherr, private communication.

III. NUCLEAR STRUCTURE CALCULATIONS

Some of our staff, in collaboration with physicists from Oak Ridge National Laboratory, are engaged in an extensive program of shell-model calculations of the level structures of nuclei in the 1p, (1d,2s), (1f,2p), and (1g,2d,4s) shells. The philosophical orientations of these studies have been to employ the largest (i.e., most realistic) vector spaces feasible for the various families of nuclei and to attempt to treat sequences of related nuclei simultaneously, in a coherent, unified fashion. The problem of the residual Hamiltonian has been approached both from the criteria of consistency with nucleon-nuclon data and of consistency with the trends of experimental level energies within a given region. The results obtained to date from this series of investigations[303,91,95,140,153,139,120,173] have been generally very successful in correlating and predicting almost the complete gamut of observables which can be measured in experimental nuclear structure physics. It seems reasonable to hope that refinements and expansions of the techniques that we are pursuing will bring us even closer to the goal of quantitatively predicting the behavior of complex nuclei from basic principles.

The beneficial effects of close communication between this theoretical project and the various experimental nuclear physics programs in the laboratory promise to be great. The evolution of the theoretical studies is guided and stimulated by results from experiments such as those described in the preceding discussions. At the same time, many future experiments in the laboratory are being directed towards those areas most critical to evaluating and correcting the development of the theoretical program. The complete set of uniquely flexible and powerful shell-model codes developed at Oak Ridge is now operational on our laboratory's "in-house" computer, and are hence readily available to both staff and graduate students. In addition to facilitating collaboration on the well developed program of theoretical studies just mentioned, convenient access to the codes also makes it possible for physicists not primarily interested in the structure aspects of a problem to quickly and easily generate sophisticated, realistic wave functions for almost any amenable nucleus. This aspect of the capability is being utilized, for example, to aid in the analysis of an $^{16}O(p,p')$ experiment directed primarily towards understanding the reaction mechanism. Such reaction mechanism studies can now be pursued with minimal ambiguities devolving from the use of over-idealizations for the wave functions which enter the problem. The facility is also expected to be of great utility to the members of the MSU Nuclear Theory Group in as much as they will be able to quickly ascertain the shell-model-structure implications of their work on such topics as the derivation of effective interactions based on nucleon-nucleon potentials and the effects of core-polarization and exchange corrections upon inelastic scattering cross-sections.

The most extensive organized program[152] at the moment involves the evaluation of the matrix elements of magnetic dipole, electric quadrupole and β-decay operators. We are using the shell-model wave functions already derived for nuclei in the regions A=13-23, A=27-38 and A=135-145. This project is designed to complete the evaluation of our present stage of progress, and also to provide theoretical predictions to many interested experimentalists both at MSU and elsewhere. Future programs include detailed model-empirical studies of effective-charge assumptions and investigations of simple truncation schemes designed to make realistic shell model treatments of presently intractible regions of nuclei feasible. The forging of close links with the groups pursuing detailed microscopic analyses of the (p,p') and (^{3}He,t) reactions is also a development whose desirability is self evident and which is being effected.

IV. STUDIES IN ASTROPHYSICS

Current problems relating to the origin of light elements are being actively studied in the laboratory by members of our staff especially interested in this area of physics. In the most extensive program, the uncertainties shrouding the creation of the elements Li, Be, and B are being studied in proton-spallation experiments. These elements are neglibly present in the charged-particle fusion reactions which synthesize heavier elements from hydrogen and helium. In addition, they are too fragile to survive the temperatures found in the deep interiors of stars, the site of most element-synthesizing nuclear processes. Current hypotheses postulate the origins of Li, Be and B in proton spallation of nuclei from C to Si, but differ widely in the specifics of the process. One theory involves spallation of ^{16}O, ^{24}Mg, and ^{28}Si by 500 MeV protons at sites distant from the stars emitting the protons. A later, alternate, theory suggests as the dominant mechanism of production the spallation of ^{12}C, ^{14}N, ^{16}O, and ^{20}Ne by less energetic protons in the immediate vicinity of stars. The quantitative predictions of these theories involve the isotopic ratios of ^{6}Li/^{7}Li and ^{10}B/^{11}B, and it is these features of the spallation process that our experiments are primarily designed to measure. (Of course, any theory accounting for the present observed abundances of these isotopes must consider not only their formation rates but also their differential destruction in the intervening astrophysical time period.)

The experimental technique employed in our studies measured the formation rates of spallation products of masses 4 through 11 at proton energies between 20 and 50 MeV as a function of spallation-fragment energy and of angle to the beam direction. (Mass measurements alone are sufficient to determine the isotopic ratios in question, since the β-decay lifetimes involved in transmuting, for example, ^{11}C to ^{11}B, are astrophysically short). The combined energy-mass measurements are accomplished by a time-of-flight measurement (T) combined with energy measurement (E) in solid-state detectors. The product ET^2 is proportional to the mass of the reaction product. A sample of the data, displayed in a yield vs ET^2 plot, is shown in Fig. IV-1. This experimental approach circumvents almost all of the problems which have handicapped previous investigations of this type of process. Integral to its success, of course, is the narrow ($\sim$0.2 nsec) burst width of the MSU Cyclotron.

Results obtained from spallation of ^{12}C have been published,[108,135] and extensive preliminary information is available from study of ^{14}N and ^{16}O. An investigation of ^{20}Ne is presently in process. From these studies it appears that the presently observed terrestrial abundances of ^{11}B and ^{10}B are consistent with the mass 11/mass 10 ratio observed in proton spallation of ^{12}C, ^{14}N, and ^{16}O in the 20-50 MeV range of proton energies. The mass 7/mass 6 ratio observed in spallation is significantly larger than terrestrial measurements indicate, however, and there is hence the need to postulate a ^{6}Li depleting process ($^{6}Li(p,\alpha)$ for example) in order to bring this aspect of the problem into consistency. Hopefully, the detailed final results of this investigation will contribute fundamentally to our understanding of the origins of lithium, beryllium and boron in the universe.

Another aspect of astrophysical element building has been studied[171] in an archtypically synergistic interaction between groups in our laboratory who were originally pursuing quite unrelated research aims. The astrophysical problem is that of the vital and fundamental "3α" process, by which ^{12}C is synthesized by successive fusion of two alpha particles into ^{8}Be, followed by fusion of ^{8}Be with an additional alpha to form the second excited state (E=7.6 MeV) of ^{12}C. The reaction rate $P_{3\alpha}$ depends critically upon the precise excitation energy E of the ^{12}C excited state:

$$P_{3\alpha} \approx \exp[-x/kT]$$

$$x = [M_{12}-3M_{\alpha}]c^2 + E$$

The previously available data on this excitation energy have been mutually contradictory and this problem came to the attention of staff members working in the astrophysics area. At the same time, staff members studying the masses of isobaric mass multiplets had just developed a powerful technique (see Sec. VI.A.2) for making absolute mass determinations with very high accuracy. A collaboration between the two groups has quickly established a new value for the energy of the critical level in ^{12}C which differs by $+12 \pm 2$ keV from the value used in the standard calculations of the helium burning cycle. This seemingly small difference is likely to effect substantial changes in our ideas on succeeding aspects of helium-burning nucleosynthesis.

V. NON-NUCLEAR PROGRAMS

In recent years several of our staff members have been involved in scientific investigations in fields fundamentally unrelated to nuclear physics. Our knowledge as a group, and as individuals, of a broad spectrum of powerful experimental techniques has been invaluable in these interdisciplinary projects. The cyclotron and associated equipment have, of course, been the essential tools in our hands.

Of the two projects discussed below, the one on nitrogen fixation has been in collaboration with an MSU plant biologist, while the one on trace-element analysis has so far involved cyclotron personnel only.

V.A. Nitrogen Fixation

The remarkable process of cell differentiation in the human embryo was learned by most of us in our high-school years if not earlier. The process occurs in all the higher plants and animals and is responsible for their great diversity. Lacking, however, is an understanding of the mechanisms involved in the development of organisms and of the influence of environmental factors. Blue-green algae exhibit phenomena analogous to basic developmental processes encountered in the higher forms of life. In filamentaiou forms of blue-green algae, for example, special cells called heterocysts arise from the vegetative cells not at random but at rather regular intervals. The function of the heterocysts was for many years considered a "botanical enigma". It has recently been suggested that the heterocyst is the sole site of nitrogen fixation in these algae. [On the practical side we note that agriculture depends upon atmospheric nitrogen fixed by various blue-green algae.] Evidence on this proposition is inconclusive in spite of great interest and much work on the subject. Destructive biochemical techniques such as centrifugation and sonication have not lead to definitive experimental results.

Our approach is to obtain pictorial, invivo, evidence from ^{13}N autoradiography. Because of the short half-life (10 minutes) of ^{13}N, it must be used where it is produced, and a cyclotron or similar accelerator is required for its production.

We use the $^{16}O(p,\alpha)^{13}N$ reaction with 20-MeV protons incident on a 15-MeV thick target of Li_2Co_3. The chemical separation following production requires a small sample. We use 50 mg packed into a cylinder less than 4 mm in diameter. When the beam is properly focussed and aligned it penetrates the target to a Faraday cup where it is monitored throughout the bombardment. The target holder is shown in Fig. V-1.

The production cross-section is energy dependent but averages around 20 mb. Hence, bombardment with a 1 μamp beam produces ^{13}N at the rate of 10^9/sec. At the end of a saturation bombardment there are $\sim 10^{12}$ ^{13}N atoms. This is 2×10^{-11} of the target atoms and equivalent to $\sim 3 \times 10^{-8}$ atmospheric cc of N_2 gas. To within our factor-of-two accuracy all of the calculated ^{13}N activity is collected in gaseous form after chemical treatment utilizing mainly hot copper, hot copper oxide and liquid nitrogen. Further chemical processing is required to guarantee that nitrogen gases more rapidly fixed than N_2 are not fed to the algae.

The activity collected was counted until it had decayed by a factor of 10^4. The decay curve was a single exponential with half-life = 9.84 minutes. There was no trace of ^{11}C (half-life

20 minutes). This is important because the algae assimilate CO_2 more readily than N_2.

We have seen some tracks originating in algae and are presently working to improve our photographic techniques. In comparison to ^{14}C autoradiography which has become routine, ^{13}N autoradiography should be more difficult because of the paucity of low-energy, highly-ionizing positrons. Most of the positrons are near minimum ionizing. A reasonable solid angle for seeing minimum-ionizing tracks requires thick emulsions, which are more difficult to develop quickly and without distortion. In addition to the present project, development of ^{13}N autoradiography should be of value in future biological research.

V.B. Trace Element Analysis

The nation is alarmed about threats to human well-being from various forms of pollution. Detection of what appears to be unusually high amounts of mercury in fish has, for example, led to government actions including lawsuits and fishing restrictions. With the realization that this is but one of a large class of problems, some potentially more dangerous, we decided to investigate the feasibility of trace-element analysis using various techniques that have been developed for studies in nuclear physics. These techniques may also be of value in scientific indexing and materials science studies.

Two complimentary schemes are being explored. One employs accurate energy measurement of selected particles in nuclear scattering and reactions. The other is charged-particle activation analysis.

V.B.1 Energy Measurement—The kinematic energy loss in elastic scattering from a nucleus increases with decreasing mass of the target, increasing mass of the ion, and increasing scattering angle. With 4×10^{-4} resolution the energy measurement of an α-particle (or a heavy ion) scattered at a large angle can be used to distinguish between neighboring isotopes of any element. If a heavy element is present as a trace impurity amongst light elements, then the number of scattering events originating from the heavy component is enhanced relative to those from the light component if one makes the measurment below the Coulomb barrier for the heavy component. Furthermore, use of an incident energy below the Coulomb barrier suppresses inelastic scattering from the heavy elements, thereby increasing the signal to background ratio for elastic scattering from all elements.

A feasibility study to determine preliminary sensitivity limits of this technique has been made by scattering 22 MeV α-particles at 85° from a 20μgm/cm^2 deposit of Au and Bi each on a 1/8 mil film of mylar. The scattered α-particles were detected with Si surface barrier detectors. The results of a few mintues' measurement can be seen in Fig. V-2. The fractional atomic concentration of Au (or Bi) is 1/1800 so that with 150 counts in the peak for Au (or Bi) and no background above the Bi peak, the lower limit of detectability in this measurement may be set at 5-10 p.p.m.

(p,α) reactions below the Coulomb barrier for heavy elements are being investigated for the measurement of light mass trace impurities. (p,α) cross-sections for heavy elements are very small if the incident proton energy is below the Coulomb barrier. This may enhance cross-sections for the light mass components relative to the heavy by several orders of magnitude and thus lend itself to use in measurement of trace quantities of light impurities in the presence of an abundance of heavy elements.

An example is shown in Fig. V-3 where a 97.8% enriched target of ^{90}Zr with no detectable trace (<0.05% - ORNL spectroscopic assay of target composition) of Al was used for sub-coulomb (p,α) measurements. At least two α-groups resulting from traces of Al are observed along with those from other trace impurities while none is seen from ^{90}Zr. The lower limit for detectability of traces of light elements, though difficult to estimate without knowing (p,α) cross-sections, is likely in the vicinity of 10 parts per million.

V.B.2. Charged-Particle Activiation Analysis—Accurate quantitative analysis (including neutron activation analysis) for many heavy trace elements (e.g. mercury, thallium, lead, etc.) is often subject to large errors due to unknown losses of the material of interest in the course of chemical processing related to the analysis. Frequently the compounds in which the elements are bound are unknown and, more often than not, highly volatile. To avoid this difficulty we are attempting to work with systems that have undergone minimal chemical processing.

Thus far our work has concentrated on the mercury-in-fish problem and has been aimed at outlining the problems confronted in activation analysis with charged-particle beams. We have worked with a raw fish (Coho salmon from Lake Michigan) and a processed fish (pickled herring from a cocktail party). Gamma rays and x-rays are detected with Ge(Li) and Si(Li) detectors. In order to familiarize ourselves with some of the experimental difficulties and to establish the sensitivity limits of these methods with "as-is" specimens, we have sprinkled the samples with known amounts of mercury. Results obtained thus far are promising. For example, the sensitivity limit for mercury in pickled herring (as-is from the jar) is ~ 1 part in 10^5 by weight. This was obtained without any attempt to optimize beam energy, sample form or choice of activity. We believe an additional factor of 100 in sensitivity will be easy to achieve. Neutron activation analysis of these samples would have been very difficult because of the ^{24}Na resulting from the salt in the sample.

VI. RESEARCH FACILITIES

In the summer of 1965, when our previous five year proposal was prepared, the MSU Cyclotron had just started operation and the nuclear physics instrumentation of the laboratory was a hodgepode of crude, temporary facilities. Reading from the proposal one notes that the positive ion extraction system for the cyclotron had not yet been installed, the beam transport system was not yet constructed, and the only experimental setup consisted of the old Rochester scattering chamber standing about 15 feet from the cyclotron without steering magnets or analyzing equipment. Silicon detectors of 5 mm thickness (25 MeV proton) and sodium iodide were the only particle detection devices, the pulse analysis equipment had no provisions for data manipulation, and our only output arrangement was so cumbersome that readout often required more time than data taking. In the ensuing five years the instrumentation configuration of the lab has changed dramatically. The cyclotron now operates routinely on a 24 hour, 7 day a week basis furnishing beautifully precise proton, deuteron, helion and alpha beams to any of six beam lines in three experimental rooms. The permanent facilities on the six beam lines are appropriate for a wide variety of nuclear experiments and also, increasingly, for many non-nuclear and applied uses. Experimenters also have available a computerized data processing system for fast, exceptionally versatile processing of data, including one of the few fully operational time-sharing systems in existence—with this time-sharing system a powerful concurrent computing capability is obtained from the data processing system such that all the laboratory's digital computing is now provided internally.

One of the significant hallmarks of our research instrumentation is the extensive degree of internal design and construction of the research equipment. As a general guideline we try to design and fabricate our research equipment whenever we are faced with a requirement which cannot be met by catalog-item type commercial units or where it appears that significant performance improvements can be achieved by internal construction. Thus for example the entire beam transport system was fabricated in our own facility including bending magnets, coils, quads, sextupoles, beam pipes, slits, viewing systems, etc. Likewise the computer interface and the time-sharing software package are the result of our own efforts. On the other hand, the computer proper, the Enge split-pole spectrograph, the system of TV monitors, etc. are commercially purchased standard units. Our do-it-yourself tendency on instrumentation has three major advantages: 1) we are able to achieve more effective, sophisticated systems, directly tailored to experimental requirements, and hence generally contribute in a major way to the advance of the instrumentation aspect of nuclear science; 2) we are normally able to accomplish development and prototype fabrication of advanced systems much more economically than commercial concerns; and 3) by exposing our students to instrumentation development, we impart to them a considerably broader training experience than is often typical in a nuclear lab. (Instrumentation experience is likely to form a valuable bridge if the student later takes a position in some of the many non-nuclear areas involving application of nuclear techniques.) In the coming years we plan to continue an active instrumentation program with the objective of further developing and improving our nuclear facilities in the most economical fashion possible while at the same time providing important broadening of the training and experience of our students.

In the following subsections we review the present status of our major research facilities and our plans for further development of these facilities.

VI.A. High Resolution Charged Particle Facility

The most outstanding present feature of our research instrumentation is our recently developed state-of-the-art capability in high resolution nuclear reaction studies.[170] With this facility, complete system resolutions of 5 keV have been achieved in proton and deuteron induced nuclear reaction studies with bombarding energies as high as 40 MeV. Fig. VI-1 shows a typical recent spectrum demonstrating the system performance. This capability, which we believe is at present unequalled in any other facility, is achieved with an accelerator whose initial capital cost was slightly under one million dollars, i.e., one of the least expensive medium energy accelerators.

VI.A.1. High Resolution System—Essential details of the high resolution system are shown in Fig. VI-2 which is an "equivalent circuit" drawing of the high resolution beam line. At the left of the Fig. is the "equivalent cyclotron" consisting of ion source, acceleration system, and focusing and dispersing elements. For a cyclotron operating with single turn extraction (assumed as a condition in the following discussion), the simple equivalent circuit shown is in fact quite realistic.

The sinusoidal acceleration produces a particle beam with a coherent spread in energy directly correlated with the time variation of the voltage. The cyclotron magnet acts as a combined focusing and dispersing system, and even though these actions are spread over hundreds of turns, the net result is a transfer matrix identical to that of a simple bending magnet and quadrupole system. Higher order multipoles may also be implied if non-linearities in the cyclotron are appreciable.

If the single turn extraction restriction is lifted the equivalent cyclotron is similar to the one shown, except that particles from different turns appear to leave the cyclotron in a slightly different direction as if they had come from a displaced source. In Fig. VI-2 this effect is indicated schematically by the dashed source and the heavy dashed arrow at the exit port. Such an enlarged source would have catastrophic consequences on the high resolution system described here. Single turn extraction is therefore an essential requirement for this system.

From the equivalent cyclotron the beam is directed to the target by the transport system, an array of focusing and dispersive magnet elements, and finally brought to a dispersed focus on the target. The fact that the beam has in the process passed thru intermediate foci at locations called "Box 3" and "Box 5" is irrelevant since no slits are employed at either of these locations. The properties of the final dispersed focus on the target are qualitatively the same as would result from a single simple bending magnet, i.e., a rather large spot whose size is determined mainly by the total energy spread of the beam but with a coherence such that particles of energy $E+\delta E$

go to a small region on one side of the target, particles of energy E-δE pass to a similar region on the other side of the target, and other energies correspondingly in between. Assuming no time variations in magnets, the size of the region in which particles of given energy focus is determined by the size of the cyclotron source and the total system magnification.

Beyond the target, scattered particles enter the Enge spectrograph,[a] (another dispersive and focusing system) and come to a focus at the detector. At this stage the very important concept of "dispersion matching" as proposed by Cohen[b] is used. This condition is achieved if rays of energy E and E±δE, etc. when directed back from some assumed detector thru the spectrograph to the target, go to just the same points on the target as the corresponding energies coming from the cyclotron. Given this condition all elastically scattered particles will clearly come to a focus at the detector regardless of whether their original energy was E+δE, E-δE or something between. In this condition the width of the observed elastic line at the focal plane of the spectrograph is then independent of the beam energy spread to first order, and is in fact determined by the width of the cyclotron source and system aberrations. Such an arrangement is achieved in practice by appropriate shifting of the strengths of quadrupole singlets in the transport system to give the desired dispersion.

In a similar fashion to the elastic scattering, inelastic lines will have all lost a fixed amount of energy corresponding to the excitation energy of the nuclear state, and will also

[a] J. E. Spencer and H. A. Enge, Nuc. Instr. & Meth. 49(1967)181.
[b] B. L. Cohen, Rev. Sci. Inst. 30(1959)415.

be focused to a narrow group at the appropriate focal plane position, and with line widths likewise independent of the beam energy spread. Since the ability to resolve particle groups corresponding to different nuclear states is determined by the ratio of line width to separation at the spectrograph focal plane, the narrowing of the lines from various nuclear levels leads directly to higher resolution.

An important detail is to provide a rapid means for adjusting parameters controlling the line widths in order to optimize resolution. This function we accomplish with the "resolution meter" diagrammed in Fig. VI-3. It consists of a 5 mm Si(Li) solid state detector with a brass entance slit which has one jaw 0.1 mm thick, and the other 0.05 mm thick. With an aperture of typically 0.05 or 0.1 mm this slit and counter then serve as an ultra-sensitive position sensing system—beam penetrating either jaw of the slit is degraded in energy and appears as a distinct energy group to the counter giving typical spectra as shown in Fig. VI-4. With appropriate circuitry and count rate meters, the ratio of the high energy transmission peak to the total of the three peaks is presented on a console meter. Since the fractional transmission through this slit is approximately inversely proportional to line width, this ratio is the desired "resolution meter". Watching this meter, focusing elements, aberration corrections, dispersion controls, plate position, etc. can all be adjusted to optimize system resolution. The resulting changes from calculated control settings are generally small but nevertheless of great importance. Improvements in resolution by factors of two are typical.

Two special feedback stabilization circuits are employed in the system, one for compensating bending magnet drifts, the other to keep the cyclotron rf amplitude in its proper range. From Fig. VI-2 it is obvious that a shift in the strength of any bending magnet will move the position of the central ray relative to the resolution meter slit. Given such a shift a compensating change can be effected by any other magnet (at least in so far as the position error is concerned), i.e., one servo system on one magnet is adequate to correct a small bending change in any element of the system. The slit counter gives a ready reference standard for this circuit. One desires to have a servo adjustment of some magnet so as to have equal counts in the two lower energy peaks of Fig. VI-4, i.e. equal beam on the right and left jaws of the slit. Rather arbitrarily we have elected to control the spectrometer magnet with this servo system—the action of the circuit is then to keep the elastic line locked at a fixed position in the spectrograph focal plane. (We note in passing that for small shifts, the action of this circuit leaves the position of the linear focus undisturbed, and even for large shifts a given fractional change in a dipole element has a vastly more catastrophic effect on resolution than a similar change in quadrupoles or sextupoles, and so position is properly the primary reference for such a stabilization circuit.)

The second special feedback circuit, on the cyclotron rf, is in principle unnecessary in a dispersion matched system since a small change in the rf (within the range allowed for single turn extraction) induces no effect other than a simple one-to-one change in the beam energy, and such a change is of course compensated by the dispersion matching in a fully matched system. Nevertheless transmission considerations and non-linear phenomena make it convenient and valuable to stabilize the rf. This is accomplished by sensing the beam on a feedback slit located just at the cyclotron exit port and sending an amplitude feedback correction to the rf to keep the beam balanced on this slit (an arrangement very similar to the standard feedback system on Van deGraaff accelerators). With this circuit in use the cyclotron beam remains steady for long periods with no adjustment required.

With the experimental configuration described, a well tailored cyclotron can be an exceedingly powerful high resolution tool for nuclear reaction studies. Since the total resolution of such a system hinges primarily on the quality of the accelerator source, cyclotrons with their high-luminosity positive ion source should regularly achieve significantly higher resolution than accelerators depending on negative ion sources. Our present resolution in fact does not appear to be limited by the source—emittance measurements on the cyclotron external beam discussed in Sec. VI.C. imply a resolution approximately two times better than we are now obtaining. Studies are in progress to check system aberrations and ripple either of which could cause broadened lines. With some luck resolutions twice those we are now achieving should be possible. (Unfortunately, the study program to accomplish this is likely to require 6 to 12 months.)

VI.A.2. Absolute Energy Calibration—We have also recently succeeded in calibrating our beam transport system and spectrograph to unprecedented accuracy over the whole operating range, thus complementing the high resolution properties with good knowledge of absolute energy values. This was accomplished by a "momentum matching" method[149] which requires the simultaneous detection, at the same position of the focal plane, of reaction products from two different reactions such as, for example, the ground state protons and deuterons from $^{12}C(p,p)^{12}C$ and $^{12}C(p,d)^{11}C$. This overlap condition is satisfied only for the unique beam energy at which the magnetic rigidities of the outgoing protons and deuterons are equal. For the above reactions at a laboratory scattering angle of 15.0°, the momentum matching yields E_p(beam = 33.691 ± 0.0022 MeV and B_ρ(spectrograph) = 332.256 kG-in. The 3.0 keV error ($\sim 1/10^4$) is a representative uncertainty for this method and is dominated in this case by the 1.1 keV uncertainty in the mass of ^{11}C. Table IV-1 lists other reaction pairs and the beam energies at which the momentum match is achieved. This calibration technique will allow high precision energy measurements in a number of experiments where absolute determinations are essential.

VI.B. Time-of-flight Systems

The cyclotron phase selection system produces exceedingly short beam pulses. Pulses with full width at half maximum of 0.2 nanoseconds can be readily achieved (as is discussed in Section VI.C.). In addition to being very narrow, the pulses are also stable in time relative to the cyclotron rf and the rf can therefore be used as a convenient readily available reference clock for the timing circuits. Also a pulse selection system is being tested which allows skipping of pulses in the event the natural cyclotron repetition period is too short. With this pulse capability it is effective in many situations to make velocity measurements to determine for example neutron energies (as is common in many laboratories) and also in some instances in lieu of or in addition to dE/dx measurements as an aid in difficult particle identification problems. The spallation studies described in Sec. IV nicely illustrate this last application—the point of interest in the experiment was the mass yield which is uniquely determined independent of Z by a measurement of E and v. This was accomplished in a single counter using the pulsed beam with an rf crossover trigger to mark t=0. If dE/dx had been measured rather than v, a complicated Z dependence would have resulted and in addition the dE/dx detector would have been very difficult to construct. Another recent experiment on the bombardment of ^{14}N by deuterons also used a time measurement instead of dE/dx for particle identification. The experiment hence involved only one detector and the resolution was significantly improved over that obtained with the usual dE/dx-E telescope (only 1 detector surface layer is involved in the E-t system versus three for dE/dx-E).

In addition to these significant applications of the time-of-flight (TOF) technique in charged particle studies, the technique is essential in the determination of neutron energies. Moreover, the need for precise timing is most pressing in such studies since the energy is determined directly and solely from the TOF. We have an interm neutron TOF system in use at present, while a much more powerful final system is under development. This later system should have quite exceptional capabilities complementing the high resolution charged particle facility discussed in the previous section.

Since in a typical cyclotron bombardment there are more nuclear gamma rays produced than neutrons, it is essential to separate neutron-induced pulses from gamma-induced pulses. An intense prompt gamma ray group arises from the target and in addition, there is a time-random distribution of gamma rays from capture of slow neutrons in the shielding walls and other surroundings of the detector.

For discrimination we use the familiar pulse-shape effect whereby light produced in inorganic scintillators by protons and alpha particles (from neutron interactions in the scintillator) has a slower long-term decay than light produced by electrons (from gamma-ray interactions in the scintillator).

The pulse-shape effect is illustrated in Fig. VI-5, which is a two-dimensional display of neutron and gamma-ray pulses originating from the interaction of 30-MeV protons with aluminum. Neutrons are in the lower band, gamma-rays in the upper band. Sorting and display of the pulses was accomplished with the aid of our computer and the TOOTSIE program. The solid lines are empirically-determined boundaries with which the neutron/gamma descision is made in the computer.

We have developed two neutron areas, one for observing neutrons produced at 0°, and the other for the angular range 5° to 95°. Both areas are indicated on the plan view shown in Fig. VI-6. Flight paths from 5 to 15 meters long are available at 0°. After passing through the target the beam is magnetically deflected into a beam dump. The detector is in the next room behind another 4 feet of concrete. The result is a very low background. We have plans to construct a magnetic deflection system for the beam that will enable us to vary its angle of incidence on the target, and thus measure a neutron angular distribution with a fixed flight path similar to our present 0° path. Having the target and beam dump in one room and the detector in a separately shielded room leads to clean neutron spectra.

For our interim angular-distribution geometry the target, beam dump, and detector are all in one room and flight paths are restricted by the geometry of the room to maxima of 10 meters at the more forward angles and to 4 meters between 60° and 95°.

One of the experiments which has been performed with the neutron TOF apparatus in this experimental area is a measurement of the angular distribution of the ^{27}Al(p,n)^{27}Si reaction. The phase-selection slits described in Sec. VI.C.2 were used and enabled us to take data with a resolution of less than 0.3 nsec. A typical neutron spectrum obtained with the 3~~0~~2-MeV proton~~s~~ beam is shown in Fig. VI-7. The energy of the ground-state neutrons is 26.3 MeV. (The groups corresponding to the 0.78 and 0.96 MeV states of ^{27}Al are only partially resolved due to the target thickness which accidentally was thicker than intended in this run.)

Our pulse selection system, which is now being tested, will relieve restrictions arising from the fact that high-energy neutrons from beam burst n arrive at the detector at the same time as lower energy neutrons from burst n-1, still lower-energy neutrons from n-2, etc. Since the cyclotron always operates in a single turn extraction mode it is possible to do this pulse selection internally just after the ion source where the energy is low and hence discarded pulses give no activation or contribution to the neutron background. The system utilizes a pair of deflecting plates mounted just behind the source extraction electrode so as to displace the orbit for the first half turn onto a selection slit 180° from the source. The logic is digital, allowing elimination of n-1 out of n pulses for any value of n. The lengthening of the time interval between beam bursts then shifts the overlap energy in the neutron detectors to much lower values, thus allowing the pulse height threshold to be lowered with consequent gain in detection efficiency and broadening of the range of observed energies.

The pulser system has been tested by observing its effect on a thick-target, gamma-ray TOF spectrum. Figure VI-8 shows a portion of the spectrum with and without pulser operation. Both runs had the same amount of beam on target. It is clear that: 1) There was no loss of intensity of the transmitted beam bursts. 2) The eliminated bursts were completely eliminated. 3) Signal-to-noise ratio was higher by a factor of n (n was 10 in this test) with the beam pulser. Improvements in long-term stabilization of the synchronism between cyclotron rf and the cancellation pulse will soon be completed and the beam pulser will be put into regular use in neutron TOF experiments.

VI.C. Cyclotron

One of the main programs of the laboratory is centered on continuing studies of our cyclotron which are aimed at understanding its behavior in as much detail as possible and implementing such improvements as may come to light in these studies. This program has two important results: 1) the unique combination of a well instrumented experimental capability, and a sophisticated, theoretical program has enabled us to extend significantly the general understanding of fundamental physical phenomena in cyclotrons, and 2) the nuclear research capabilities of the cyclotron have steadily improved, and will continue to improve as a result of modifications which have evolved from these studies. The superlative radial emittance is a prime example of these improvements. In the construction proposal for the cyclotron we predicted an emittance of 50 millimeter-milliradians (mm-mr), a figure some 30 times better than the only emittance data then available for a cyclotron. Our operating proposal of five years ago reported 40 mm-mr for the results of radial emittance measurements when the cyclotron began operation. By comparison our present normal value is 0.7 mm-mr.[141] Evolution of the phase selection system, stabilizing circuits, controls, etc. have been comparably striking. As a result the cyclotron at this time is clearly one of the outstanding nuclear research instruments in the world and accelerator studies now in progress should lead to still further improvements. The following subsections cover a selection of topics relative to cyclotron operation and improvement.

VI.C.1. Available Beams—The construction proposal for our cyclotron was based on a maximum proton energy of 40 MeV. In the course of design and construction, refinements of the pole tip shape made it clear that energies up to 56 MeV could be achieved; however, by that time a number of major components were already on order with capabilities significantly lower than really proper for energies of 50 MeV and higher. The resulting total design has given a cyclotron of exceptional precision and reliability at energies up to 40 MeV, but which is increasingly difficult to run and maintain as the energy is pushed toward 50 MeV. Thus at present the maximum routinely usable proton energy is 45 MeV, even though proton energies up to 56 MeV have been occasionally achieved in accelerator test runs, and published nuclear experiments have employed energies up to 53 MeV.

Figure VI-9 shows presently available particles and energies as solid lines, and other energies or ions up to the maximum $B\rho$ of the magnet as dotted lines. At any given time the operational maximum energies are determined by the status of certain limiting components, which is in turn determined by an involved network of decisions relating to program emphasis and optimization of resource allocations. Our present centering coil arrangement is an excellent illustration of the diverse factors which must be weighed in making such decisions. These coils were added several years ago to facilitate beam centering and are a major factor in the routine running of very precise beams. Two alternate designs for the coils were available. One could be installed in a two day shutdown but infringed on the rf tuning range by an amount equivalent to 6 MeV in proton energy; the other required a two month shutdown to install but with no effect on the rf. We elected the two day installation design, considering the two months of operating time thereby saved as more valuable than the 6 MeV change in the maximum proton energy. As a result of this and other similar decisions, we have arrived at the present de facto operating situation indicated in Fig. VI-9. We anticipate that at some unspecified future time a major failure will force an extended cyclotron shutdown. At that time we will undertake a thorough rennovation of the machine, making all the necessary changes required for extending the operating capabilities up to the full range of the magnet. In the meantime, experiments for which the additional energy is crucial are held in abeyance.

The dotted lines in Fig. VI-9 corresponding to heavy ion beams represent a different type of problem, namely our lack of an adequate ion source for heavy ions. Studies at Oak Ridge and Dubna have clearly established high arc power as the key parameter in successfully obtaining good yields of highly charged heavy ions from a cyclotron type source. The highly successful Oak Ridge program is, for example, presently utilizing a 75 Kw power supply to drive the arc, whereas one Kw arc power is the maximum achievable in our present facilities. As a result we have been unable to obtain certain desirable heavy ion beams even though we have confirmed thru acceleration of equivalent light ions ($^{3}He^{+}$ for $^{12}C^{4+}$ etc.) that the cyclotron was in exactly proper working configuration for such beams.
As it appears likely that an appropriate high power arc supply can be obtained through government surplus channels, we are at present not requesting funding for such a unit. When an appropriate supply becomes available, we should be able to rapidly proceed to activate most of the heavy ion beams indicated in Fig. VI-9.

IV.C.2. Single Turn Extraction and Phase Selection—One of the major points of emphasis in the MSU cyclotron development program has been the pioneering of the concept of single turn extraction. With such a configuration all particles travel through exactly the same number of revolutions from source to extraction. Moreover, the beam dimensions are very small compared to the magnet gaps and apertures of the electrical components, and non-linear effects are therefore quite small. The output beam is then, to excellent approximation, a simple linear transformation of the ion source, and no dilution of phase space density is introduced. By contrast, the multi-turn extraction system conventionally employed in cyclotrons leads to relatively poor extraction efficiency (50-70%), and to a much larger radial emittance.

While the preservation of beam quality has been our primary motivation in working toward single turn extraction, an important auxilliary benefit is the clean, low loss operation which results. Figure VI-10 is for example a plot of turn structure in our internal beam taken with the differential probe. The sharp spatial separation of the final turns makes 100% extraction efficiency routine so that activation of the cyclotron and radiation damage to components are minimal.

Having thus touted the virtues of single turn extraction, let us turn to the question of how one achieves such operation. The necessary conditions have been extensively discussed in the literature[10]—very briefly the essentials are accurate stabilization of magnetic field, rf frequency, and rf voltage, toghther with restriction of the beam to a narrow range of rf phase positioned at the effective top of the rf wave. The stabilization of the magnet and rf have been steadily improved by our engineering staff down to present levels of 2 in 10^5 for the magnet, 1 in 10^8 for rf frequency, and 2 in 10^4 for rf voltage, representing exceptional accomplishments as compared with normal cyclotron practice. The positioning of the occupied phase interval at the top of the rf wave is accomplished by a simple algorithm which is a standard part of the machine set-up procedure.

The much more intricate problem of selecting a narrow phase group has been the subject of extensive studies[141] which have led us to the successful development of a unique and highly effective phase selection system. The crucial element of this system is the positioning of selection slits at the points of maximum effectiveness. An idea of the type of phenomena involved can be obtained from Fig. VI-11 which gives computed radius and phase differences for a series of rays which left the ion source under identical conditions except for 2° shifts in starting time relative to the rf. The radial separation for given phase difference is seen to be strongly modulated and a phase selection slit can be either highly effective or quite ineffective depending on where it is placed. From the results of Fig. VI-11 and other similar studies (including position and direction displacements corresponding to the source emittance) a phase selection system was designed based on two slits placed to intercept the beam after 18 and 28 turns. The performance of this system has been outstanding, as is indicated in Fig. VI-12 which gives the results of an experimenal measurement of the phase width via observation of the time distribution of gamma rays from the beam hitting the internal probe. The distribution is triangular (as the calculations predict) with full width at half maximum of 0.2 nanoseconds which corresponds to 1.4° in phase. At this level the phase width contribution to the beam energy spread is small—energy spreads as good as 0.04% fwhm have been observed for the full external beam.

VI.C.3. Low Energy Beams—In the initial design of the cyclotron we assumed that the machine would not compete effectively with Van de Graaffs in their energy range and therefore terminated our magnetic field mapping at a level corresponding to 11 MeV protons. This proved an ill-advised decision since our magnetic analysis system is basically a fractional device and can readily work at levels down to one in 10^4 at all energies. This resolution corresponds, for example, to 500 ev at 5 MeV, and this highly attractive feature has been used advantageously in a number of experiments. Because of this interest in low energies, in the fall of 1969 we carried thru further mapping of the cyclotron field so that control settings can now be generated for arbitrarily low energies.

A further difficulty has been encountered in our low energy operations because our standard 220 turn operating mode leads to a dee voltage which is too low to extract particles effectively from the ion source. This difficulty will soon be remedied by results of a current thesis project aimed at developing an alternate 75 turn operating mode for the cyclotron. The lower turn number will in fact lead to much better fractional precision than we now achieve at high energies, and should therefore yield low energy beams with very outstanding characteristics.

VI.C.4. Computer Control System—One of the major difficulties facing an experimenter at our laboratory is the massive array of equipment which must be properly setup without the assistance of operators. Thus typically the experimenter must setup the cyclotron, make a series of required adjustments, setup the transport system, check the beam characteristics, setup his detection system, check its characteristics, setup his data processing system nearly always involving the computer, and finally, when all these elements are working properly, take data. While each step in this process is reasonably straightforward, the concentration required to set all elements properly is substantial and detracts from the ability of the experimenter to think about his experiment. Since budget problems apparently will not allow the hiring of operators at any time in the forseeable future and since the capabilities of our computer and our understanding of the cyclotron make computer control intrinsically feasible, we have for sometime been working on a low priority basis toward realization of such a system so as to relieve some of the strains on the nuclear physics users.

About one year ago a prototype section of a computer control system, which set the cyclotron trim coil currents, was installed and tested for some months. The results of these tests provided the basis for a greatly improved design—hardware and software for this new system are being steadily assembled although staff reductions from last year have significantly slowed the work such that we do not now expect the system to be operational until sometime in 1971. When available, the system will be of great value in allowing cyclotron users to more completely concentrate on their primary objectives.

VI.D. Computer

As was indicated in the introductory remarks our computer facility has evolved into an exceptionally powerful and versatile facility which is in many ways the focal point of the activities of the laboratory, handling nearly all data taking on-line and all data processing and computing. A typical faculty member or graduate student will tend to have several interactions per day with the computer making the preparation room a beehive of activity. The rapid turn-around-time on computations, which results from the time-sharing, enormously enhances ones effectiveness in any numerical exploration of a problem—in fact the fast feedback of factual information and consequent rapid progress often gives a pleasant (but regretfully illusory) feeling that one is much smarter than he used to be. Similarly, totally new data processing configurations can be setup in minutes or hours which in the days of wired program devices would likely have required months or years to realize. The ET^2 mass identification hookup for our spallation experiments is a typical example of a highly functional data processing algorithm which, with the computer system, is routinely set up in a few minutes. In the following subsections key properties of our computer configuration are briefly reviewed.

VI.D.1. System Hardware—The MSU Cyclotron Laboratory owns a XDS Sigma Seven Computer which includes the following:

CPU	with mapping and access protection
Memory	32K core of 32 bit words with parity check 4.5 Megabyte file RAD 5.4 Megabyte high speed RAD 2 Nine track tape transports
I/O	Line Printer Card Reader Card Punch Plotter (with our own vector operating controller) Console Teletype User Teletype

To this sytem we have interfaced:

ADC's	4 Northern Scientific 13 bit 50 MHz ADC's coupled through a special logic module. The experimenter can choose various coincidence and routing configurations. He may select any of 1 to 4 ADC's to run in coindicence mode, or two groups of doublets, etc. A routing box associated with the ADC's makes three extra bits avaiable for real time routing so that one ADC may feed up to 8 multichannel analysers in the Sigma. 1 Texas Instruments Successive approximation ADC with analog multiplexor (to allow computer monitoring of cyclotron set points etc.).
Crt's	3 scopes, 1 CPU driven Fairchild large screen scope and 2Textronix 611 Storage scopes. These allow interactive data taking and analysis with the storage scopes making only small demands upon the CPU. Associated with the scope are 3 banks of 32 toggle switches through which real-time interaction between user and computer is accomplished. (A buffer system for the Fairchild scope is being constructed.)
others	A memory dump interface has made our old ND-160 wired 2-D analyser a vastly more useful instrument. We also have interfaced a prototype controller for six trim coils and have a test set up for measuring cyclotron beam turn pattern. (These two systems are major parts of the computer control system discussed in the cyclotron section.) We are also in the process of interfacing the controls on our new high precision scattering chamber.

VI.D.2 System Software—At the time our computer was purchased, we perceived that commercial systems software would not give us use of the full machine capacity. A group of our graduate students (Plauger, Kopf, Merritt and Au) inspired by the visions of Professor Kane proceeded to develop and debug a supervisor and monitor system known as Janus which to our knowledge is the most effective time-sharing processing system yet realized in a nuclear laboratory. Operational features include:

1. Multi-programming with Symbiont I/O.
2. File manipulation.
3. Interactive CRT displays allowing real-time interaction with incoming data and "off-line" data analysis.
4. Rapid interrupt servicing (8 μs turn around time!)

To illustrate what this means to the experimenter, the following situation is typical. Simultaneously:

1. 2 experimenters taking data.
2. 1 experimenter checking his data as it comes in.
3. 1 experimenter analysing (through live display) data which he has taken in a previous experiment.
4. 3 students debugging FORTRAN programs.
5. Plotter grinding away on plots of spectra.

How can we do this? The difference between the JANUS system and others is that it does not timeshare users, it timeshares tasks with each task assigned its own monitor. This allows the resident supervisor to occupy only 3K of core! Yet, due to the full use of the memory mapping feature of the Sigma, each user may program as though he had the full 128K addressable space available.

VI.D.3. Specialized Software—This section describes a series of major data taking and operating programs specifically adopted to our own research facilities.

1. An impressive monitor called TOOTSIE allows the experimenter to use any of a number of experimental configurations through the teletype. The necessary code is automatically patched together. The necessary ADC's and display(s) are attached and the computer is ready to go to work. Examples of some of the often used two and three parameter configurations are:

2 parameters:	E vs ΔE (2 counter telescope) $E(\Delta E)$ vs E (2 counter telescope) ET^2 vs E (spallation studies) XE/E vs E (position counter)
3 parameters:	dL/dT vs L vs T (neutron TOF) ΔE_1 vs ΔE_2 vs E (3 counter telescope)

2. POLYPHEMUS, a high speed multichannel analyser.

3) A monitor called MOIRAE allows interactive data analysis via CTR display.

4. HYDRA-using routine provides up to 32 Multichannel Analysers any of which may be displayed on line.

5. EVENT, a data recording task for acquisition at low rates, using magnetic tape storage.

6. SETOP, a code which generates a complete list of settings for all cyclotron and beam transport system controls. Particle, energy, and beam line are specified via the teletype.

VI.D.4 <u>Scientific Software</u>—This section briefly lists or describes a series of major scientific programs now operational on the Sigma. The list is not complete but hopefully gives an adequate general impression.

1. JULIE, the well known large and versatile ORNL DWBA code.

2. The LRL code SAMPO, an automated peak strip code.

3. SNOOPY, an optical model code by P. Schwandt.

4. TAMURA, a DWBA code by Haybron and Tamura at ORNL.

5. SHERIF AND BLAIR, an optical model code by H. S. Sherif of Univ. of Washington. (Code not yet debugged.)

6. The Oak Ridge Shell model code as described in Section III.

7. All MSU accelerator codes, including CYCLONE a uniquely complete code which gives a rapid complete calculation of cyclotron particle orbits from ion source to exit port, and a series of other well known codes developed at MSU and widely used here and elsewhere for analysis of cyclotron behavior.

VI.D. Lithium-Drifted Germanium Detectors for Charged Particle Spectroscopy

Because of the numerous problems in obtaining silicon semiconductor detectors capable of high resolution yet with thcknesses adequate for stopping 40-50 MeV protons we have undertaken a program of developing lithium-drifted germanium for charged-particle spectroscopy. This program has led to impressive accomplishments in several areas. In 1966, for example, we detected 160 MeV protons with a resolution of 650 keV FWHM (this resolution was mostly beam energy spread). This remains the highest energy to which such detectors have been applied. This work was soon to be followed by the development of high resolution proton detectors capable of stopping 50 MeV protons. A best resolution of 21 keV FWHM was achieved. (More typical is the 30 keV resolution achieved in two extensive studies, ^{40}Ca(p,p') and ^{48}Ca(p,p'), both done at 40 MeV). To date, these detectors have been used on inelastic proton scattering studies on ^{40}Ca, ^{48}Ca, ^{50}Ti, ^{51}V, ^{52}Cr, ^{58}Ni, ^{60}Ni, ^{62}Ni, ^{64}Ni, and ^{209}Bi.

During the development of the Ge(Li) charged particle detectors several important applications and techniques were discovered. A single-crystal directionally-sensitive gamma-detector with Compton suppression capabilities was developed. This device is commonly marketed as the "DUODE".[a] One of its illustrative applications is in imaging radiotheraputic sources implanted in the body. During the course of testing charged particle detectors it was discovered that a single Ge(Li) detector could be used as a conversion coefficient spectrometer. The technique is comparable in sensitivity to existing techniques but is considerably more economical to impliment. This scheme has subsequently been used on numerous occasions in β-γ spectroscopy experiments. Techniques for structuring the electrodes of the Ge(Li) detectors have been applied such that one may measure the specific ionization of the particle simultaneous to the energy measurement thus enabling the identification of the particle.

Most recently the detector development program has been studying possible applications in detection of pions. Here the main concern has been directed toward techniques allowing the observation of the pion decays in the Ge(Li) detector.

a. Available from Princeton Gamma Tech.

VI.E. On-Line Mass Separator

Our decay scheme experiments are generally moving toward shorter lived isotopes that are farther from the line of beta stability. Generally these involve nuclei that cannot be studied by reaction scattering experiments and should give considerable added insight into problems of nuclear structure.

Unfortunately, as one produces activities further and further from the line of beta stability, it becomes increasingly difficult to produce only the one activity desired. More nuclear reactions become possible and the excitation functions overlap considerably. Life-times are also short and on-line mass separation is hence usually necessary in order to do careful identification and study. Unfortunately, the usual mass separators are both inefficient and expensive (typically $\gtrsim \$150{,}000$).

As an exploratory study we are in the process of adapting an electrostatic quadrupole mass filter for use as an on-line mass separator. This device is relatively inexpensive ($\approx \$20{,}000$) and has valuable auxilliary uses (as a residual gas analyzer for vacuum systems, etc.).

The on-line mass separator system will consist of a number of parts: 1) radioactive nuclei will recoil from the production target into a helium gas filled space and be thermalized and neutralized; 2) the helium and the radioactive atoms will be pumped through a capillary tube (laminar flow) and transported outside the cyclotron beam area; 3) most of the helium gas will be kinetically skimmed away as the gas flows out of the end of the capillary tube leaving the more massive radioactive atoms to recoil into an ionizer; 4) the radioactive atoms will be ionized and mass analyzed by the quadrupole filter; and 5) the mass separated nuclei will be collected and counted using conventional techniques.

At present the mass filter (purchased using funds obtained from the NSF Science Development Grant) produces impressively accurate mass spectra. All other components have been individually tested and function properly and in a few weeks we expect to begin final tests of the complete system.

VI.F. Other Facilities

Our discussion of Research Facilities could readily include a description of a number of items not as yet mentioned. Important progress has been made in many areas including beam line instrumentation, the new precision 48" scattering chamber, the fast rabbit system, the ^{3}He recovery system, various gas target facilities, etc. While discussion of these facilities would be informative an adequate perspective view of our research facilities has hopefully been already conveyed by the previous material and so it seems reasonable to omit further detailed discussion. (We would of course be happy to respond to specific inquires if some point of interest is inadequately covered.)

STAFF

STAFF

The faculty of the MSU Physics and Chemistry Departments with principal research in nuclear phenomena are:

Professors

S. Austin*
H. Blosser*
A. Galonsky*
M. Gordon*
C. Gruhn*
S. Haynes
E. Kashy*
W. Kelly*
H. McManus

Assoc. Profs.

W. Benenson*
G. Bertsch (Sep. 1971)
G. Crawley*
K. Koltveit
W. McHarris
J. Nolen (Sep. 1970)*
B. Wildenthal*

Asst. Profs.

T. Arnette*
F. Bernthal (Sep. 1970)
J. Borysowicz

*=summer salary from cyclotron operating grant.

Scientifically this group operates as a coherent whole, collaborating on experiments, sharing research facilities, and joining in seminars and discussions. In carrying out these endeavors the normal working pattern consists of a spontaneous forming and reforming of many collaborations in accord with the research interests of the various individuals and reflecting such random factors as meetings in halls or conversations at coffee and also often heavily influenced by the character of nature as uncovered in the evolving results of experiments and calculations. Superimposed on this scientific coherence are various somewhat arbitrary administrative distinctions. Thus in the above faculty list only those persons marked with an asterisk are considered as attached to the NSF Cyclotron operating grant. The nuclear theory program under Prof. McManus and the nuclear chemistry program under Prof. McHarris are administratively viewed as AEC supported. The major facilities (the cyclotron and the computer) provided and largely maintained by the NSF grants are however utilized by the whole group on an equal basis and the scientific output reflects a complicated mixing of effort of the whole group. The list of publications given in the Appendix is thus formally a list of the publications of the NSF supported subset of the nuclear faculty (i.e. the asterisk marked group). In spite of this, in looking at the authors in this listing the names of the other nuclear faculty are seen to occur with great frequency due to the collaborations and in these cases the work is partially supported by the Atomic Energy Commission in addition to the NSF support provided by the cyclotron operating grant.

Also, increasingly the scientific output of the laboratory is enhanced by collaborations with visitors from other laboratories. A number of interactions of this type are evident from the list of publications. Moreover, the superior resolution characteristics of our spectrograph facility are apparently leading to development of a number of new collaborations which is highly desirable as the output of this facility is now severely impeded by a plate scanning bottleneck and collaboration with groups experienced in scanning is of great help in circumventing this problem.

With respect to the NSF supported faculty the present size of the group is just as anticipated in our proposal of five years ago but with the direct emphasis on nuclear physics somewhat enhanced as a result of having replaced Professors Johnson and Kane (who resigned during the period) by Professors Crawley and Wildenthal. We are also exceedingly pleased that Dr. J. Nolen will be joining us in Sept. filling an Associate Professor position provided under the NSF Science Development Grant to MSU. Since Dr. Nolen has not participated in the preparation of this proposal and his publications are not included in the listing in the appendix we append at the end of this section a brief one-page resume indicating his experience and areas of interest.

In addition to the faculty the scientific output of the laboratory depends heavily on our Research Associates and Graduate Students. Through the previous five year period we have had an average of approximately five persons on research associate appointments at any given time, the number reaching a peak of six and being programmed to decrease to four in our 1971 budget. Normally these appointments are for a two year period although in one or two cases an additional year has been added to allow completion of lengthy projects. These appointments have been highly productive in terms of augmenting the research output of the laboratory and also by way of providing a stimulating and varied research experience for the young scientists involved. Publications of our research associates are included in the listing in the Appendix.

Our graduate students also contribute greatly to the scientific productivity of the laboratroy and in addition, emerging as trained scientists, they represent one of the important products of the laboratory. Our graduate program from the beginning has followed the now increasingly popular trend of allowing students broad flexibility in the selection of thesis topics. Thus we require only that the thesis topic be (a) appropriate to the fundamental purpose of teaching the student to do effective research, (b) of mutual interest to the student and some faculty advisor and (c) compatible with the facilities and other programs of the laboratory. This policy has led to a much broader range of thesis topics than is normal for a nuclear laboratory as is evident from a study of the list of thesis titles which follows. In the present difficult job situation this broadened training has had the important advantage of giving our students a special attraction. Thus for example, students who have been involved in systems programming find themselves still being sought out by recruiters, students with substantial instrumentation experience are still in 1970 receiving multiple job offers, and even students who have intensively concentrated on pure nuclear problems find the instrumentation experience which one inevitably soaks up in the environment of our laboratory a valuable asset in seeking positions. We believe our graduate training philosophy is soundly based, yielding scientists trained in a way which the society needs and can absorb and even though we are implementing a modest scaling down of the number of students, we plan to continue a vigorous graduate program aimed at providing our students a broadly based research experience which can form a sound base for a future productive career in a wide spectrum of scientific activities.

The names of the students who have completed Ph.D.'s since our previous proposal was submitted, their thesis titles and their present positions are listed below. The list is restricted to students whose thesis supervisors are marked with an asterisk in the faculty list. Seven other students have completed Ph.D.'s in the five year period under the guidance of faculty from the nuclear theory group and nuclear chemistry group. While these latter students have utilized and benefited from the facilities provided by the cyclotron operating grant they are formally considered as attached to the other groups and are therefore not included in the listing.

1966

Ronald L. Auble—A Study of Nuclear Energy Levels in ^{121,123,125}Sb and ^{127}I using β and γ-ray spectroscopy—Staff Physicist-Oak Ridge National Laboratory.

Richard Berg—Precise Method for Pre-calculation of Cyclotron Control Settings—Asst. Prof.-Univ. of Maryland.

Merritt L. Mallory—Phase Space Density Studies on Cyclotron Ion Sources—Staff Physicist-Oak Ridge National Laboratory.

1967

Louis M. Beyer—The MSU Six Gap β-ray Spectrometer and its Application to β-γ studies of ^{83}Sr and ^{131m}Te—Assoc. Prof.-Murray State Univ.

George J. Berzins—High Reoslution γ-ray Spectral Studies of the Decays of ^{117,119g,119m,129g,129m}Te—Staff Physicist-Los Alamos Scientific Lab.

Robert C. Etherton—Conversion-Electron and γ-ray Experiments with the Decay of Bromine-82 and Strontium-83—Prof.-Murray State Univ.

Raymond L. Kozub—An Investigation of the (p,d) Reaction on N=Z Nuclei in the 2s-1d Shell—Asst. Prof.-Texas A&M.

1967(cont.)

Lorenz A. Kull—An Investigation of (p,d) Reactions in 1p Shell Nuclei—Staff Physicist-General Atomic Corp.

1968

John O. Kopf—Janus, a Realtime Time-sharing Computer System for use in Nuclear Physics Experiments—Staff Physicist-LRL, Berkley.

James L. Snelgrove—Energy Dependence and Spectroscopy with $^{16}O(p,d)^{15}O$ and $^{15}N(p,d)^{14}N$ Reactions—Staff Physicist-Argonne National Lab.

1969

Dwight B. Beery—γ-ray Spectroscopy Studies of Excited States of Odd Proton (odd mass) Nuclei in the Z=50-62 N=64-82 Region—Assoc. Prof.-Manchester College.

James J. Kolata—Proton Spin Flip in the Reactions $^{12}C(p,p')^{12}C^*(4.44)$ and $^{120}Sn(p,p')^{120}Sn^*(1.17)$—Research Assoc.-Univ. of Pittsburgh.

Kenneth M. Thompson—Inelastic Proton Scattering at 40 MeV from even Nickel Isotopes—Staff Physicist-Argonne National Laboratory.

Phillip J. Plauger—Spectroscopy in the Titanium Isotopes via (p,d) and (p,t) Reactions—Staff Physicist-Bell Laboratories.

Robert A. Paddock—A Study of the Energy Levels of ^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar and ^{38}Ca by the (p,t) Reaction—Asst. Prof-Ripon College.

1970

William L. Pickles—Elastic Scattering and Reactions in the Bombardment of ^{14}N by 20 MeV Deuterons—Staff Physicist-LRL, Livermore.

George F. Trentleman—An Experimental Test of the Isobaric Multiplet Mass Equation—Research Assoc.-MSU.

Scientific Resume—Jerry A. Nolen, Jr.

Professor Nolen took his BS at Lehigh University (1961) and his PhD from Princeton (1965). During his graduate studies he held a Woodrow Wilson Fellowship (1961-62). After completing his PhD he spent one year as an Instructor at Princeton and then two years as a Post-doctoral Fellow at the Argonne National Laboratory. Since Spet. 1968, he has been an Assistant Professor at the University of Maryland. Dr. Nolen's main research interests have been in multiparticle transfer reactions and in the determination of nuclear coulomb energies. Some recent publications are:

Study of the Ca^{48}(He^{3},p)Sc^{50} Reaction, with H. Ohnuma, J. R. Erskine, J. P. Sciffer, and P. G. Roos, Phys. Rev. 177, 1695 (1969).

Comparison of Spectroscopic Factors from (p,p_0) and (d,p) Reactions on Barium Isotopees, with G. C. Morrison, N. Williams, and D. vonEhrenstein, Proc. of the Second Conference on Nuclear Isosopin, Asilomar, Calif., March 1969.

Couomb Energies and Nuclear Radii, Contribution to the International Conference on Properties of Nuclear States, Montreal Canada, 1969, p. 321, (with J. P. Schiffer).

Couomb Energies—An Anomaly in Nuclear Matter Radii, with J. P. Schiffer, PL 29B, 396, 1969.

On Coulomb Energies, The Anamalous Isotope Shift of Nuclear Radii, and Core Polarization by the Neutron Excess, with J. P. Schiffer and N. Williams, PL 29B, 399, 1969.

Level Structure of Sc^{48} from the Ca^{48}(He^{3},t) Reaction, with H. Ohnuma, J. R. Erskine, J. P. Schiffer, and N. Williams, Phys. Rev. C., 1, 496, 1970.

Study of the (d,p) Reaction on the Even-A Barium Isotopes 130-138, with D. vonEhrenstein, G. C. Morrison, and N. Williams, Phys. Rev. C., to appear June 1970.

BUDGET

BUDGET

Our cost estimates for the five year period covered by this proposal are based on a detailed estimate for the first year as shown on the following page and an 8% per year increment in subsequent years. Funding on this basis would maintain the staff of the laboratory at its present level through the five year period, assuming cost escalation factors continue to behave as they have in the recent past. The detailed cost estimate for the first year totals to $819,500. The 8% escalation estimate then implies costs of $885K, 956K, 1032K, 1115K for the following years or a total for the period of $4,017,500. As in the previous five years, we will annually submit revised detailed cost estimates. If the present rising cost trend should level off, these revised estimates would be reduced as compared to the above figures.

The estimate of $819,500 for 1971 is 9% above the $750,000 grant which we received for the present year though the program level anticipated for 1971 is if anything slightly reduced as compared with 1970. This disparity is due predominantly to a rather large increase in the indirect cost item from $187,000 in 1970 to an estimated $225,310 in 1971 even though the salary estimate for 1971 is lower than that for 1970 ($369,370 versus $374,520). This increase in indirect costs is a combined effect of a change from 58% to 61% in the negotiated overhead for MSU and the fact that the gradual transition from the

Proposed Budget (January 1, 1971 thru December 31, 1971)

Proposal for Support of the Nuclear Physics Program of the Michigan State University Cyclotron.

SALARIES:

	NSF	MSU
Faculty	52,240	104,480
Research Assoc.	41,700	-------
Admin. Prof.	65,260	15,820
Clerical Tech.	14,750	5,750
Regular Labor	71,720	23,810
Student Labor	19,600	-------
Grad. Res. Asst. (22)	104,100	-------
Salary Subtotal	369,370	149,860
Fringe Benefits	29,500	19,960
Indirect Costs 61%	225,310	91,410
Total Salaries & Indirect Costs	624,180	261,230

OTHER EXPENDITURES:

	NSF	MSU
Cyclotron Electricity	24,000	0
Computer:		
Rental Equip.	18,000	0
Maintenance Agree.	28,500	0
Supplies	16,300	0
Travel	6,000	0
Publications	12,000	0
Expendable Equip.	45,000	0
Targets & Detectors	18,000	0
Perm. Equip.	27,500	0
TOTAL PROJECT (rounded)	$819,500	$261,200

old NSF 20% overhead rule to the negoiated rate has now been completed. The University will in this year and future years charge the grant the full overhead allowed by NSF regulations thus reducing the spendable money available to the project. (The total unfavorable impact of the change in overhead rules on the project has, however, been greatly reduced by the gradual transition and the cooperation of the University in setting up this arrangement has contributed greatly to the progress and productivity of the Laboratory.)

The 1971 budget presumes several offsetting adjustments in the project staff. The faculty salaries item is increased to allow for the summer salary of Dr. Jerry Nolen who will join us in September filling a position provided under the NSF Science Development Grant. This increase, along with increases due to salary raises, is more than offset by planned reductions in our Research Associate staff (by one) and in our Graduate Research Assistants (by two). We note that this latter change is in keeping with a departmental policy of gradually reducing the number of graduate students to produce a better balance between supply and demand. While reducing the number of graduate assistants is clearly prudent and proper in present circumstances, it is also of great value to make such reductions gradually thus maintaining our graduate student recruiting channels intact and resulting we hope in the admission of a reduced number of more talented students.

Moderate increases in several of the "other expenditure" categories are based on bringing these items into line with our present spending experience and are "bare bones" allowances for such essentials as targets, dry ice, liquid nitrogen, repairs of purchased electronics, detectors etc. The increase in these items we emphasize is in comparison with this years budget rather than this years expenditures, the difference between these two occurring because it has been possible for the past two years to have the budget items for these categories smaller than expenditures due to fund carryovers from the more adequate allowances of earlier years. These fund carryovers are now exhausted and supplies for 1971 and following years will have to be fully provided from the operating funds for those years. We have therefore programmed a reduction in salaries in order to provide a reasonably optimized supplies allocation.

The comparison of our 1970 program level with that which our proposed budget would provide for 1971 can also be judged by deducting the indirect cost item from the budgets for the two years so as to focus on the spendable money. The resulting figures are $563,000 for 1970 and $594,000 requested for 1971 or an increase of 5.5%. This percentage is clearly somewhat lower than the present annual escalation of costs and therefore the budget implies slightly reduced program support for 1971. We believe however that we will be able to offset such a reduction by further increases in efficiency and thus continue to raise the research productivity of the Laboratory.

In making up our budget we have conscientiously tried to weigh the disparate motivations to minimize the request on the one hand so as to reduce the demand on scarce basic research funds versus consideration of the fact that our facility has many unique capabilities and the research objectives of the national nuclear physics program will be most rapidly advanced by relatively full exploitation of a facility with such capabilities. The budget presented is our best thought as to a proper compromise between these factors.

APPENDIX: Staff Publications 1965-70

We list on following pages publications by our staff for the period Jan. 1965 thru Aug. 1970. The publications marked with an asterisk (*) indicate work at another laboratory either by staff members on leave or by staff members who joined the project during the period. The complete year 1965 is included in the list even though part of that year was also covered in the previous proposal since these references are now in complete form whereas previously they were largely listed as "to be published". In referring to references from the text we have used a numbering system corresponding to the numbers in this Appendix. Articles published, articles submitted and abstracts are grouped separately.

We have not included any listing of talks, seminars, national committee assignments etc. although faculty from the project have been frequently involved in such assignments. Invited papers, which have totaled nine in the 5 year period are also not explicitly listed, nor are fellowships and other awards. We cannot however refrain from mentioning a recent signal honor to one of us (E. Kashy) who was one of only eleven American physicists to receive Guggenheim awards in the present year. We are all pleased at this recognition of an exceptionally talented physicist who typifies the spirit and vigor of the laboratory.

APPENDIX

PUBLICATIONS 1965 - 1970

1. THE FOCUSING AIR CORE MAGNETIC CHANNEL FOR THE MSU CYCLOTRON, R.E. BERG AND H. G. BLOSSER, IEEE TRANS. ON NUCL. SCI. 12#3, 393 (1965).

2. SECTORED CYCLOTRONS, H. G. BLOSSER, IEEE TRANS. ON NUCL. SCI. 12 #3, 985 (1965).

3. A STUDY OF THE EXCITED STATES OF 127I POPULATED IN THE DECAY OF 127TE AND 127MTE, R. L. AUBLE AND W. H. KELLY, NUCL. PHYS. 73, 25 (1965).

4.* A CHANGE FROM STRONG TO WEAK COUPLING BETWEEN 25MG AND 27AL, G. M. CRAWLEY AND G. T. GARVEY, PHYS. LETTERS 19, 228 (1965).

5. STUDY OF THE 40CA(4HE,2*4HE) REACTIONS, R. W. BAUER, G. HEYMANN, W. KOSSLER, N. S. WALL, C. R. GRUHN, REV. MOD. PHYS. 37#3, 369 (1965).

6.* THE 3HE(3HE,2P)4HE REACTION, J. P. ALDRIDGE, III, B. H. WILDENTHAL AND D. H. YOUNGBLOOD, REV. MOD. PHYS. 37, 430 (1965).

7.* LEVELS OF RH101 POPULATED BY THE DECAY OF PD101, J. S. EVANS, E. KASHY, R. A. NAUMANN AND R. F. PETRY, PHYS. REV. 138, B9 (1965).

8.* VACUUM CHAMBER WITH STABLE PERMEABILITY IN A HIGH-POWER ACCELERATOR, A. GALONSKY, G. DEL CASTILLO, AND F. F. DYER, JOURNAL OF NUCLEAR ENERGY PART C, VOL. 7, 585 (1965).

9.* ANALYSIS OF SINGLE EXCITATIONS IN INELASTIC DEUTERON SCATTERING FROM 60NI, 60ZR AND 120SN NUCLEI, R. K. JOLLY, PHYS. REV., 139, B318 (1965).

10.* COUPLED CHANNELS ANALYSIS OF ONE AND TWO PHONON STATE CROSS SECTIONS IN (D,D') ON 60NI, T. TAMURA AND R. K. JOLLY, PHYS. LETTERS, 18, 295 (1965).

11.* STUDY OF ISOBARIC STATES VIA (P,P) AND (P,N) REACTIONS ON EVEN SAMARIUM ISOTAOPES, R. K. JOLLY AND C. F. MOORE, PHYS. LETTERS 19, 139 (1965).

12. SINGLE TURN EXTRACTION, M. M. GORDON, IEEE TRANS. ON NUCL. SCI. VOL. NS-13, NO. 4, 48 (AUG., 1966).

13. REPORT FROM THE 1966 INTERNATIONAL CONF. ON ISOCHRONOUS CYCLOTRONS, H. G. BLOSSER, NUCLEONICS 24, 54 (1966).

14. PROBLEMS AND PERFORMANCE IN THE CYCLOTRON CENTRAL REGION, H. G. BLOSSER, IEEE TRANS. ON NUCL. SCI. 13#4, 1(1966).

15. PHASE SPACE DENSITY STUDIES ON CYCLOTRON ION SOURCES, M. S. MALLORY AND H. G. BLOSSER, IEEE TRANS. ON UCL. SCI. 13#4, 1963 (1966).

16. CONTROL OF THE MICHIGAN STATE UNIVERSITY CYCLOTRON, R. E. BERG, H. G. BLOSSER AND M. M. GORDON, IEEE TRANS. ON NUCL. SCI. 13#4, 394 (1966).

17. THE MSU 53 MEV CYCLOTRON, H. G. BLOSSER AND A. GALONSKY, IEEE TRANS. ON NUCL. SCI. 13#4, 466 (1966).

18.* HOLE STATES IN CA43 AND CA47, T. W. CONLON, B. F. BAYMAN AND E. KASHY, PHYS. REV. 144, 941 (1966).

19. MEASUREMENT OF HIGH ENERGY GAMMA-RAYS WITH GE(LI) DETECTORS, R. E. BERG AND E. KASHY, NUCL. INSTR. AND METHODS 39, 169 (1966).

20.* J-DEPENDENCE IN THE FE56(P,D)FE55 REACTION, C. A. WHITTEN, E. KASHY AND J. P. SCHIFFER, NUCL. PHYS. 86, 638 (1966).

21.* INELASTIC PROTON SCATTERING ON THE ISOTOPES 62NI, 64NI, 63CU AND 65 CU AT 17.5 MEV, A. L. MCCARTHY AND G. M. CRAWLEY, PHYSICAL REVIEW 50, 935 (1966).

22. EXCITED STATES IN 82KR POPULATED BY THE DECAY OF 35 H 82BR, R. C. ETHERTON AND W. H. KELLY, NUCL. PHYS. 84, 129 (1966).

23. A STUDY OF 123SB LEVELS POPULATED IN THE BETA DECAY OF THE HIGH SPIN ISOMER OF 123SN, R. L. AUBLE AND W. H. KELLY, NUCLEAR PHYS. 81, 442 (1966).

24. LEVELS OF 85SR POPULATED IN THE DECAY OF 85Y AND 85MY, D. J. HOREN AND W. H. KELLY, PHYS. REV. 145, 988 (1966).

25. BETA AND GAMMA SPECTROSCOPIC STUDIES OF 9.7 D 125SN, R. L. AUBLE AND W. H. KELLY, NUCLEAR PHYS. 79, 577 (1966).

26.* SPINS OF LEVELS IN 41SC, D. H. YOUNGBLOOD, B. H. WILDENTHAL AND C. M. CLASS, NUCLEAR SPIN-PARITY ASSIGNMENTS, (ACADEMIC PRESS, NEW YORK, 1966).

27.* A COMPARISON OF THE EFFECTIVE TWO-NUCLEON INTERACTION IN 2S 1/2 - 1D 3/2 SHELL NUCLEI WITH A SURFACE DELTA INTERACTION, P. W. M. GLAUDEMANS, B. H. WILDENTHAL AND J. B. MCGRORY, PHYSICS LETTERS, VOL. 21, P. 427 (1966).

28.* TRANSMISSION OF 8 AND 15 MEV NEUTRONS THROUGH ORIENTED 165HO, E. G. SHELLEY, T. R. RISHER, R. S. SAFRATA, J. MCCARTHY AND S. M. AUSTIN, PHYS. LETTERS 19, 684 (1966).

29. LARGE-ANGLE ELASTIC SCATTERING OF ALPHA PARTICLES BY 39K, 40CA, 44CA, AND 50TI, C. R. GRUHN AND N. S. WALL, NUCLEAR PHYSICS 81, 161, (1966).

30. PROTON SPECTRA FROM REACTIONS INDUCED BY 30.5 MEV ALPHA PARTICLES, L. W. SWENSON AND C. R. GRUHN, PHYS. REV. 146, 886 (1966).

31.* DISTORTED WAVE PREDICTIONS OF OBSERVED J DEPENDENCE IN THE (D,3HE) REACTIONS, B. M. PREEDOM, E. NEWMAN AND J. C. HIEBERT, PHYS. LETTERS 22, 657 (1966).

32.* (D,P) AND (D,T) REACTION STUDIES ON 144SM, 148SM AND 150SM, R. K. JOLLY AND C. F. MOORE, PHYS. REV. 145, 918 (1966).

33. THE BEAM TRANSPORT SYSTEM OF THE MICHIGAN STATE UNIVERSITY CYCLOTRON, G. H. MACKENSIE, E. KASHY, M. M. GORDON AND H. G. BLOSSER, IEEE TRANS. ON NUCL. SCI. 14#3, 450 (1967).

34. EXCITATION ENERGY OF THE FIRST EXCITED STATE OF C12, AND OBSERVATION OF A COHERENT DOPPLER EFFECT, J. J. KOLATA, R. AUBLE AND A. GALONSKY, PHYS. REV. 162, 957 (1967).

35. THE 12C(P,T)10C REACTION AT 43 MEV, W. P. JOHNSON, G. M. CRAWLEY AND W. BENENSON, INTERNATIONAL NUCLEAR PHYSICS CONFERENCE (GATLINBURG, 1966) 942, ED. R. L. BECKER ACADEMIC PRESS 1967.

36. EXCITATION OF 6LI AND 7LI BY INELASTIC PROTON SCATTERING AT 24.4 MEV, G. M. CRAWLEY AND S. M. AUSTIN, INTERNATIONAL NUCLEAR PHYSICS CONFERENCE (GATLINBURG 1966) P. 165, ED. R. L. BECKER ACADEMIC PRESS 1967.

37. EXCITED STATES OF 10C FROM THE 12C(P,T)10C REACTION AT EP = 43 AND 52 MEV, W. BENENSON, G. M. CRAWLEY, J. D. DREISBACH AND W. P. JOHNSON, NUCLEAR PHYSICS A97, 510 (1967).

38.* GALILEO GALILEI, HIS LIFE AND HIGH WORKS, BY RAYMOND J. SEEGER. BOOK REVIEW BY G. M. CRAWLEY, AUSTRALIAN JOURNAL OF SCIENCE, 30#1, 35 (1967).

39.* INELASTIC SCATTERING IN THE 2S 1D SHELL. I. EVEN-A NUCLEI, G. M. CRAWLEY AND G. T. GARVEY, PHYS. REV. 160 981 (1967).

40. 36K DECAY AND T = 1 ANALOG IN 36 AR, R. E. BERG, J. L. SNELGROVE AND E. KASHY, NUCL. INSTR. AND METHODS 52, 153 (1967).

41. ENERGY REPRODUCITILITY IN BEAM ANALYZING MAGNETS, J. SNELGROVE AND E. KASHY, NUCL. INSTR. AND METHODS 52, 153 (1967).

42. THE 14N(P,D(N13 REACTION AT 30 MEV, R. L. KOZUB, L. A. KULL AND E. KASHY, NUCL. INSTR. AND METHODS 52, 153 (1967).

43.* MEAN LIFETIME OF THE 8.88 MEV STATE IN 16O, R. E. PIXLEY AND W. BENENSON, NUCL. PHYS. A91, 177 (1967).

44. HIGH RESOLUTION GAMMA-RAY SPECTROSCOPIC STUDIES OF 119TE ISOMERS, G. BERZINS AND W. H. KELLY, NUCL. PHYS. A92, 65 (1967).

45. COINCIDENCE STUDIES OF 131MTE, 6. M. BEYER, G. BERZINS AND W. H. KELLY, NUCL. PHYS. A93, 436 (1967).

46. DECAY SCHEMES OF 70 MIN 129GTE AND 33 D129MTE, G BERZINS, L. M. BEYER, W. H. KELLY, W. B. WALTERS AND G. E. GORDON, NUCL. PHYS. A93, 456 (1967).

47. COINCIDENCE-ANTI-COINCIDENCE GAMMA RAY SPECTROSCOPY WITH A NAI(TL) SPLIT ANNULUS AND A GE(LI) DETECTOR, R. L. AUBLE, D. B. BEERY, G. BERZINS, L. M. BEYER, R. C, EHTERTON, W. H. KELLY AND W. C. MCHARRIS, NUCL. INSTR. AND METHODS, 51, 61 (1967).

48. GE(LI)-NAI(TL) STUDIES OF THE DECAY OF 117TE, G. BERZINS, W. H. KELLY G. GRAEFFE AND W. B. WALTERS, NUC. PHYS. A104, 241 (1967).

49. GE(LI) - NAI(T) ANGULAR CORRELATION STUDIES OF GAMMA CASCADES IN THE DECAY OF 119MTE, G. BERZINS AND W. H. KELLY, NUCL. PHYS. A104, 263 (1967).

50. CONVERSION ELECTRON MEASUREMENTS OF TRANSITIONS FOLLOWING THE BETA DECAY OF 131MTE, L. M. BEYER AND W. H. KELLY, NUCLEAR PHYS. A104, 274 (1967).

51. A SINGLE CRYSTAL GE(LI) COMPTON SPECTROMETER, C. R. GRUHN, J. V. KANE, W. H. KELLY, T. KUO AND G. BERZINS, NUCLEAR INSTRUMENTS AND METHODS 54, 268 (1967).

52.* INTERACTION OF FAST NEUTRONS WITH ORIENTED 165HO, T. R. FISHER, R. S. SAFRATA, E. G. SHELLEY, J. MCCARTHY, R. C. BARRETT AND S. M. AUSTIN, PHYS. REV. 157, 1149 (1967).

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Table I-1: Spectroscopic factors S extracted from $^{16}O(p,d)^{15}O$ data with standard and improved DWBA analysis.[a]

Proton Energy (MeV)	Standard DWBA			Improved DWBA		
	$S(1p_{1/2})$	$S(1p_{3/2})$	$\frac{S(3/2)}{S(1/2)}$	$S(1p_{3/2})$	$S(1p_{3/2})$	$\frac{S(3/2)}{S(1/2)}$
31.82	2.5	2.2	0.88	2.6	5.7	2.2
38.63	2.8	2.2	0.79	2.3	3.9	1.7
45.34	3.5	2.2	0.63	2.3	3.8	1.7
Sum Rule	2	4	2	2	4	2

a. Ref. 134.

Table I-2: Spectroscopic factors extracted from $^{28}Si(p,d)^{29}Si$ data and predictions of simple shell model and rotational models.

E_{exp} (MeV)	J^{π}	C^2S_{exp}	$C^2S^{b.}_{SM}$	$C^2S^{c.}_{ROT}(n=+4)$
0.00	$5/2^+$	3.45	3.92	1.26
0.77	$1/2^+$	0.64	0.83	0.28
0.95	$3/2^+$	0.32	----	0.46
2.65	$5/2^+$	0.47	0.54	
2.90	$3/2^+$	-0.81	----	

b. ref. 91

c. under assumption $\Psi = .707(K=5/2(202)+.707(K=1/2(211))$

Table I-3: Spectroscopic factors and energies measured and calculated for the (p,d) reaction on ^{34}S, ^{35}Cl and ^{37}Cl.

Final Nucleus	J^{π}	T	E_{exp} (MeV)	E_{calc} (MeV)	$S(j)_{exp}$	$S(j)_{calc}$
^{33}S	$3/2^+$	1/2	0.00	0.00	1.85	1.87
	$1/2^+$	1/2	0.84	1.00	0.50	0.85
	$5/2^+$	1/2	1.97	2.20	0.03	0.17
	$3/2^+$	1/2	2.31	2.31	0.16	0.25
	$5/2^+$	1/2	2.87	2.74	1.29	1.58
^{34}Cl	0^+	1	0.00	0.00	0.84	0.94
	3^+	0	0.15	0.41	0.95	1.06
^{36}Cl	2^+	1	0.00	0.00	1.05	1.09
	3^+	1	0.78	0.83	1.44	1.49

Table I-4: Reaction Q-values and mass excesses for the T_Z=-3/2 nuclei ^{9}C, ^{13}O, and ^{21}Mg.

Element	Reaction	Q-value (MeV)	Mass Excess (MeV)	Mass Excess Previously Reported (MeV)
^{9}C	^{12}C(^{3}He,^{6}He)^{9}C	-31.578±.008	28.911±.009	28.906±.004
^{13}O	^{16}O(^{3}He,^{6}He)^{13}O	-30.506±.013	23.103±.014	23.11 ±.070
^{21}Mg	^{24}Mg(^{3}He,^{6}He)^{21}Mg	-27.512±.018	10.912±.018	10.95 ±.120

Table I-5: Empirically determined coefficients for the mass equation $M=a+bT_Z+cT_Z^2$ using the latest T_Z=-3/2 mass excess values. The last column indicates the coefficients of a T_Z^3 term assuming the equation to have the form $M=a+bT_Z+cT_Z^2+dT_Z^3$. The coefficients were determined from a weighted least squares fit, and the χ^2 for the fit with the quadratic equation is indicated.

mass	a(β,T) MeV	b(β,T) MeV	c(β,T) MeV	χ^2	d(β,T) keV
9	26.343 ±.004	-1.3185±.003	0.266±.003	4.0	0.0083±.0039
13	19.257 ±.0027	-2.1802±.0035	0.256±.003	.002	0.0002±.0035
21	4.8987±.0046	-3.6573±.005	0.240±.0048	1.28	0.0057±.0051

TABLE VI-1

Possible Reaction Pairs for Momentum Match Energy Calibration
Calculations are for $\theta_{LAB}=15.0°$

Reaction 1	Excitation Energy 1	Reaction 2	Excitation Energy 2	Beam energy[a] (MeV±keV)	Beam Particle	Magnetic Rigidity of outgoint Particles (Kg.in)
$^{12}C(p,p)^{12}C$	0.0	$^{12}C(p,d)^{11}C$	0.0	33.691±2.2	P	332.256
$^{12}C(p,p)^{12}C^*$	4.4398±.3	$^{12}C(p,d)^{11}C$	0.0	29.009±2.2	P	282.884
$^{16}O(p,p)^{16}O$	0.0	$^{16}C(p,d)^{15}O$	0.0	27.336±2.5	P	299.009
$^{16}O(p,p)^{16}O$	0.0	$^{16}O(p,d)^{15}O^*$	6.180±4.	40.106±8.	P	363.381
$^{16}O(p,p)^{16}O^*$	6.1305±.4	$^{16}O(p,d)^{15}O$	0.0	20.981±2.5	P	219.312
$^{16}O(p,p)^{16}O^*$	6.1305±.4	$^{16}O(p,d)^{15}O^*$	6.180±4.	33.607±8.	P	299.600
$^{12}C(d,d)^{12}C$	0.0	$^{12}C(d,t)^{11}C$	0.0	38.502±3.	D	498.783
$^{12}C(d,d)^{12}C^*$	4.4398±.3	$^{12}C(d,t)^{11}C$	0.0	29.203±3.	D	398.802
$^{16}O(d,d)^{16}O$	0.0	$^{16}O(d,t)^{15}O$	0.0	28.867±4.	D	431.974
$^{16}O(d,d)^{16}O^*$	6.1305±.4	$^{16}O(d,t)^{15}O$	0.0	16.283±4.	D	254.009
$^{16}O(d,d)^{16}O$	0.0	$^{16}O(d,t)^{15}O^*$	6.180±4.	48.096±12.	D	558.980
$^{16}O(d,d)^{16}O^*$	6.1305±.4	$^{16}O(d,t)^{16}O^*$	6.180±4.	35.232±12.	D	433.230
$^{15}N(p,p)^{15}N$	0.0	$^{15}N(p,d)^{14}N$	0.0	17.446±1.6	P	238.220
$^{15}N(p,p)^{15}N$	0.0	$^{15}N(p,d)^{14}N^*$	2.3128	22.174±1.6	P	268.898

[a] error reflect uncertainty in the masses.

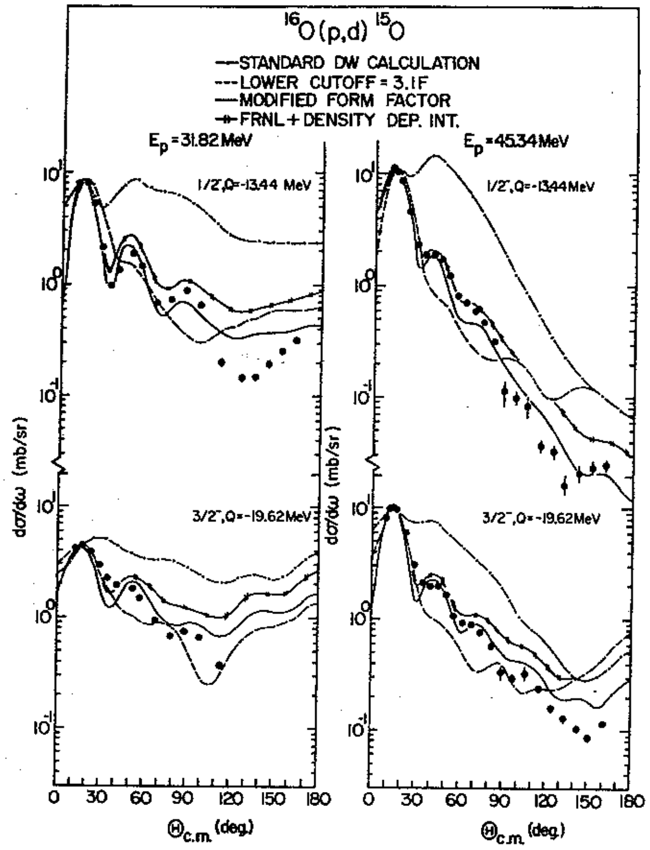

Fig. I-1. Measured shapes of the angular distributions of the $^{16}O(p,d)^{15}O$ reaction and the results of standard and improved DWBA calculations.

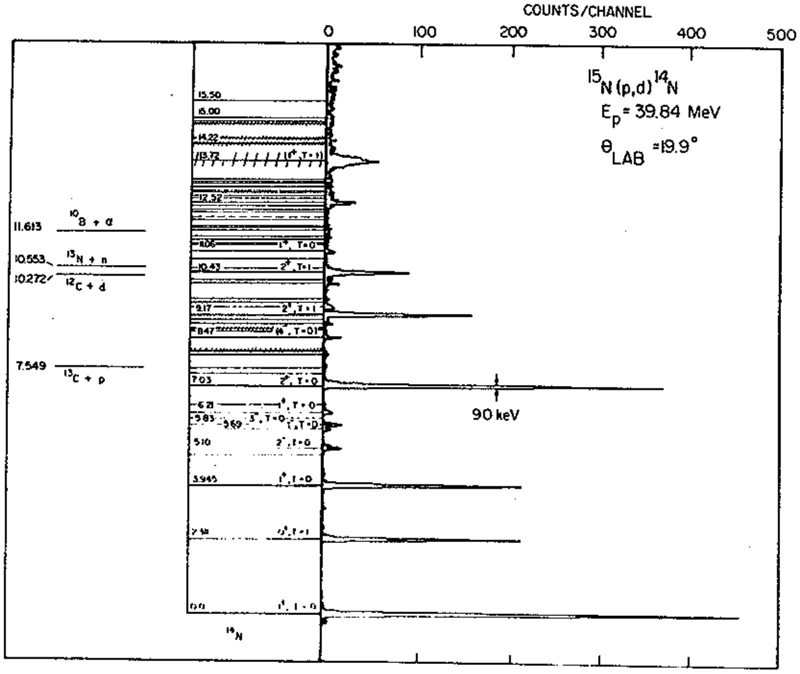

Fig. I-2. Energy level diagram of ^{14}N compared to pulse height spectrum from $^{15}N(p,d)^{14}N$.

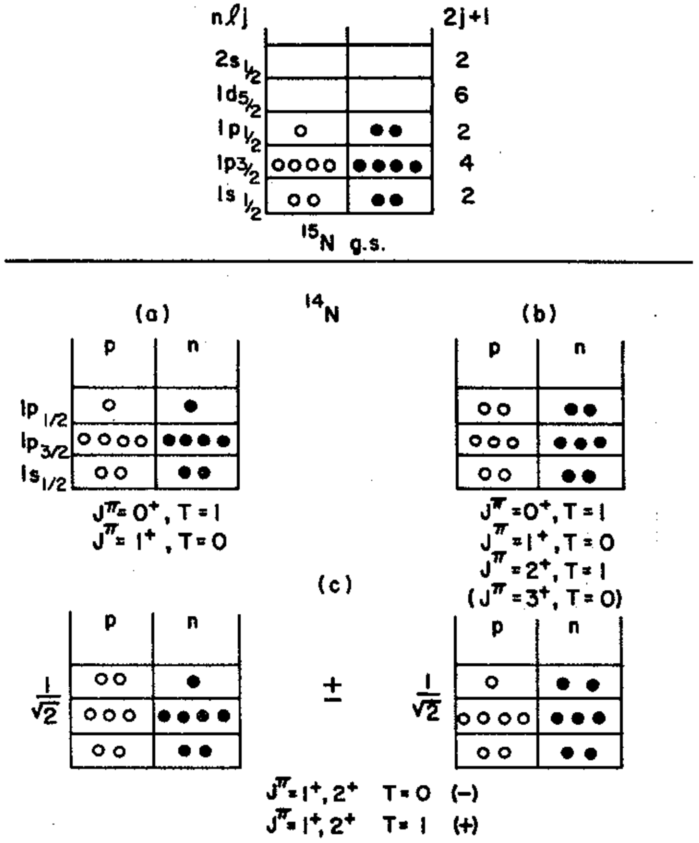

Fig. I-3. Shell model scheme for A=14 and 15.

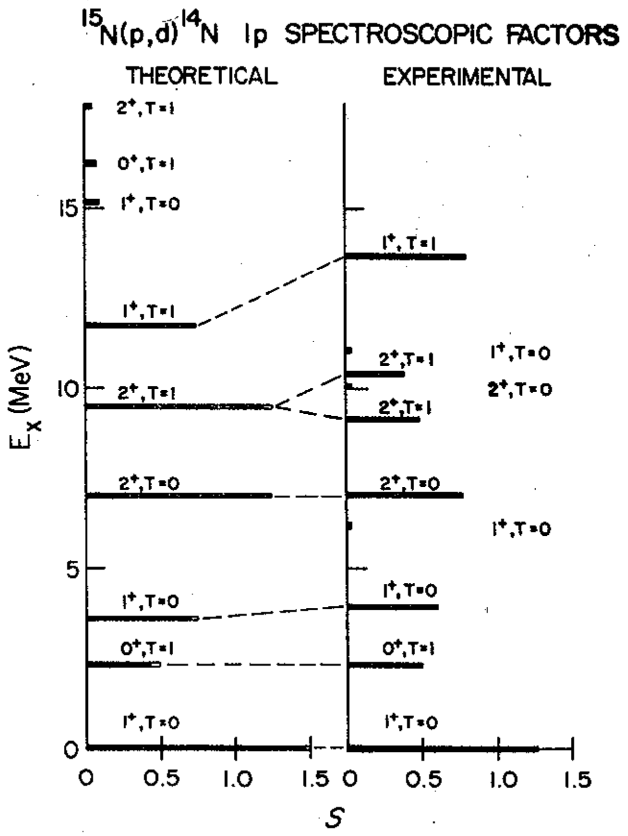

Fig. I-4. Comparison of experimentally obtained spectroscopic factors for $^{15}N(p,d)^{14}N$ with those predicted by Cohen and Kurath.

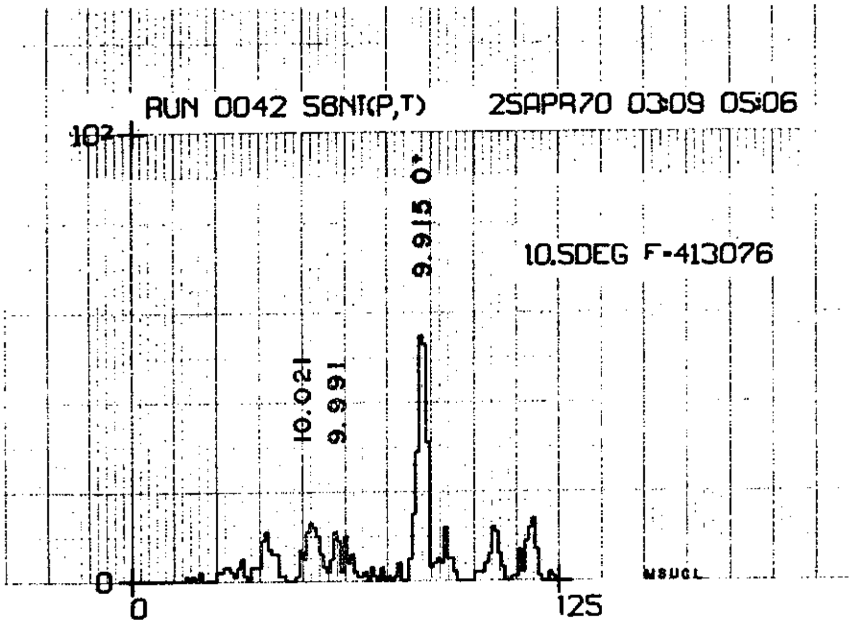

Fig. I-5. Spectrum of ^{58}Ni(p,t)^{56}Ni reaction taken with a position-sensitive solid-state detector in the split-pole spectrograph.

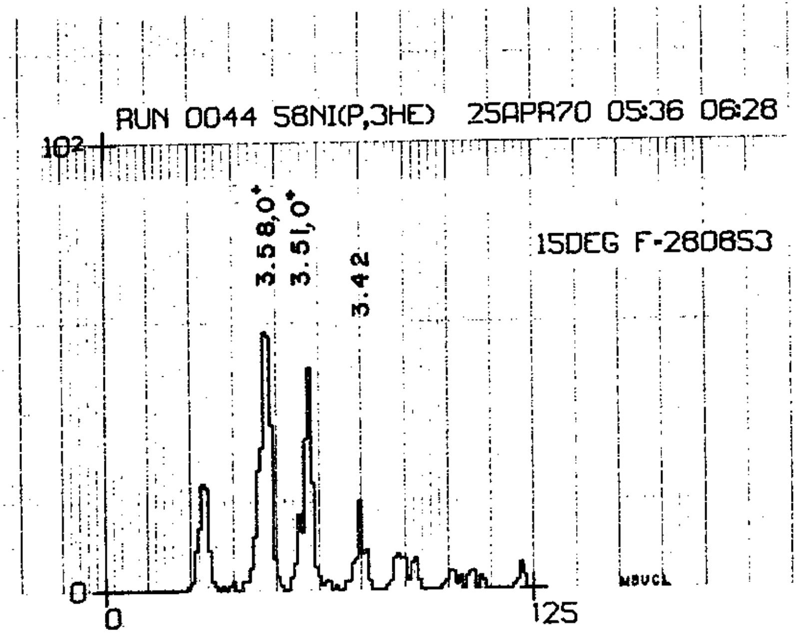

Fig. I-6. Spectrum of ^{58}Ni(p,^{3}He)^{56}Co reaction taken with a position-sensitive solid-state detector in the split-pole spectrograph.

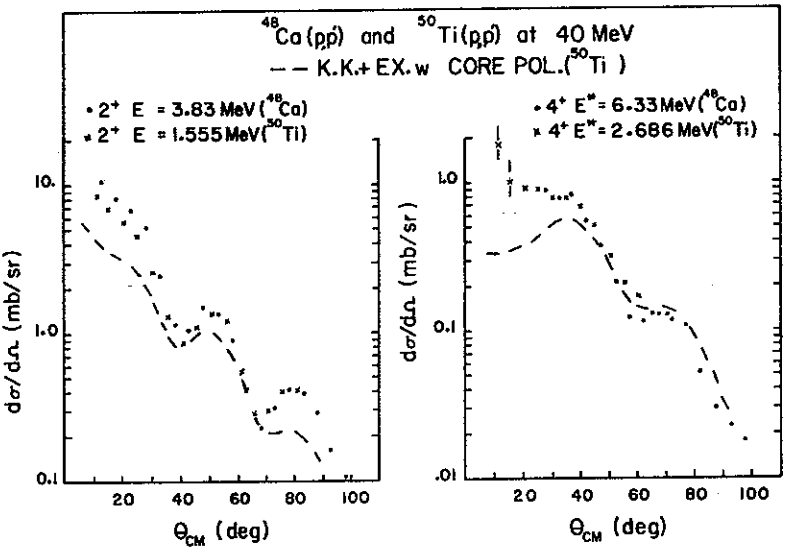

Fig. I-7. Differential cross-sections of the (p,p') reaction to the 2^+ first excited states of ^{48}Ca and ^{50}Ti.

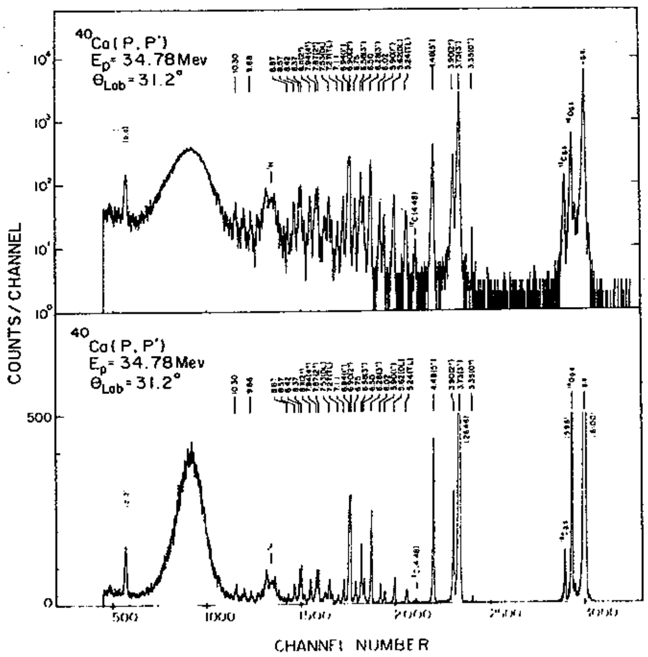

Fig. I-8. Spectrum of the ^{40}Ca(p,p') reaction obtained with Ge(Li) particle detection. Resolution is 25 keV FWHM.

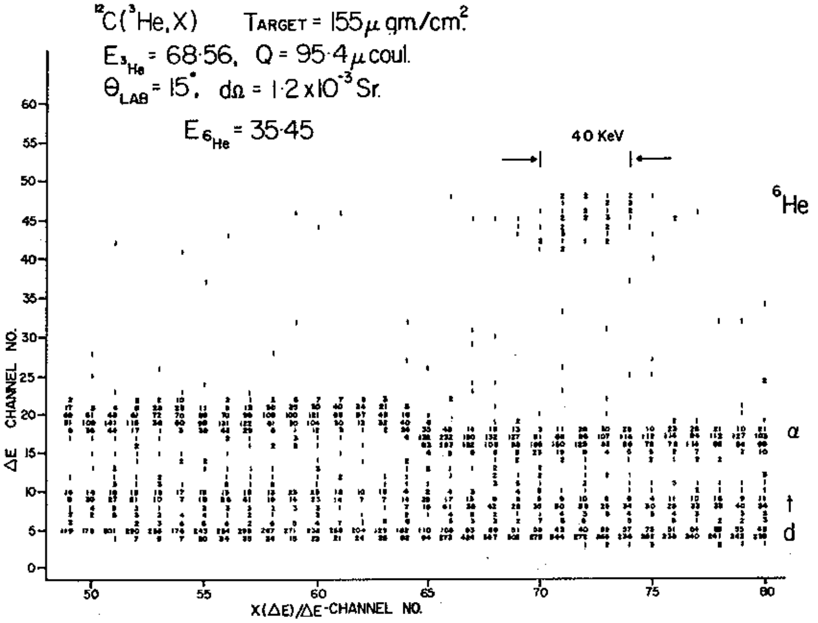

Fig. I-9. Display of array obtained from position-sensitive detector; note the unambiguous identification of ^{6}He particles.

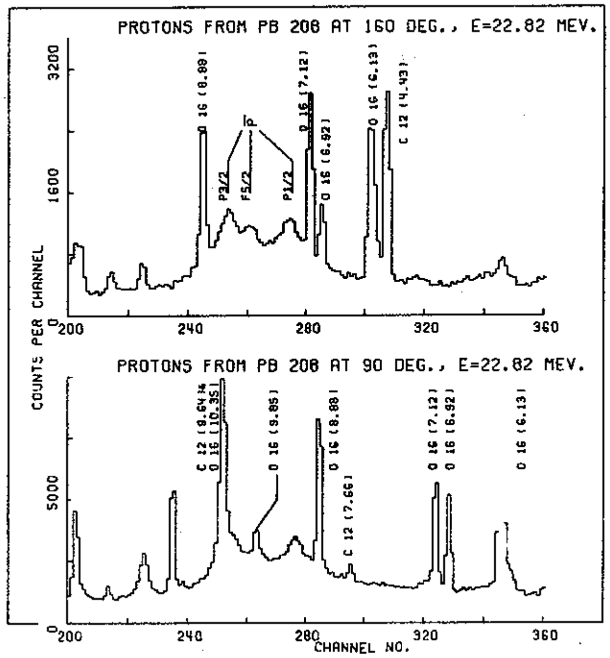

Fig. I-10. Spectra from the $^{208}Pb(p,n\bar{p})$ reaction.

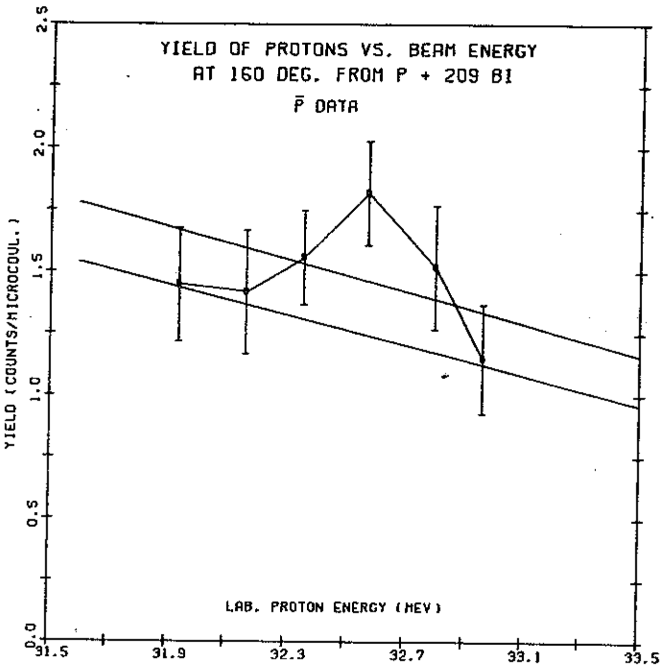

Fig. I-11. Excitation function of $(p,n\bar{p})$ protons from bombardment of ^{209}Bi at energies close to presumed $T=T_z+2$ resonance.

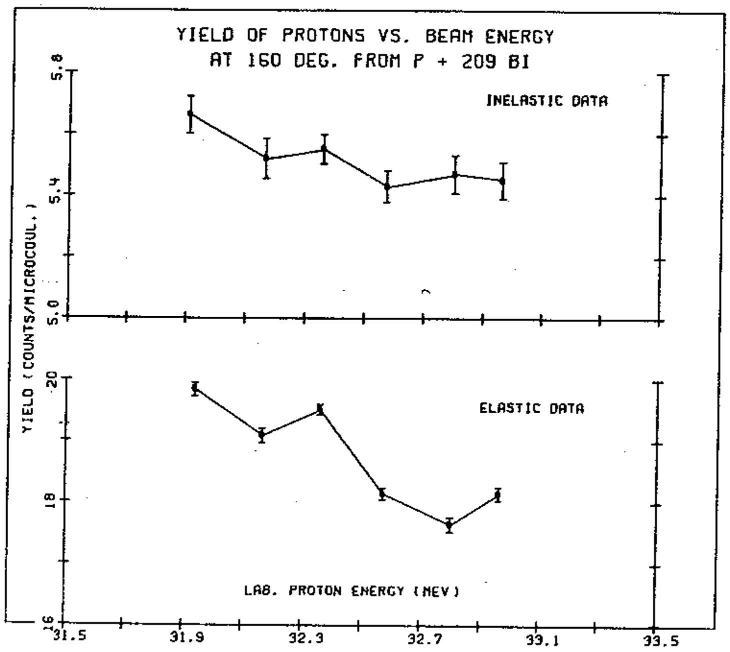

Fig. I-12. Excitation functions of (p,p) and (p,p') protons from bombardment of ^{209}Bi at energies close to presumed $T=T_z+2$ resonance.

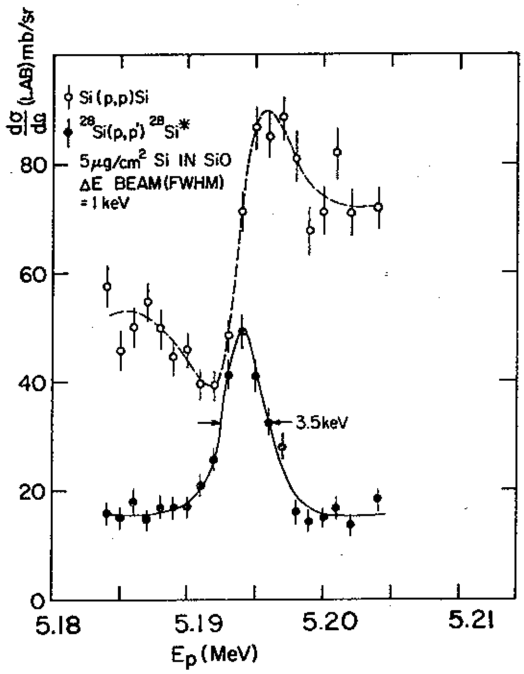

Fig. I-13. Excitation functions of elastic and inelastic proton scattering from ^{28}Si in the region of the 5.19 MeV resonance.

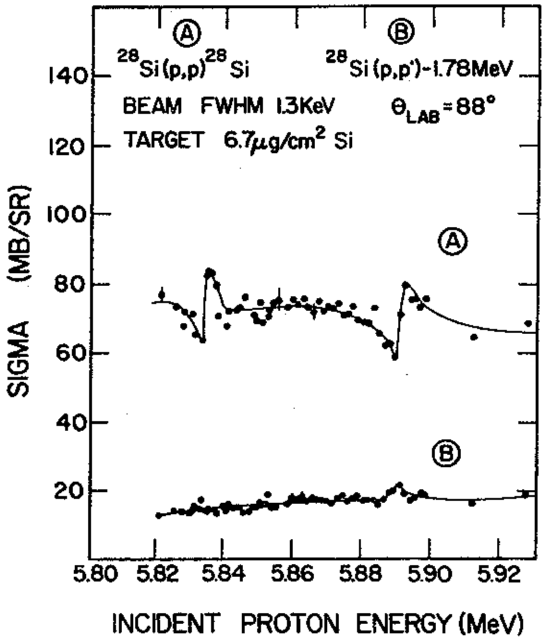

Fig. I-14. Excitation functions of elastic and inelastic proton scattering from ^{28}Si in the vicinity of the T=3/2 resonance.

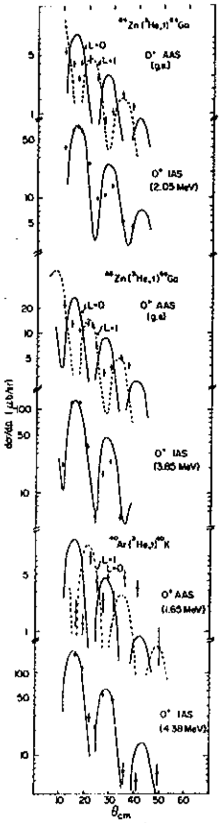

Fig. I-15. Angular distributions of (^{3}He,t) reactions to 0^+ analog (IAS) and anti-analog (AAS) states with macroscopic DWBA calculations.

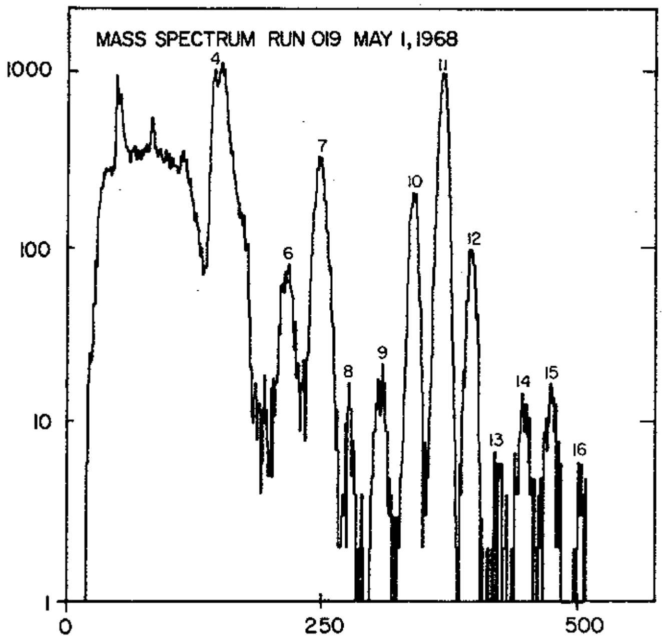

Fig. IV-1. Mass spectrum of spallation fragments obtained with time-of-flight technique.

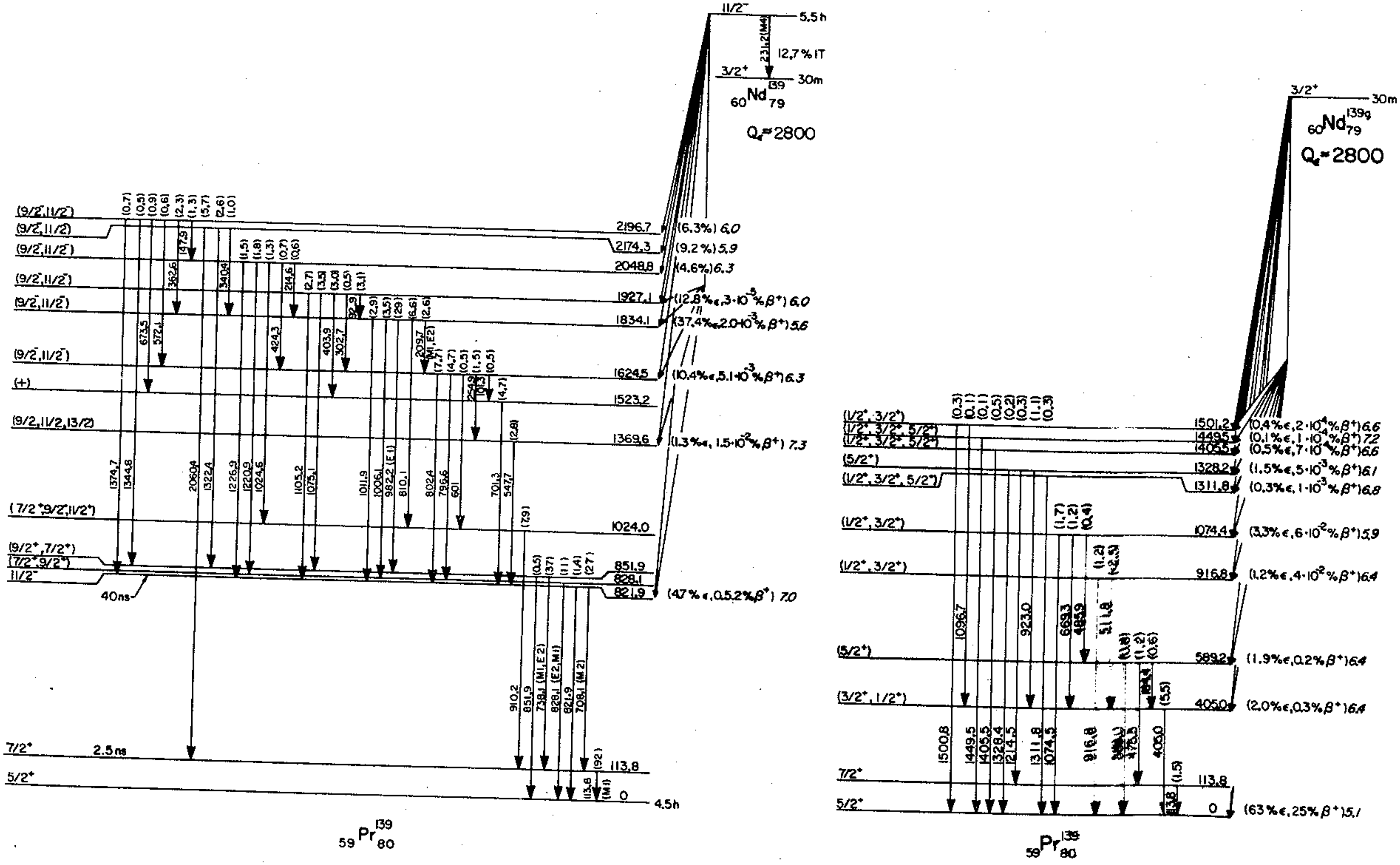

Fig. II-1. Decay schemes of Nd^{139m} and Nd^{139g}. All energies are given in keV and (total transition) intensities are given in percent of the disintegrations of the respective parent. The $\beta+/\epsilon$ ratios are calculated values and the log ft values (in italics on the right-hand sides of the levels) are calculated on the basis of 5.5-h and 30-min half-lives.

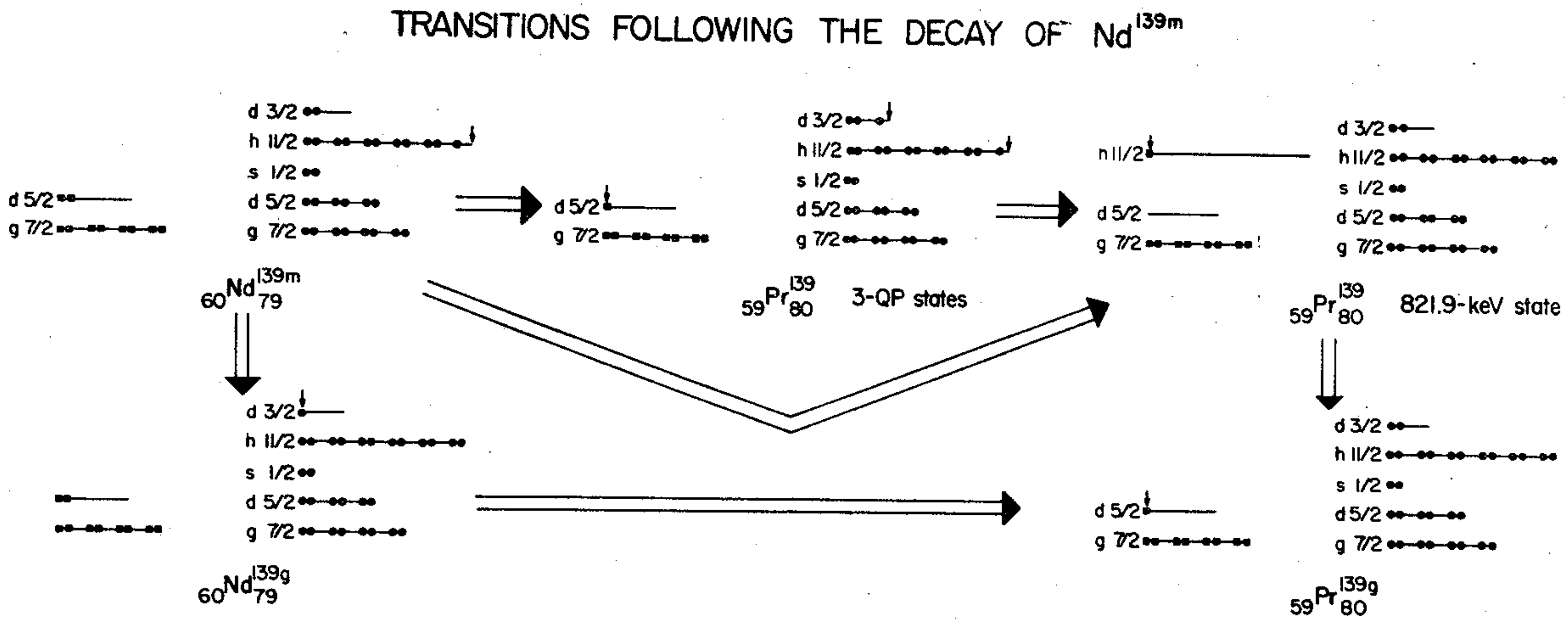

Fig. II-2. Symbolic shell-model representations of some important transitions between Nd^{139} and Pr^{139} states.

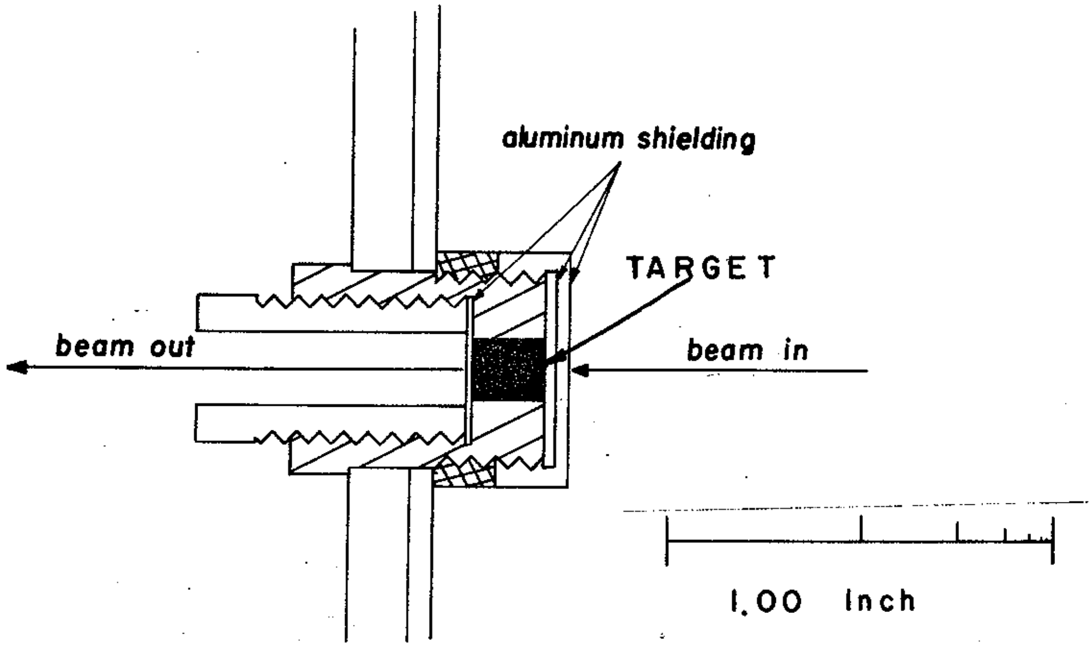

Fig. V-1. Diagram showing details of the target assembly used for the production of ^{13}N via the $^{16}O\ (p,\alpha)$ reaction.

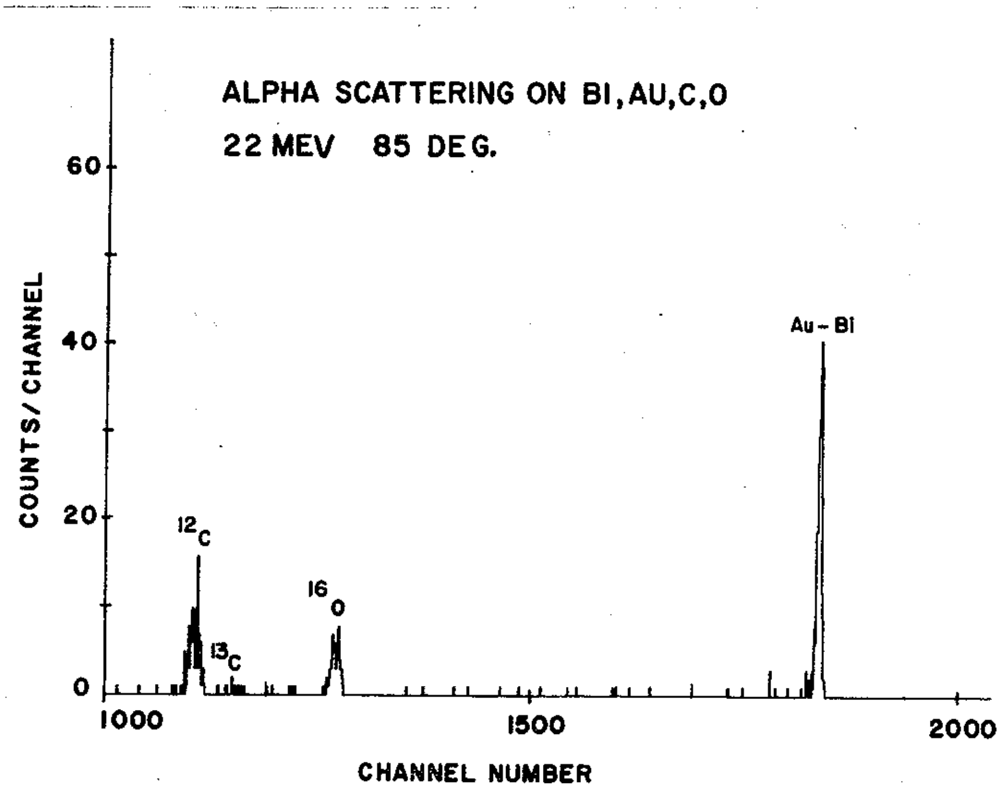

Fig. V-2. Spectrum of alpha particles elastically scattered from mylar target with a thin gold-bismuth layer. The large kinematic shift, the clean spectra, and the large heavy-element cross-section enhancement are all clearly illustrated.

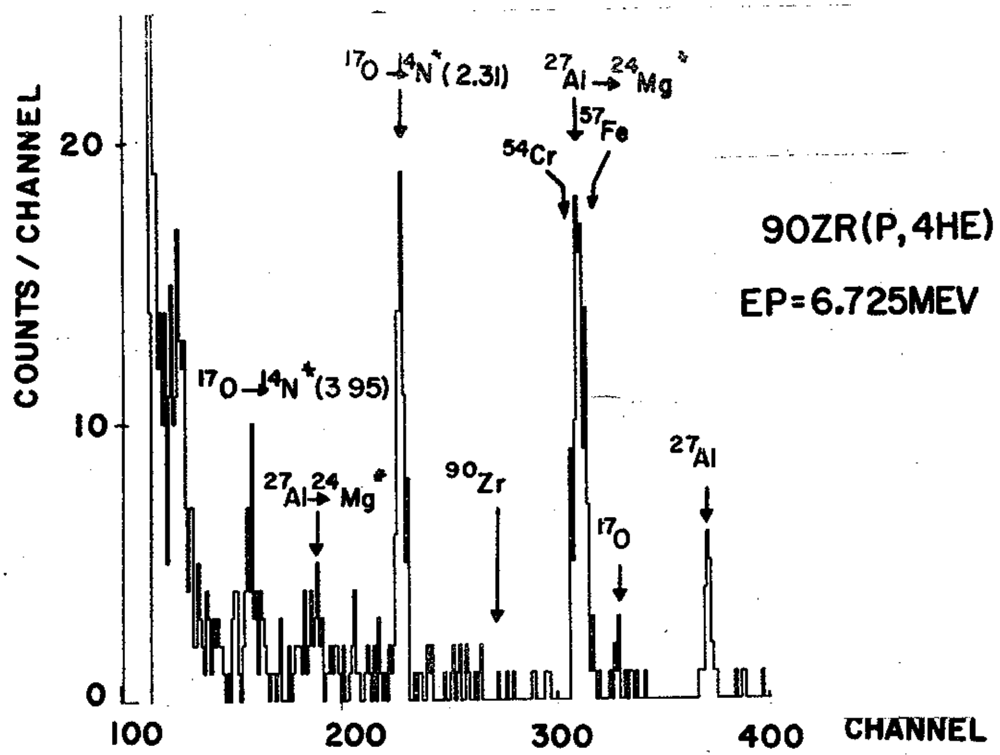

Fig. V-3. Spectrum of alpha particles produced by proton bombardment of a spectroscopically pure zirconium target. Many strong lines from trace quantities of light impurities can be clearly seen.

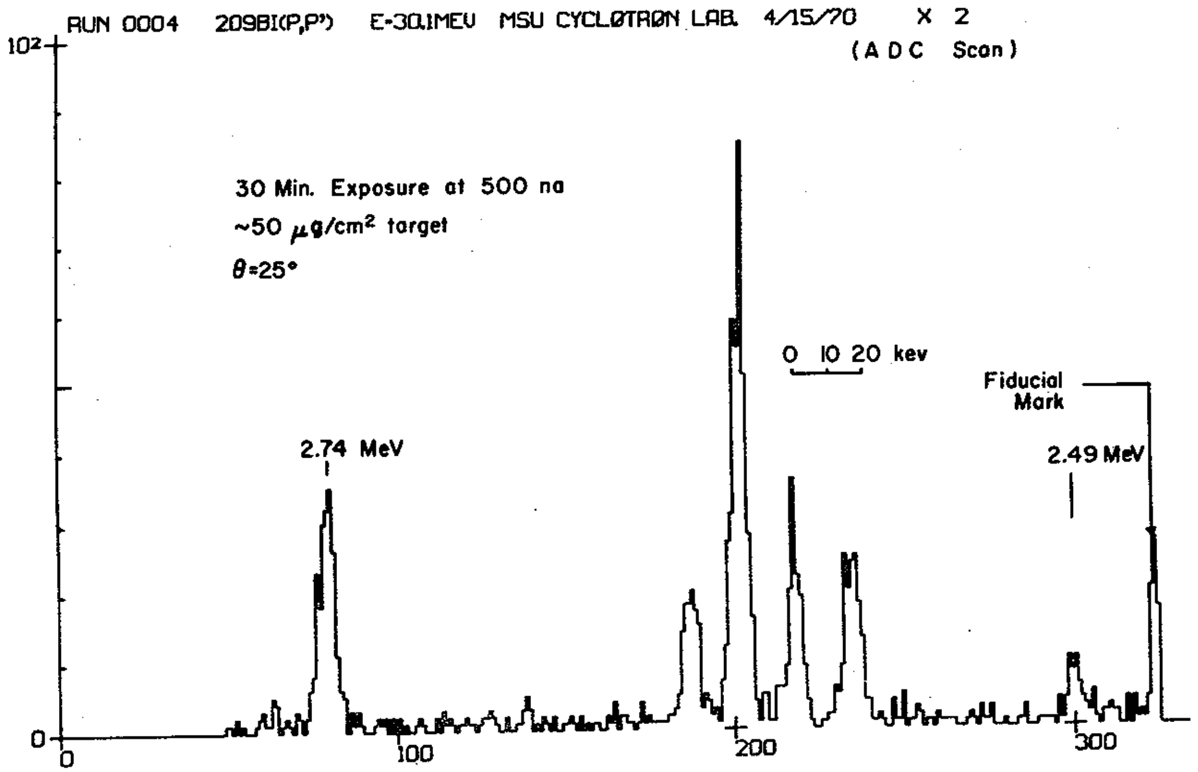

Fig. VI-1. A portion of the inelastic proton spectrum from ^{209}Bi at 30.1 MeV bombarding energy. The data were recorded by exposing photographic plates at the focal plane of the Enge spectrograph. Resolution is 5 keV.

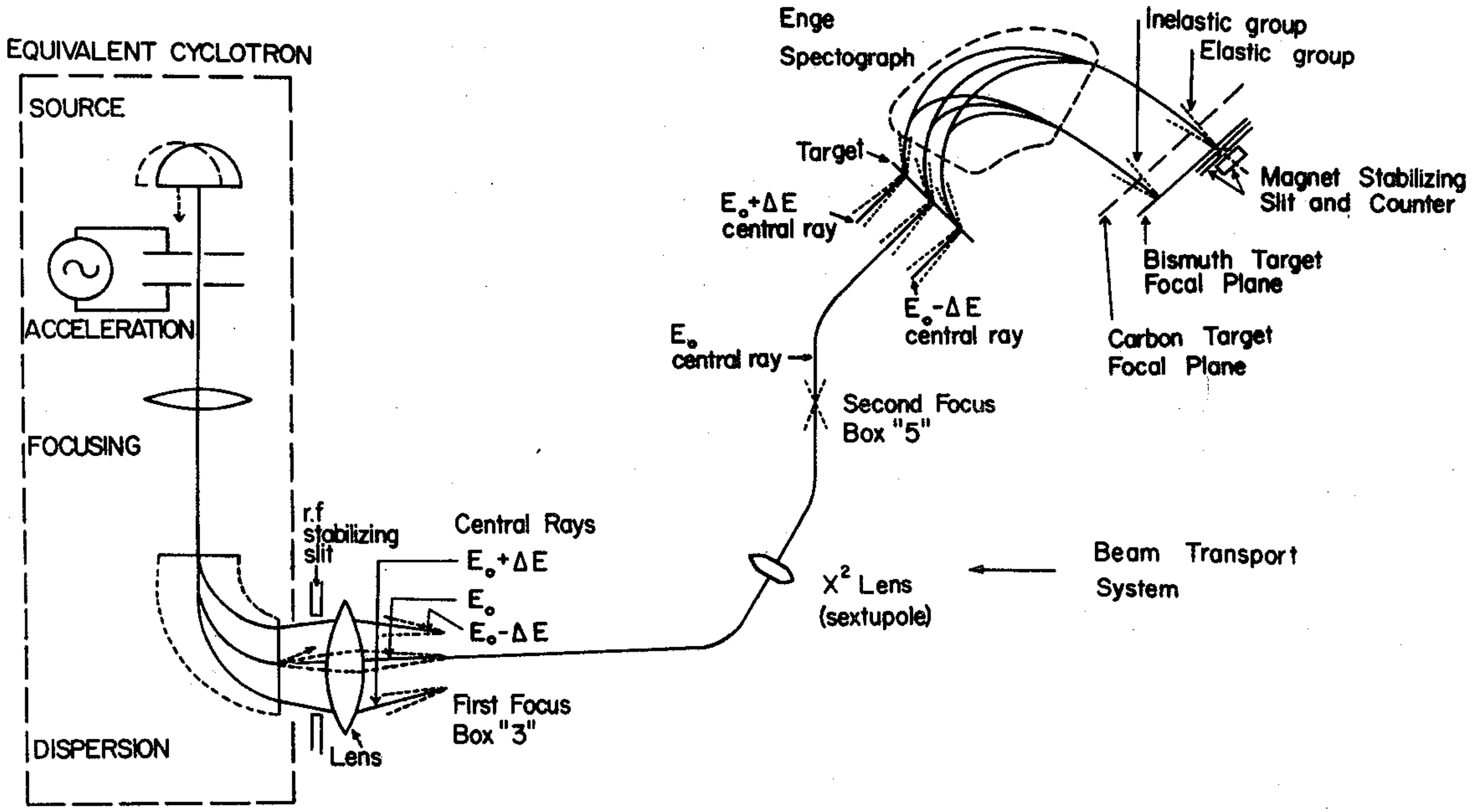

Fig. VI-2. "Equivilant circuit" drawing for our high resolution spectrograph facility. The magnet stabilizing slit and counter (frequently also referred to as the "resolution meter") is shown in more detail in Fig. VI-3.

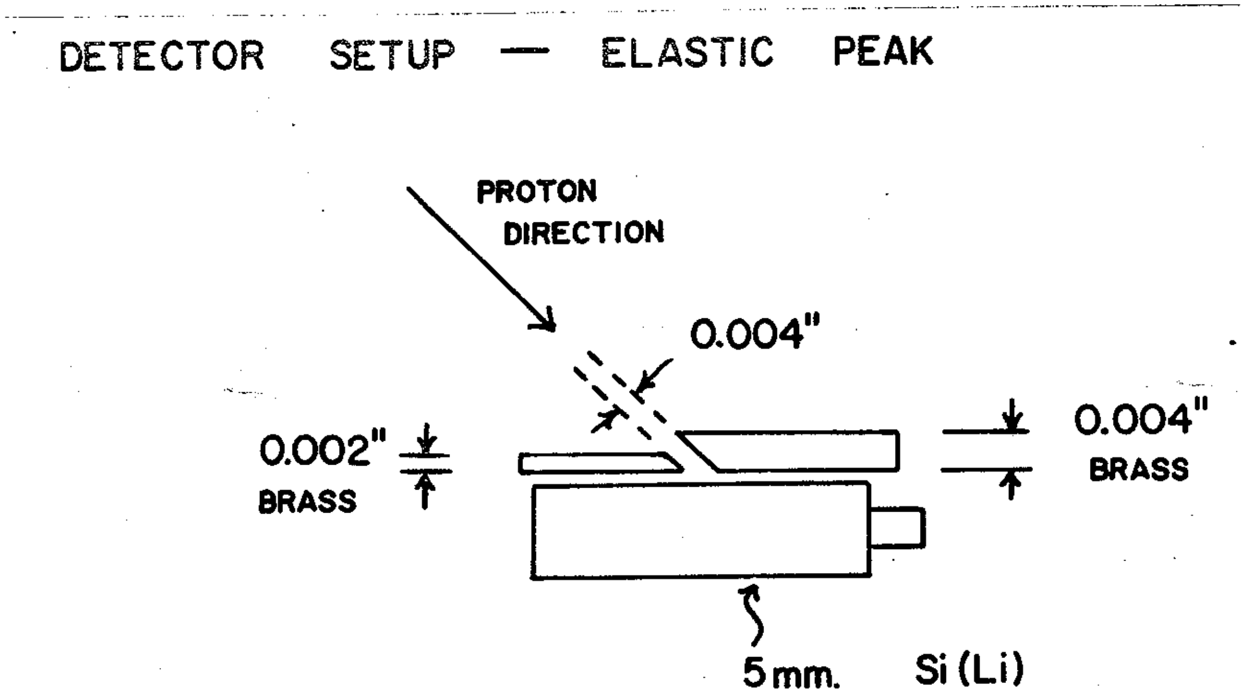

Fig. VI-3. Detailed view of the slit and detector setup used in the "resolution meter". Protons penetrating either slit jaw are shifted in energy with respect to the transmitted group and are therefore "marked" by the energy shift corresponding to the respective jaws.

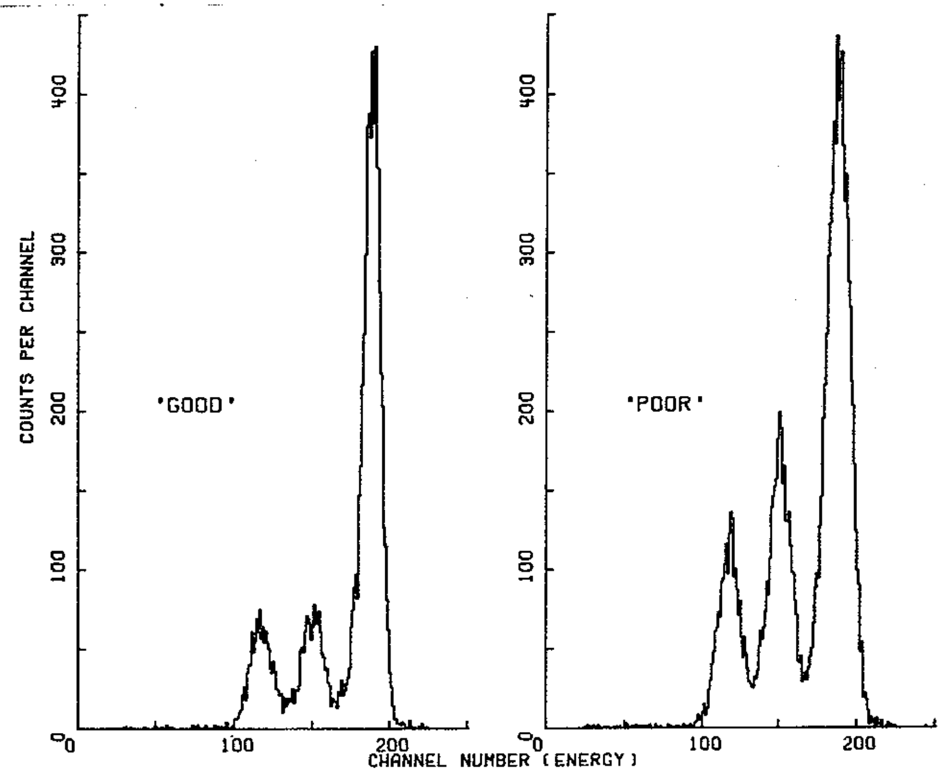

Fig. VI-4. Typical resolution meter spectra. In each case, the right hand peak is produced by particles passing thru the slit aperture while the two lower energy peaks are from portons penetrating the slit jaws. With optimum conditions, 85% of the protons have been observed in the high energy transmission group with a 0.004" slit.

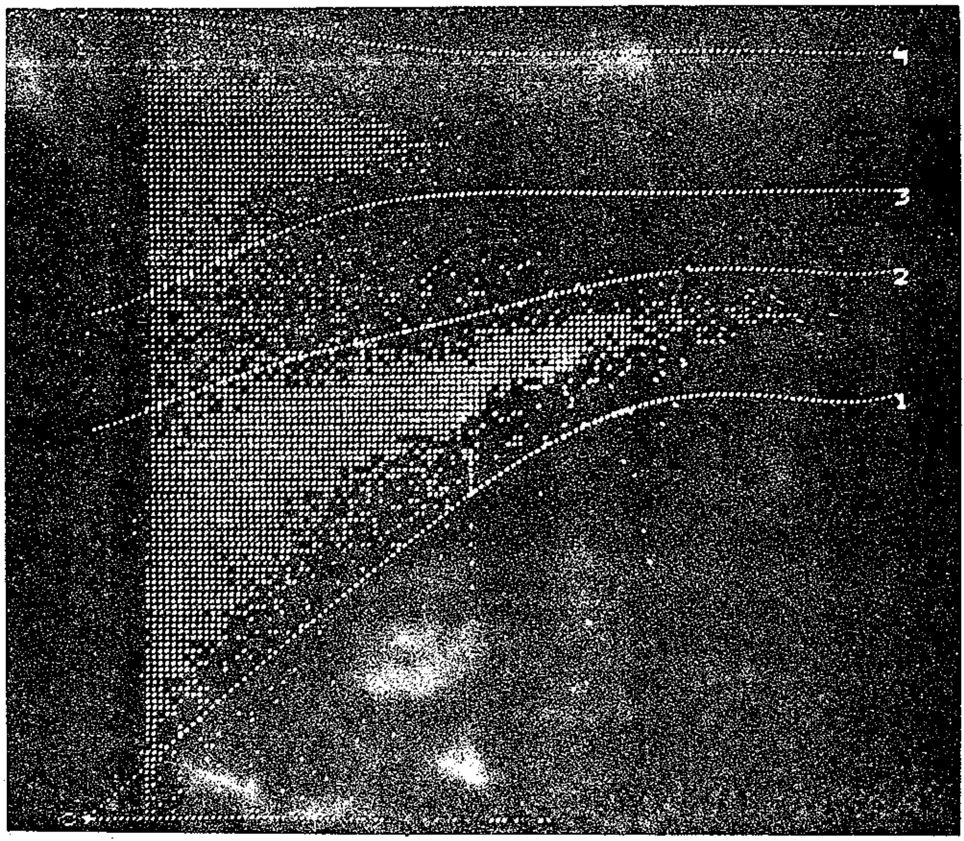

Fig. VI-5. Two dimensional plot of pulse shape discrimination signal versus time. Using a computer algorithm pulses between lines 1 and 2 are accepted as neutrons, those between lines 3 and 4 are accepted as gammas, and those between lines 2 and 3 are rejected as ambiguous.

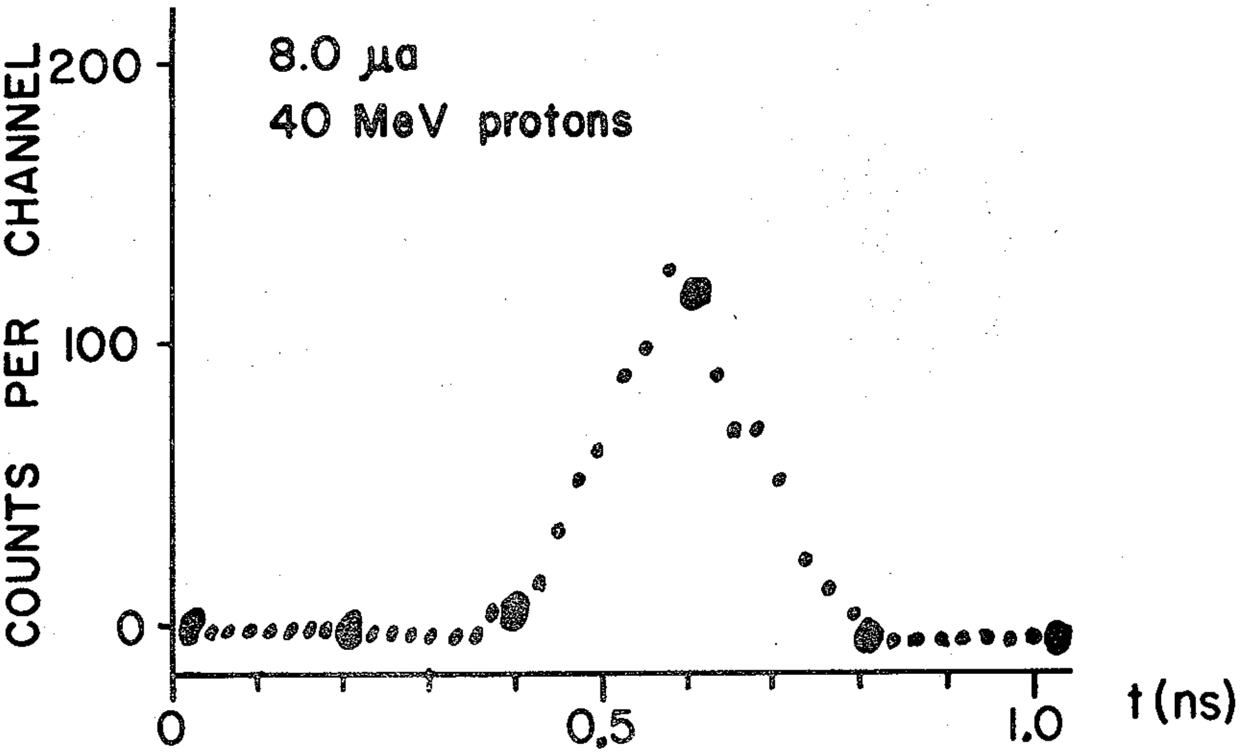

Fig. VI-12. Measured time distribution of high energy gamma rays from the internal probe with the phase selection system in use. The triangular distribution is 0.2 ns wide at the half maximum point. The 8 ua time average current indicates the instaneous current during the pulse to be about 3 ma.

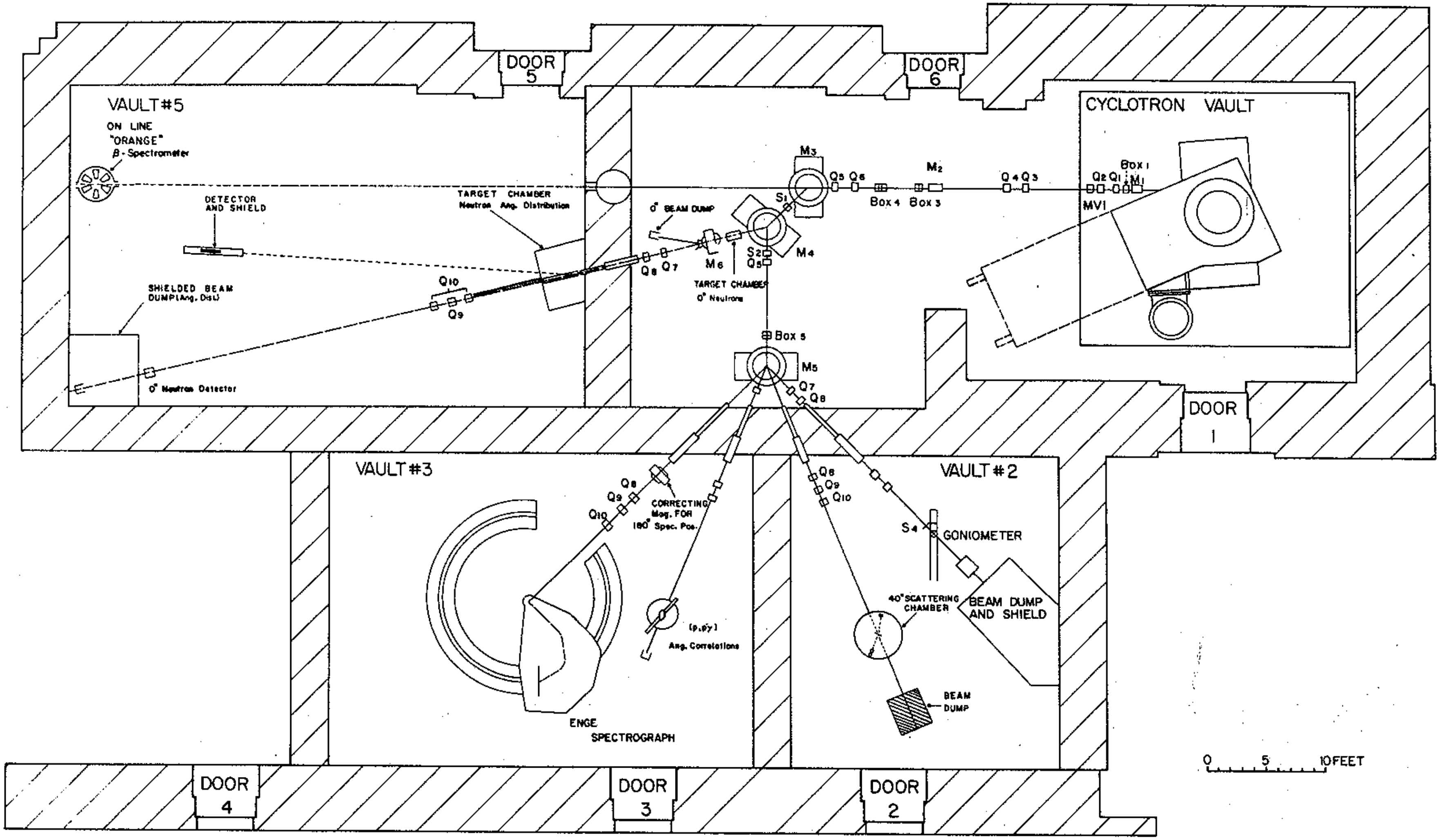

Fig. VI-6. Layout of Cyclotron experimental areas as of August 1970. The new neutron angular distribution facility which is being designed will have a fixed flight path extending to the left from "Box 5" and a moveable magnet to bring the beam into Box 5 from any angle.

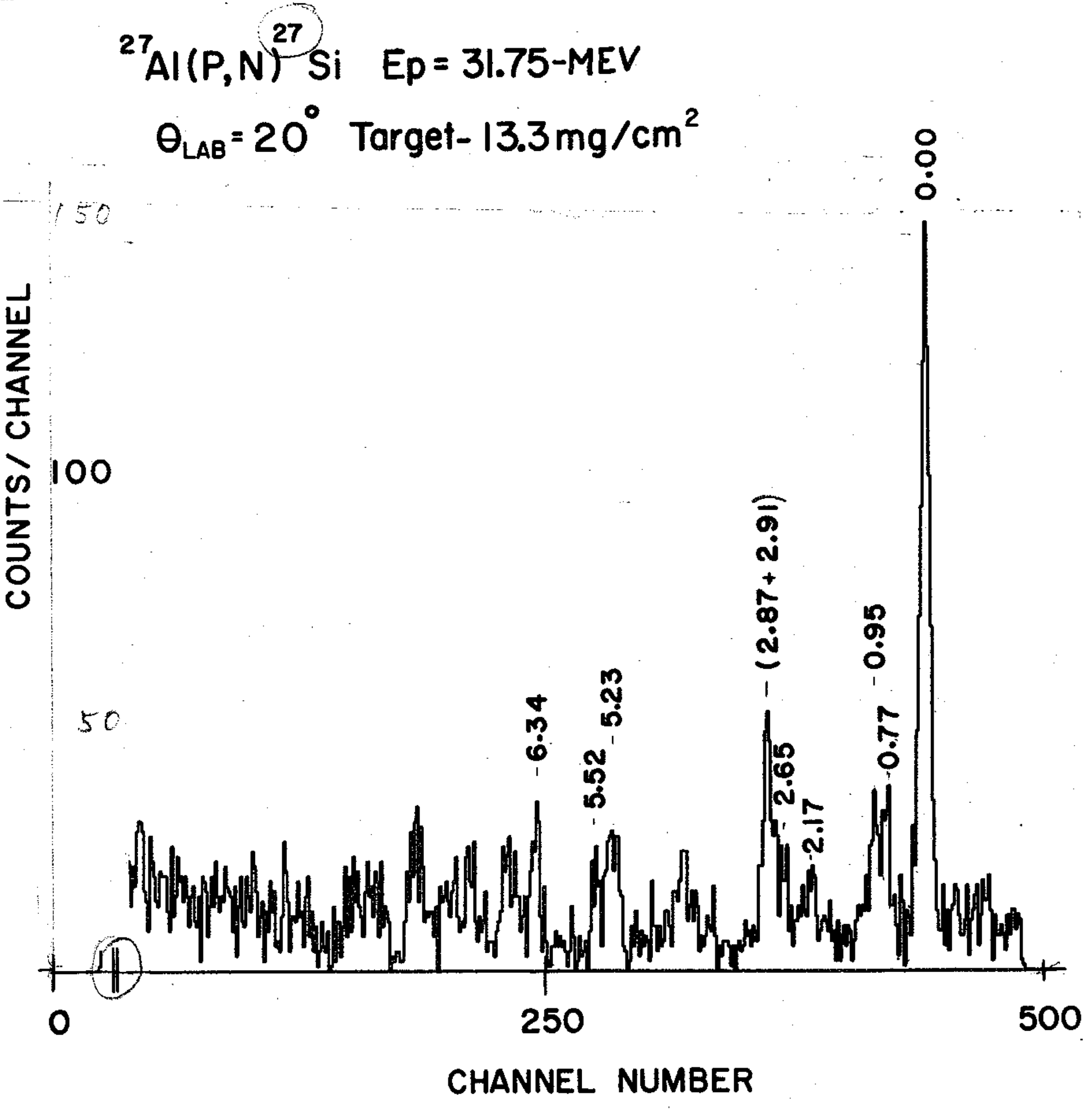

Fig. VI-7. Typical neutron energy distribution taken in the temporary angular distribution facility in vault 5.

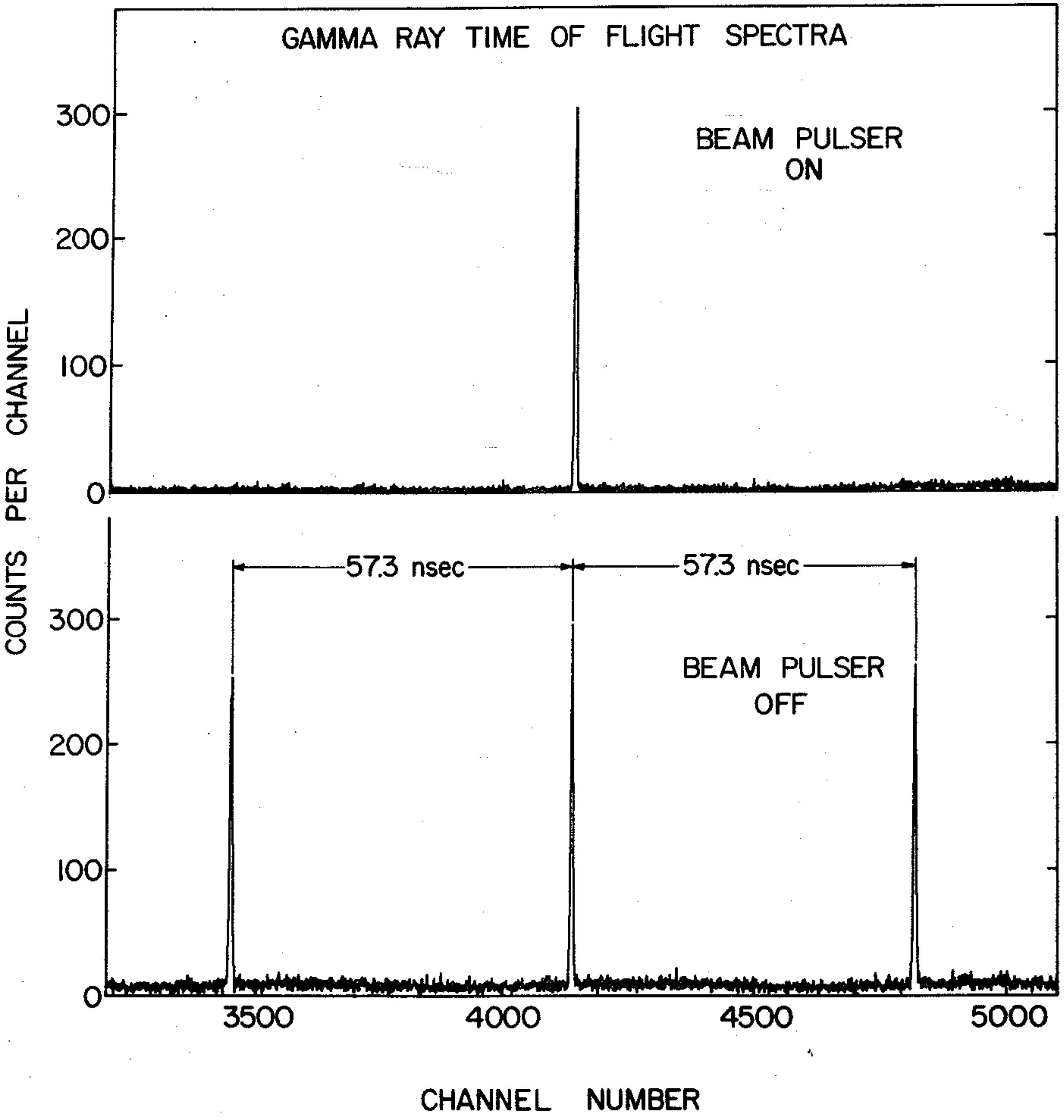

Fig. VI-8. Test results with the pulse selection system operating in a 1 out of 10 mode. Pulses before and after the transmitted pulse are seen to be cleanly eliminated. Note the reduced background when the pulse selection is in use.

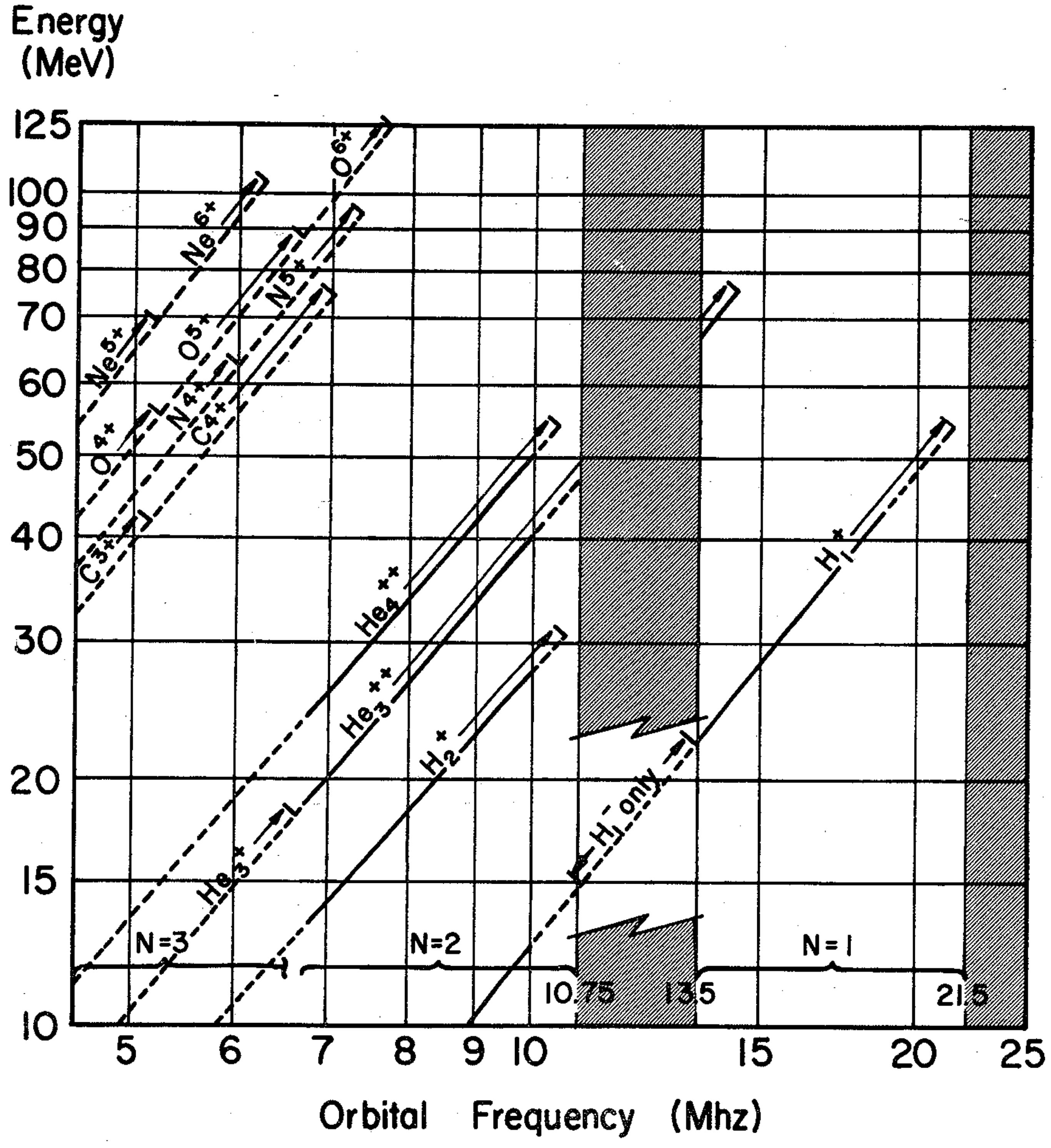

Fig. VI-9. Plot of energy versus orbital frequency for the MSU Cyclotron for various ions. Solid lines indicate operational range as of August 1970. Dotted lines show other energies and ions consistent with maximum bending capability of the cyclotron magnet.

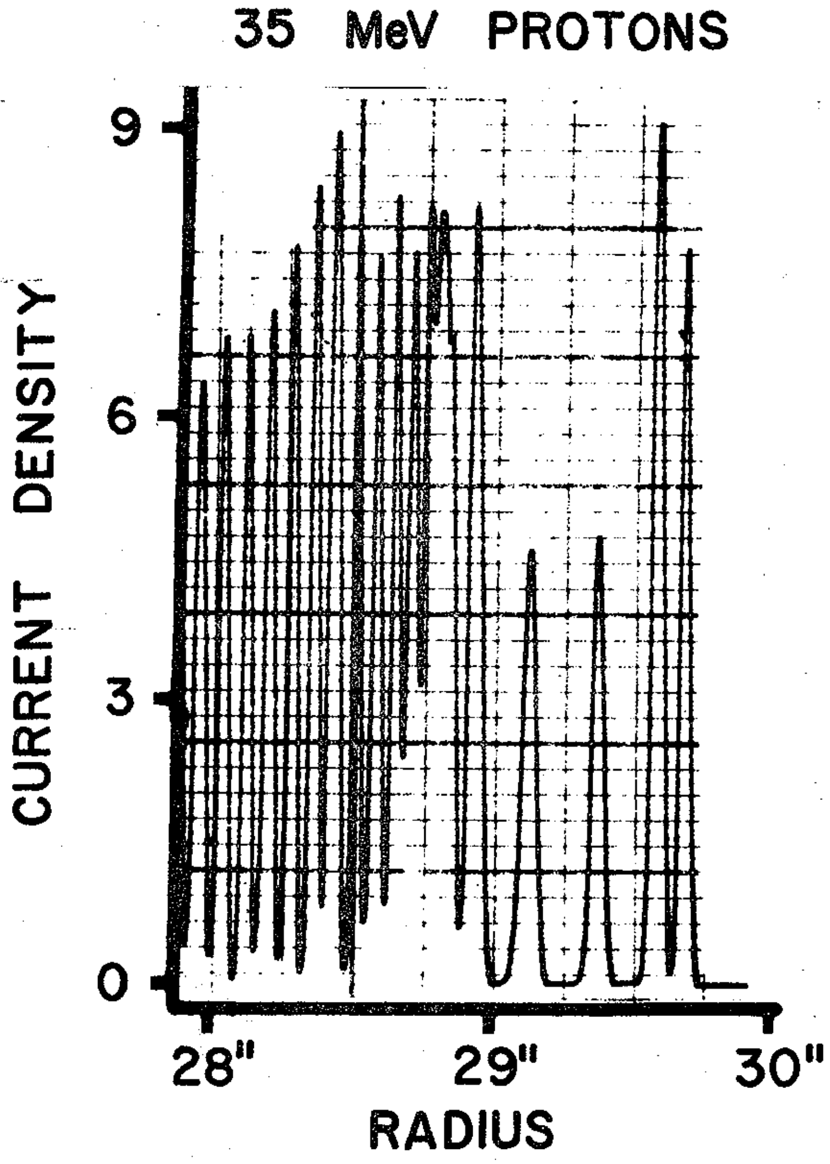

Fig. VI-10. Chart recorder plot of measured turn structure at large radii in the MSU Cyclotron. At the left is the normal turn structure of centered accelerated beam. Near 28.7" the ν_r=1 resonance acts to build up a coherent radial amplitude which triples the turn separation and in the vicinity of 29.3" gives empty regions between turns of width greater than the adjacent turns. With such turn patterns, extraction efficencies of 100% are routinely obtained.

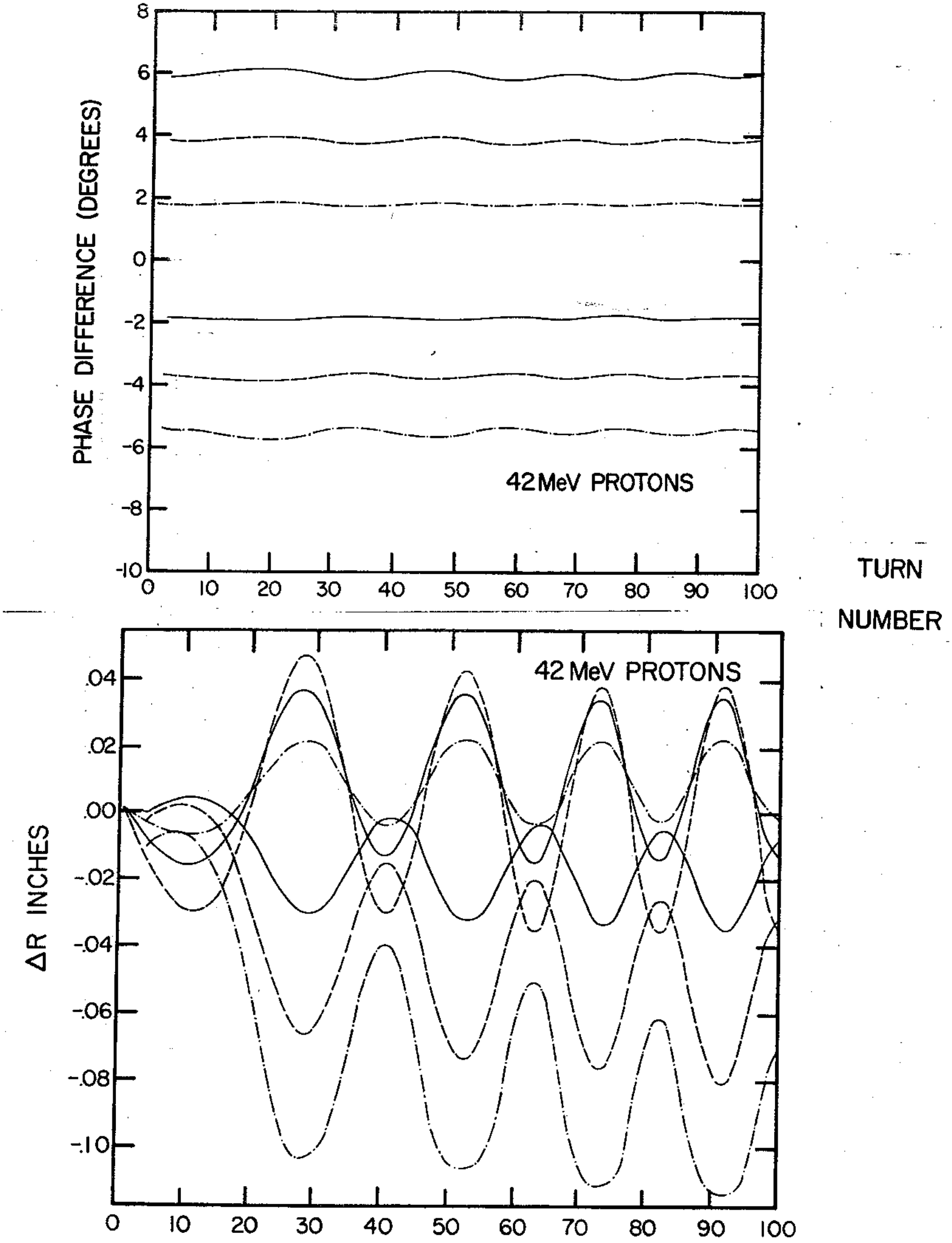

Fig. VI-11. Top: Computed difference in phase of successive turns for six rays displaced by ± 2°, ± 4°, and ± 6° in starting time from a reference central ray. Bottom: Difference in radial position of successive turns of same set of rays. The phase difference is seen to be essentially constant whereas the radius difference is sharply modulated. On the basis of these results a slit near turn 28 is seen to have maximum effectiveness in selecting a narrow phase group.