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ANNUAL REPORT

December 1972 - November 1973

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I. INTRODUCTION

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This progress report describes the basic research, and the development of experimental techniques, carried out at the Center for Nuclear Studies at the University of Texas at Austin during the period from December 1, 1972, to November 30, 1973. This year we have made a major change in the format of our report in that it includes all of the programs in the laboratory, in contrast with previous years, when results were sorted out in accord with the sources of funds. These individual reports have involved substantial duplication, since laboratory collaborations are flexible and independent of funding boundaries. In addition, nearly all of the experimental programs use the EN tandem Van de Graaff accelerator, which is operated almost entirely through a contract with the Atomic Energy Commission. The programs that use the tandem accelerator are then in a very real sense supported by the AEC, even though operating support may be from some other source. To indicate the relative contributions to our program from various sources we indicate in Table I the percentage of operating support from each source for the year 1972-73.

The progress report is divided into two main parts. Section II deals with experimental research activities, and Section III describes theoretical research. Most of the theoretical work is devoted to Theoretical Nuclear Physics; the experimental research, on the other hand, falls into the categories of experimental Nuclear Physics, Atomic Physics, Nuclear Astrophysics, and in addition, research instrumentation. Nearly all the work is indicative of close collaboration between theorist and experimentalist, and some work has been done in collaborative efforts with other laboratories.

At the beginning of section II, we have attempted to give a summary of the experimental activity of the Center during 1973. The remainder of Section II gives a more detailed presentation of the work. Similarly, we have tried to give a summary of the theoretical research carried out in

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1973, at the beginning of Section III before giving separate accounts of our research activities. Each individual report is intended to describe the status of experiments or theoretical studies which often are presently in progress and incomplete. The appearance of specific numerical results and conclusions here does not constitute publication, and this report should not be quoted in part or whole without permission of the investigators.

The past year has been one of the most productive in the history of the Center for Nuclear Studies -- 48 refereed journal research papers have appeared in print, in the areas of theoretical and experimental nuclear Physics, nuclear astrophysics, atomic physics, and research instrumentation. Twenty more papers have been accepted for publication, and 14 additional papers have appeared, authored by faculty or staff of the Center in collaboration with researchers at other institution, amounting to a total of nearly one hundred publications during 1973.

(T. Tamura)

Table I Principle Research Contracts for the UT Center for Nuclear Studies Programs for the Year 1972-73

Institution or Agency	Grants or Contracts No.	Per Cent of Total
1. Atomic Energy Commission	AT(40-1)2972	49.7
2. National Science Foundation	6P-23282	5.0
3. Air Force Office of Sponsored Research	72-2158	10.5
4. Office of Naval Research	N00014-67-A-0126-0012	15.2
5. Welch Foundation	F-496	1.9
6. Sloan Foundation	BR-1457	1.5
7. Research Corporation	6859,6358	1.5
8. University of Texas		14.7

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II. EXPERIMENTAL RESEARCH

II. A. INTRODUCTION AND SUMMARY

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1. Experimental Nuclear Physics

The experimental nuclear physics program of the Center for Nuclear Studies continues to be unusually vigorous and productive. During 1973, a far greater percentage of our efforts than usual in past years went into the development of a number of new experimental systems for detailed nuclear structure studies, which are described later. Some ongoing programs of research have been essentially completed, and an unprecedented number of new programs were initiated during 1973, which accounts for the exceptional length of the section on experimental work in progress in this report. This wealth of new ideas and techniques along with a great wealth of meaningful data illustrates, we think, the continued vitality and energy of the nuclear physics research effort at the Center, and its renewed dedication to significance and excellence.

Work published during 1973 dealt with (d,p) spectroscopy of ^{108,110}Ag; (p,p') and (p,d) studies of ^{135,136}Xe; (p,p') studies of ^{96}Mo; a survey of gamma cascades in ^{252}Cf fission fragments; a detailed experimental and theoretical investigation of the proton decay of the ^{89}Y analog of the ^{89}Sr ground state; and, a new method of spin determination using ^{4}He-heavy ion angular correlations. A number of papers were also published by Davids on gamma decays of exotic nuclei, in collaboration with a group at Brookhaven. Papers were also published by Hoffmann and Moore describing an in-beam axial β-ray spectrometer, and a high-resolution charged particle time-of-flight mass identification system. Work submitted but not yet published deals with (d,p) studies of ^{85}Kr, and inelastic scattering of ^{11}B from ^{208}Pb.

Turning to the work in progress, we stress the essential unity of our various research programs. The study of nuclear structure via nuclear reactions is a house of many mansions. We have concentrated on those areas where we already have a considerable expertise, as well as

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developed facilities, for some time now. The new research instrumentation on which much of our work has been concentrated this year has been carefully planned to complement or extend dramatically many of our ongoing programs. Many of our new programs will be carried out in very close collaboration with the active nuclear reaction theory group at the Center, led by Tamura and Udagawa.

One of the new programs to which a great deal of effort has been devoted is that of charged particle and/or gamma ray angular correlations. Braithwaite, Olsen, and Obst are presently running three experiments of this type. The first of these experiments is a perturbed angular correlation measurement for $^{12}C(^{12}C,\alpha)^{20}Ne(2^+)$, where the ^{20}Ne nucleus and its de-excitation gamma-ray are detected in coincidence. The success of the experiment hinges on the possibility of detecting ^{20}Ne at 0^o, in a specific charge state. Observation of the de-orientation of the nuclear spin of ^{20}Ne in the +9 charge state will give an accurate determination of the absolute magnetic moment of the nucleus. The second experiment involves determination of the spin of the "famous" 14.08 MeV state in ^{12}C, which has previously been assigned as 4^+, 3^-, and 2^+! This remarkable uncertainty can be resolved using $^{12}C(^{12}C,^{12}C')^{12}C^*(14.08) \rightarrow \alpha_o$, and observing the $^{12}C'$ and α_o in coincidence. The last experiment involves detection of the double-gamma-decay of the 0^+ first excited state of ^{90}Zr, using four paired 5" by 5" NaI detectors in coincidence with an annular proton detector, via $^{90}Zr(p,p')$. Resonant enhancement of the (p,p') cross section at back angles for certain energies can be taken advantage of in these studies.

Another new program involves the study of fractionated single-nucleon states at high excitation in the mass 40 and 90 regions. These experiments are being performed by Hoffmann, Coker, and Riley using a biased magnetic quadrupole spectrometer. At 10 MeV incident deuteron energy, neutron states at excitations of $E_x \approx Q_{dp}$(g.s.) + 2.22 MeV can be studied at 13 keV resolution. These studies promise to "bridge the gap" between slow neutron scattering studies and conventional (d,p) studies of low-lying states, to complete our picture of the distribution of single-particle strength in the nuclei under study, which presently include ^{31}Si, ^{41}Ar, and ^{97}Zr.

The program of nuclear spectroscopy in the vicinity of the N=50 neutron shell has occupied an important place in the Center's research effort for several years now. Riley and Olsen are presently undertaking a study of the low-lying levels of $^{79,81,83}Kr$ via (d,p), which might ultimately be the only study of its kind in the literature due to the general unavailability of the required isotopic enrichments. To get around the problem, the group uses Kr gas with three radically different enrichments, and carries out cross-identifications. The even Kr isotopes, $^{80,82,84,86,88}Kr$, are also being studied via the (t,p) reaction at 17 MeV using the Los Alamos triton beam. The inelastic scattering of photons from $^{84,86}Kr$ is also being studied as a supplement to the (t,p) work. A very detailed DWBA and coupled-channel analysis of the (p,p') data has been completed.

Hoffmann and Moore are continuing their program of in-beam internal conversion electron spectroscopy begun last year. Nuclei studied to date include ^{93}Nb, ^{95}Mo, ^{103}Rh, $^{107,109}Ag$, $^{121,123}Sb$, ^{124}Sn, ^{141}Pr, ^{167}Er, ^{177}Hf, ^{197}Au, $^{206,208}Pb$, and ^{238}U. The resolution obtained is comparable to that of the better gamma-ray work, and many new transitions were observed. A large number of requests for preprints of this work have been received from nuclear data compilers.

It was suggested recently that (^{12}C,^{8}Be) is a promising reaction for populating quartet configurations in nuclei, if these configurations in fact exist, which some theorists seriously doubt. An array of 16 rectangular detectors has been constructed and is being used to explore convenient techniques for detection of ^{8}Be.

Finally, we include a report on the progress of the nucleon-nucleon scattering experiments at LAMPF in which Riley is heavily involved.

A number of gamma-gamma coincidence studies are being carried out by Davids on nuclei of astrophysical interest, particularly ^{66}Ge and ^{12}C. Indeed, the Nuclear Astrophysics program has just completed its most productive year since its initiation. A large number of experimental and theoretical projects have reached fruition, and the large number of publications is a good indicator that the level of activity has attained a high value.

On the experimental side, the program studying proton-rich nuclides in the $60 < A < 80$ region has produced significant results related to earlier work on ^{64}Ge. The alpha-particle nuclide ^{72}Kr has been observed, and hopefully the parameters needed to determine its role in explosive nucleosynthesis will soon be measured. Our studies on the $^{23}Na(\alpha,p)^{26}Mg$ reaction have shown that its stellar rate is greater by about a factor 4 than was previously calculated from earlier data. The effect on ^{23}Na and ^{26}Mg calculated abundances has been investigated using these new results. A target transfer system ("rabbit") has been built and is in use for decay studies of proton-rich isotopes on the EN Tandem accelerator.

2. Experimental Atomic Physics

During the past year, atomic research activities have been concerned with several different types of experiments employing various methods of atomic excitation. Most of these experiments may be grouped into two general categories: (1) excitation of target atoms (or molecules) using a beam of projectiles of varying atomic species in differing atomic charge states, where X-ray or Auger radiations from the target are studied; and, (2) excitation of the beam atoms using an exciter foil, where X-ray (or Auger) radiations from the beam are studied. For convenience in the following discussion, these will be referred to as Target Excitation (TE), and Beam Foil Excitation (BF), respectively. Exceptions to this classification include the bombardment of target atoms by projectiles of the same Z or nearly the same Z.

For the most part, X-ray measurements have been performed using a high resolution (E/ΔE ≈ 300) Bragg spectrometer with a curved crystal which permits large solid-angles in the detection of incident X-rays. Auger electrons have been detected, exclusively, by a double-focussing electrostatic analyzer which has an instrumental resolution of E/ΔE ≈ 5000. This device is composed of two concentric segments of conducting spherical surfaces, at +V and -V respectively, assuring that the median path is at ground potential.

The following table summarizes the main research topics being pursued, separated according to the type of excitation and the type of spectrometer being employed.

	Target Excitation	Beam Foil Excitation
X-ray Spectrometer	Projectile Effects Chemical Effects Multiple Inner-Shell Ionization Reaction Mechanisms	Lifetimes, Cascades, and the Collision Mechanism Multiply-Excited States in He-like and Li-like Atoms Perturbation of States in Highly-Ionized Atoms
Auger Spectrometer	Projectile Effects Multiple Inner-Shell Ionization Reaction Mechanisms Total Formation Cross-sections	-- not started yet --

Although these topics are discussed elsewhere in this report (Sections II.B.-II.E.) or in published work, some indication of the content of these topics will be given here.

Multiple Inner Shell Ionization occurs when more than one electron is knocked out of the atom by the incident projectile. For example, if 1 K-shell electron and n L-shell electrons are removed by the same collision and an X-ray from a K ← L transition is observed, its line energy will be shifted upward according to the number of L-shell vacancies, since when these L-shell electrons are removed their (small) screening effects disappear. This leads to a cluster of satellite L ← K transitions that may be resolved from one another, each being identified with a particular number of L-shell vacancies.

For a particular number of initial electron vacancies in the L shell, the X-ray transition lines from different combinations of 2s and 2p vacancies are nearly degenerate in energy. In contrast, some of the Auger transitions can be distinguished by whether the vacancy is 2s or 2p. To show why this is so, consider both X-ray and Auger emissions resulting from K ← L transitions. X-ray emission involves an electric dipole selection rule that requires a 1s ← 2p configuration change for the active electron. This selection rule keeps the 2s electrons inactive, so for each X-ray transition the number of 2s-shell vacancies stays constant while the 1s ← 2p transition occurs. Thus, while there is a shift in total binding energy between the configuration with a 2s-vacancy versus that for a 2p-vacancy, this shift is present in BOTH initial and final configurations, resulting in a near cancellation and, thus, almost identical transition energies.

In contrast to X-ray transitions, Auger transitions are not restricted by selection rules as stringent as those governing radiative transitions, so more than one distinct final configuration is possible for each initial configuration. As a result, it is possible for an initial configuration with a 2s-vacancy to have more than one final configuration identical to that for an initial configuration with a 2p-vacancy. This may be seen from the following remarks, using Neon as a concrete example.

A table of possible final configurations is listed for both initial configurations, having a single L-shell vacancy. This table lists both the possible X-ray transitions and the possible Auger transitions. Those Auger transitions having identical FINAL configurations are separated in energy, as the binding energy differences in the initial configurations are not cancelled by the identical final configurations.

	Initial Configurations		Final Configurations	
X-ray Transitions	$1s^1 2s^1 2p^6$	→	$1s^2 2s^1 2p^5$	
	$1s^1 2s^2 2p^5$	→	$1s^2 2s^2 2p^4$	
Auger Transitions	$1s^1 2s^1 2p^6$	→	$1s^2 2s^0 2p^5$	Identical Final Configurations
		→	$1s^2 2s^1 2p^4$	
	$1s^1 2s^2 2p^5$	→	$1s^2 2s^0 2p^5$	
		→	$1s^2 2s^1 2p^4$	
		→	$1s^2 2s^2 2p^3$	

If there is a double K-shell vacancy (i.e. if the K shell is initially empty), the K-L transition energies shift upward fairly dramatically as the K-shell electrons screened the nuclear charge much more effectively than did the L-shell electrons. This cluster of transitions seen at these higher energies are called hyper-satellites, with each member being associated with a different initial L-shell vacancy plus an empty K-shell. Similar satellite effects can be observed as splittings in the transition lines $K\beta$, $K\gamma$, etc.

The higher the Z of the incident projectile, the more effective it is in causing multiple inner shell ionization. Varying the beam energy affects the amount of ionization, but not nearly as dramatically as varying Z. As a result, multiply-ionized states may be formed with much greater probability in heavy-ion bombardment than in conventional electron bombardment. Thus, even though much higher beam currents are available with electrons than with high-energy heavy ions, the latter will form these unusual states with a correspondingly smaller background due to simple excitations.

Some experimental effort has gone into studying the reaction mechanism of these collisions. Although a very simple, semi-classical, two-body Coulomb collision (Binary Encounter Model) appears to give good results for protons and alphas, it fails to account for some aspects of the heavy-ion collisions. This may be due, in part, to the discovery that the charge state of the projectile can drastically affect the excitation of the target.

Chemical effects have been observed in careful comparisons of yields from different molecular species with one another and with the yields from the appropriate atomic species. These chemical effects show up both as shifts in the transition energies of the various satellite peaks and as differing amounts of yield in these transitions, depending on the molecular environment. These shifts show considerable promise for applied analytical work, particularly when sample sizes are small or when a knowledge of the chemical composition of an object is desired without subjecting it to the rigors of wet chemistry.

Preliminary Hartree-Fock-Slater (HFS) calculations have been used to predict the Kβ-satellite energy shifts between Si and SiO_2 for each of the possible L-shell vacancies. For electron, proton and helium bombardments the HFS calculations showed quite good agreement with the data, but the HFS predictions for oxygen were even qualitatively wrong, as the measured energy shift DECREASED with increasing L-shell vacancy in contrast to both HFS predictions and the light-ion results.

Measurement of total cross-section for forming an excited ion in a particular charge state requires, in principle, both X-ray and Auger line intensity measurements as both of these decay channels are usually open for de-exciting the atom. Until recently, high-resolution Auger measurements had not been performed and so the total ionization cross-sections were necessarily inferred from X-ray measurements using theoretical calculations for the ratio of the yields from these two competing atomic de-excitation processes. X-ray to Auger branching ratios have been measured for most of the simple states formed by electron bombardment, and they are found in agreement with the theoretical calculations to within the accuracy of the measurements. However, recent measurements of transition strengths from complex states formed by heavy-ion bombardments show that the X-ray to Auger branching ratios depend on the details of the spectator-electron environment--e.g. the number of initial L-shell vacancies. This is in qualitative agreement with theoretical calculations, although discrepancies in the exact numerical values are suggested by these recent measurements.

Beam foil excitation of varying atomic species began with the observation of the strong Lyman (and Lyman-like) X-ray transition lines from hydrogenic oxygen (and He-like oxygen). The feature of the beam-foil X-ray spectrum that was most striking, at first glance, was that most of the spectral lines in evidence were well-separated from one another. This is to be contrasted with the situation in the optical region where a large number of transitions are overlapping and identification of a particular transition by comparison between its measured and calculated line energy is often a near impossibility. It is easy to see why this short-wavelength region is relatively uncluttered with overlapping transitions. This is because of the simplicity of the electron decays in this region, since the active (non-spectator) electron must jump to the 1s final configuration. All Lyman X-ray transitions, then, must have energies above 3/4 of the ionization energy in hydrogenic oxygen and all other X-ray transitions in hydrogenic oxygen ending with a 2s, 2p, or higher-n configuration must have no more than 1/3 of this minimum energy. Even with maximum possible screening ($Z_{eff} = 7$), the smallest energy Lyman-like transition in He-like oxygen is more than twice the energy of any hydrogenic transition to an n = 2 or higher -n configurations. Thus, <u>all</u> lines not identified in this high-energy region as Lyman or Lyman-like transitions MUST be due to the decay of multiply excited states. Since the likelihood of stripping to bare oxygen increases monotonically with its kinetic energy, these highly-stripped states may be selectively formed. As a result of the good separation between X-ray lines in this energy region, transitions from many doubly-excited states in He-like and Li-like oxygen have been assigned from a comparison between measured and calculated line energies. Other arguments were given in the assignments only for those lines where ambiguities occurred in using this energy-comparison method of assignment.

The vast majority of the multiply excited transitions in He-like and Li-like oxygen had never been seen before in any other atom, including helium and lithium. Only a few line energies from previous theoretical calculations were found, and these were seen to confirm our calculations. This small amount of theoretical work is consistent with the small amount of experimental work that preceded these measurements.

Beam-foil measurements of delayed X-ray emission are discussed in Sec.II.E. for "Atomic Research in Progress." Here lifetime measurements are discussed and a measured, non-exponential shape of the delay curve is shown for lower-lying members of the Lyman (and Lyman-like) series. Further, it is seen that the series limit region is enhanced in the delayed spectrum when compared with the prompt spectrum. The persistence of the Lyman (and Lyman-like) transitions, observed in the delayed spectrum is attributed to cascading from those states near the (appropriate) ionization limit. Preliminary measurements show that the non-exponential shapes of the low-lying Lyman (and Lyman-like) transitions are similar to one another, each being well described by a power-law shape with the same exponent value. Comparisons with simple theoretical formation models suggest that this data may aid in establishing the beam-foil collision mechanism.

The work in progress section of this report (II.E.3. and II.E.4.) discusses two experiments that are designed to perturb those nearly-unbound electrons populating long-lived states near the ionization limits in both hydrogenic and helium-like oxygen. The first of these entries discusses a Stark enhancement seen in the series limit yield for the PROMPT spectrum. A static electric field of about 10^5

volts/cm is produced in the rest frame of the ion by passing the oxygen through a magnetic field of about 8 kG at a speed of 0.05 c. This provides a new method for measuring the ionization limits. The second of these entries reports an experiment where electrons are scattered from highly-ionized oxygen using a foil-grid apparatus to re-accelerate those electrons knocked out by each oxygen ion as it passes through the foil. Structure is seen in the X-ray yield as the foil-grid voltage is varied. These peaks may be the result of a resonant excitation process in a collision preceeding an Auger or X-ray process that leads, subsequently, to a highly-excited hydrogenic final state.

Both Auger and X-ray measurements can be used to study the emissions following a beam-foil collision, including the study of delayed emissions. However, the study of X-ray measurements in a strong field region may not be extended to include Auger electrons.

It has been shown in the atomic experiments described in this report (II.E.) and in the resulting literature (II.B.,C.,D.) that it is still possible to find entirely new modes of atomic excitation even after more than half a century of atomic research!

3. Research Instrumentation

As we have noted, the past year saw continued development of research instrumentation for the on-going experimental program as well as the development of many new and novel techniques for basic nuclear and atomic physics research. The in-beam internal conversion electron spectrometer (see IIE) and the charged-particle electrostatic guide, briefly discussed in last year's report, have both performed well and are now documented in the literature (see V.A.).

The high resolution QDDQ magnetic spectrometer whose initial planning began last year is now in its final stages of design. The design, which incorporates special mirror symmetries about the geometrical center of the system allows a realistic resolution of a few kilovolts (at tandem energies) with an enormous 20 msr solid angle (section II.F.1.).

Two other instruments utilizing magnetic deflection in the study of charged particle reaction products have become operational during the past year. A sector-focussing magnet employing a high field gradient and strong edge focussing (section II.F.2.) produces approximate double focussing of up to 30 MeV protons. Another system, known as a biased magnetic quadrupole spectrometer, is now also operational (section II.F.3.) for experiments requiring particle identification with the best energy resolution from a single charged particle detector. Basically this system features a double focussing quadrupole doublet with a dipole field superimposed upon the quadrupole fields (or equivalently, the magnet center of the quadrupoles is moved from the geometric center of the quadrupoles). This device is currently being used to study (d,p) reactions to highly excited and unbound states in the residual nucleus in the mass 40 region (section II.E. 1e). Perfect p-d particle separation is obtained with 13 keV resolution.

A rather unique, computer controlled, pneumatic target transfer system ("rabbit") has been constructed (section II.E.8.) to remove activated targets to a shielded area several meters from the bombarding area in less than one second. The reduced background protects detectors and makes possible a variety of experiments not possible with in-beam measurements (section II.E.9.).

An array of 16 rectangular detectors has been constructed to measure the kinetic energy of ^{8}Be in the (^{12}C, ^{8}Be) reaction from the sum energy of adjacent detector pairs that are taken in fast coincidence (section II.E.7.). In addition, a ΔE-E detector telescope has been constructed in which a commercial 25μ-ΔE detector is followed by an E detector that is split into two adjacent semicircular active areas. This system will provide the extra condition of particle identification for ^{8}Be (section II.E.7.).

Detector fabrication continues at a ferocious rate. Many new types of detectors have been developed during the period covered by this report, including lithium drifted detectors, surface barrier transmission detectors, split detectors (all discussed in section II.E.10.) as well as a new type of position-sensitive detector (section II.E.11.) where differences in pulse rise times can be used to provide position determination in a solid state radiation detector in direct analogy with conventional position-sensitive gas proportional counters.

The accelerators have operated well during the past year, all problems encountered being overcome with a minimum of down time (II.F.1.0.). The direct extraction source has been improved (II.F.2.1.) while the Middleton-type heavy ion source (II.F.2.2.) is nearing completion and should be in operation in early January. A recent innovation is the use of the PDP-15 computer to identify a particular ion species from the ion source (II.F.3.1.).

The data acquisition facility and the data processing facility (II.G.1.) continue to expand to meet the increasing need of the experimenters.

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PHYSICAL REVIEW C VOLUME 6, NUMBER 5 NOVEMBER 1972

^{107}Ag$(d,p)^{108}$Ag and ^{109}Ag$(d,p)^{110}$Ag Reactions*

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The level structures of ^{108}Ag and ^{110}Ag have been investigated via the (d,p) stripping reaction on isotopically enriched targets of ^{107}Ag and ^{109}Ag at an incident deuteron energy of 10.0 MeV. The over-all experimental resolution was approximately 20 keV. Proton groups leading to 57 states in ^{108}Ag with excitation energies up to 2.78 MeV and 37 states in ^{110}Ag with excitation energies up to 1.66 MeV have been identified. Orbital angular momentum transfer values and spectroscopic factors have been extracted for 19 states in ^{108}Ag and for 23 states in ^{110}Ag using the zero-range distorted-wave Born approximation including an approximation for the nonlocality of the optical potential and a finite-range correction. In ^{108}Ag, six $l=0$, nine $l=2$, one $l=4$, one admixture of $l=0$ and $l=2$, and two admixtures of $l=2$ and $l=4$ are assigned. In ^{110}Ag, six $l=0$, sixteen $l=2$, and one admixture of $l=2$ and $l=0$ are assigned. It is possible that a small fraction of $l=2$ transitions in ^{110}Ag are masked with $l=4$ transitions. On this assumption, the effective numbers of neutrons outside the closed $g_{9/2}$ orbital in ^{108}Ag and ^{110}Ag are consistent with the expected values. The summed strengths of the single-particle orbitals are consistent with those of neighboring isotones.

I. INTRODUCTION

The deuteron stripping reaction has been extensively used to obtain nuclear spectroscopic information. Most of these investigations, however, have been restricted to even-even target nuclei. The shapes of the angular distributions are uniquely related to the orbital angular momentum transfer to the target nucleus,[1] and since the ground-state spin is 0^+, the final-state spin of the residual nucleus is known within limits of $\pm\frac{1}{2}$. It is natural to extend these investigations to odd-A target nuclei with an even number of neutrons. The (d,p) angular distributions are still characteristic of the l-value transfer to the target nucleus, but except for the s-wave transfer, the simplicity of restricting the choice of the final-state spin to two possible values only is lost. It is, however, of interest to study the effect of the odd proton on the spectroscopic factors of the neutron single-particle states.

In this paper we report the results of our investigation of the level structures of ^{108}Ag and ^{110}Ag via the (d,p) stripping reaction using ^{107}Ag and ^{109}Ag targets ($Z=47$), respectively. A comparison of the level structures of the isotopic nuclei ^{108}Ag and ^{110}Ag with the structure information available on the respective isotonic nuclei ^{107}Pd (Ref. 2), ^{109}Pd (Ref. 2), and ^{113}Sn (Refs. 3, 4) should yield information about the order and the degree of filling of both proton and neutron single-particle orbitals in the mass neighborhood under consideration.

The (d,p) reaction on the stable Ag isotopes has not been extensively investigated. Earlier experiments of Sperduto[5] and of Mazari[5] were restricted to the determination of the excitation energies of low-lying states of ^{108}Ag and ^{110}Ag, and no attempt was made to extract the l-value transfers. Recently, the (d,p) stripping reaction has been studied by Lopez[6] at an incident deuteron energy of 7.5 MeV. Shugart, Curry, Lock, Moore, and Riley[7] have studied the isobaric analogs of the low-lying states of ^{108}Ag and ^{110}Ag by means of proton elastic scattering from ^{107}Ag and ^{109}Ag targets. It was found that the weak-coupling approximation gives a reasonably good description of the low-lying states of the parent nuclei. A study of the (d,p) reactions on the ^{107}Ag and ^{109}Ag isotopes in

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^{136}Xe(p, p')^{136}Xe and ^{136}Xe(p, d)^{135}Xe Reactions*

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Low-lying states of ^{136}Xe with excitation energies up to 3.3 MeV are investigated via inelastic scattering of 13.982-MeV protons. Spin, parity, and deformation parameters are extracted for 13 excited states through distorted-wave Born-approximation (DWBA) analysis using a collective-model form factor. The results obtained indicate that ^{136}Xe is not a typical vibrational nucleus. A microscopic calculation for the level spectrum and the inelastic form factor, based on the quasiparticle random-phase approximation, is performed. DWBA angular distributions are calculated using a microscopic form factor. The level spectrum and the absolute magnitudes of the cross sections for most of the 4^+, 6^+, and 3^- observed states are reasonably well reproduced through these calculations. For the 2^+ states, however, the predicted level density and the distribution of the inelastic strengths disagree with the observed data. In addition, three deuteron groups leading to states of ^{135}Xe are observed. The orbital-angular-momentum-transfer values and the spectroscopic factors for these states are obtained through DWBA analysis of the data.

I. INTROUDCTION

The inelastic scattering of protons is a useful spectroscopic tool for the investigation of nuclear energy levels. Analysis of experimental data is usually carried out in the framework of the distorted-wave Born approximation (DWBA) using a collective-model form factor. The angular distribution of a particular excited state is characteristic of the orbital angular momentum transfer, which gives information on the spin and parity of the state. From the absolute magnitude of the cross section, one can extract information on the nuclear correlations in a particular excited state. For many even-even nuclei the inelastic scattering cross sections, particularly of the low-lying first 2^+ and 3^- collective states, have rather large magnitudes, indicating that the coupling between these states and the ground state is strong and consequently that the DWBA theory is not sufficiently accurate. In such cases one may improve the analysis by making use of the coupled-channel (C.C.) approximation instead of the DWBA. On the other hand, there are many cases where the low-lying spectra do not show typical vibrational character and where the inelastic cross sections are of rather small magnitudes. In such cases the description of the scattering in terms of a collective-model form factor is questionable and the use of a microscopic form factor would be more appropriate.

In this paper we report the results of a study of the ^{136}Xe(p, p')^{136}Xe and ^{136}Xe(p, d)^{135}Xe reactions. The low-lying states of ^{136}Xe have been the subject of considerable theoretical investigation,[1-4] but have received little experimental attention compared with the other stable $N=82$ even-even nuclei.

Moore, Riley, Jones, Mancusi, and Foster,[5] in a study of the (p, p') reaction through isobaric analog resonances (IAR), measured angular distributions of excited states of ^{136}Xe, nearly all of which were above 3.5 MeV in excitation. These high-lying states were interpreted as excitations of the closed neutron core, i.e., neutron-particle-hole states formed by lifting a neutron in the closed core into an orbit in the next major shell. Moore *et al.*,[5] however, made tentative spin and parity assignments to two states below 3.5 MeV excitation, namely 2^+ for the 1.31-MeV state and 3^- for the 3.26-MeV state. β-decay studies of ^{136}I isomers have been reported by Carraz, Blachot, Monnand, and Moussa[6] and by Lundan.[7] The spin assignments made in these studies were not unique, except for the few lowest states. The present ^{136}Xe(p, p') experiment was thus carried out in order to study the structure of the low-lying states of ^{136}Xe. The measurements were carried out at an incident proton energy of ~14.0 MeV. Because of the low (p, n) threshold (~0.9 MeV), it is reasonable to expect that the low-lying inelastic states would be populated predominantly through direct reaction processes. Since ^{136}Xe has a ground-state spin 0^+ (even-even), the transferred orbital angular momentum in a (p, p') reaction is equal to J of the final state and an unambiguous spin assignment to the inelastic states should thus be possible.

II. B-3

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Inelastic Proton Scattering from ^{96}Mo Through Isobaric Analog Resonances*

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Excitation functions for proton elastic and inelastic scattering to several low-lying states of ^{96}Mo have been measured in the energy range from 5.2 to 8.0 MeV. Isobaric analog resonances have been used to deduce the structure of parent states in ^{97}Mo. In particular, the ground state of ^{97}Mo was found to have parentage in four excited states of ^{96}Mo, besides the ^{96}Mo ground-state component already known from ^{96}Mo(d, p) studies. Angular distributions were measured on the prominent resonances to determine the angular momenta of the exiting protons and to obtain inelastic partial widths. Noticeable asymmetries in the inelastic yield curves are found and interpreted as arising from interference between the resonance reaction and other (direct) processes. The assignment of spin-parity 0^+ to the 1.15-MeV state of ^{96}Mo is found to be consistent with the present data.

I. INTRODUCTION

The present study of inelastic proton scattering from ^{96}Mo through isobaric analog resonances (IAR) is a part of a continuing investigation of the Zr and Mo isotopes via such a technique.[1] The primary goal of these studies has been to obtain the parentage of the ground and low-lying excited states of the parent nucleus in terms of the physical core states of the target nucleus. Thus, in the present case one determines the structure of the levels of ^{97}Mo in terms of the states of ^{96}Mo by observing the proton decay of the analogs of the ^{97}Mo levels to the various states of ^{96}Mo. If one compares the measured partial width for proton decay to a calculated single-particle proton partial width in each channel, the spectroscopic factors for the various core states populated in the decay may be obtained. In general the elastic channel widths agree well with spectroscopic factors deduced from single-nucleon-transfer reactions. Thus one can use the inelastic decay widths to obtain similarly reliable spectroscopic information impossible to extract from single-nucleon-transfer experiments.

In general the proton decay of an IAR to an excited state of the target can signify either the core-excited nature of the IAR (through the $|pC^*\rangle$ part of the IAR wave function)[2] or the particle-hole nature of the final state (through the $|nA\rangle$ or $|nA^*\rangle$ part of the IAR wave function).[3] If one is to obtain nuclear-structure information, it must be determined which of these two competing processes predominates. For a closed-neutron-shell nucleus the interpretation of IAR in inelastic channels is fairly straightforward: Particle-hole states lie at high excitation energies, so decay to low-lying states can be explained as due to the core-excited part of the IAR wave function. As one moves away from a closed neutron shell, lower-energy particle-hole configurations become available, and the interpretation of IAR becomes more obscure.

The present target nucleus, ^{96}Mo, exemplifies this latter case, having four neutrons outside the $N=50$ closed shell. These four neutrons lie predominantly in the $2d_{5/2}$ orbit, the lowest available state. However, there is also some filling of the $3s_{1/2}$, $2d_{3/2}$, and $1g_{7/2}$ orbits. This is revealed in the neutron-pickup study ^{96}Mo(d, t) by Diehl *et al.*[4] They find the fullness in the $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1g_{7/2}$ orbits to be 0.52, 0.19, 0.15, and 0.21, respectively. This complicated structure allows various particle-hole configurations to be excited at the different IAR. In spite of this difficulty it is still possible to obtain some limits on the structure of the states involved, if one knows the l value of the outgoing proton, since this is identical to the l value of the hole in the particle-hole state.

The nature of the states of ^{96}Mo is also of interest in the present investigation, especially the state at 1.15 MeV in excitation. This level was first reported in the ^{95}Mo(d, p) work of Moore *et al.*[5] It is not observed in either γ-ray[6] or internal-conversion electron studies[7] following the β decay of ^{96}Nb. The γ decay of this level has been reported in studies of ^{96}Mo$(n, n'\gamma)$[8] and of Coulomb excitation of ^{96}Mo by ^{16}O ions.[9] These latter two works both determine an excitation energy of 1.148 MeV for this state. The $(n, n'\gamma)$ angular distributions are consistent with this state having spin and parity 0^+, as is also conjectured in the Coulomb excitation work. Likewise, the level is also reported in ^{95}Mo(n, γ)[10] with a suggestion that it may be 0^+. The primary motivation for identi-

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Gamma Cascades in ^{252}Cf Spontaneous Fission Fragments*

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A γ-ray-γ-ray coincidence experiment to measure transitions in the spontaneous fission fragments of ^{252}Cf has been performed with a 0.14-cm^3 Ge(Li) detector (full width at half maximum 600 eV at 81 keV) and a 40-cm^3 Ge(Li) detector (full width at half maximum 2.8 keV at 1.33 MeV) in close geometry and repeated in an extended geometry involving shielding of one of the prompt fragments. Several low-energy cascades have been detected which were previously unreported. In addition partial decay schemes for four of the products, ^{105}Mo, ^{109}Ru, ^{111}Ru, and ^{146}La, have been suggested.

I. INTRODUCTION

The nature of the level schemes of odd-Z and odd-A fragments from the spontaneous fission of ^{252}Cf has remained for the most part a mystery. Their elucidation has been a challenging experimental problem. Lack of intensity of many of the γ transitions has prevented an investigation as complete as that obtained for the even-even fission products.[1,2] γ rays emitted by certain isotopes populated strongly in the various β-decay processes following both spontaneous fission of ^{252}Cf and neutron-induced fission of the uranium isotopes have been observed in detail.[3-10] Presented in this work are the results of two γ-γ coincidence experiments, one performed in close and one in extended geometry, which have shed considerable light on certain of the nuclei which have so far escaped a consistent analysis. This experiment, relying heavily on previous assignments of a multitude of transitions in the energy range 45 to 200 keV by x-ray–γ-ray coincidence techniques[11,12] and higher energy transitions from various sources, was made possible by the excellent resolution furnished by a Ge(Li) crystal of 0.14-cm^3 volume. The data indicate certain strong cascades and rudimentary energy level schemes for several of the products expected to be populated directly and by β decay. Also questions pertaining to previous isotope assignments in the x-ray–γ-ray experiments have been answered to some extent.

II. EXPERIMENTAL SETUP

A. Close Geometry

A 0.1-μg ^{252}Cf source between two 13μm disks of beryllium was placed directly on the beryllium window of a 0.14-cm^3 Ge(Li) detector. The Be cover stopped the fragments and removed Doppler distortions for any transition longer than about a picosecond. A 40-cm^3 Ge(Li) detector was placed approximately 19 mm from the source, at which distance the singles count rate was 10 000 counts/sec. The count rate in the smaller crystal was 5 000 counts/sec. At these rates the respective resolutions were 2.8 keV full width at half maximum (FWHM) at 1.33 MeV and 600 eV FWHM at 81 keV. The timing and linear signals were routed through standard double coincidence circuitry. With a timing window of about 150 nsec, a coincidence count rate estimated at 100/sec was encountered. The logic signal accompanied by the two linear signals was accepted by a computer program which performed a sort of the γ rays from the 40-cm^3 crystal according to windows set on the peaks in the spectrum from the 0.14-cm^3 detector. All processing was done on line. In this way 1024 channel spectra were built of γ rays from 45 to 1300 keV in coincidence with the many lines in the energy range 45–200 keV. In the following discussion, figures, and tables, these are the data referred to unless otherwise specified.

Calibrations were taken daily in both detectors with standard sources. A run of 7 days was made. During that time no adjustments had to be made on the gates. Also no gain drift for the electronics associated with the 40-cm^3 counter was found.

B. Extended Geometry (EG)

An additional experiment was performed in order to help remove some of the ambiguity involved in identification of the γ lines in the previously described spectra, i.e., the fact that γ rays both from the nucleus supplying the gate γ ray and from its possible complementary nuclei arising from the binary fission event will show up in these sorted spectra. A ^{252}Cf source mounted on a thick copper foil was positioned as shown in Fig. 1. The open-faced side of the source pointed back into a lead shield which afforded a 19 mm thick lead shield between the fragments in flight and the 0.14-cm^3 Ge(Li) detector. Approximately 3.8 cm of lead separated the fragments from a 30-cm^3 Ge(Li) detector. In this way γ rays emitted more than about 1 nsec after fission were substantially attenuated, especially the low-energy lines which

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II. B-5

The ^{88}Sr$(d, n\tilde{p})^{88}$Sr Reaction*

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The ^{88}Sr$(d, n\tilde{p})^{88}$Sr cross section has been measured at 170° for deuteron energies from 7.5 to 10.0 MeV, and the total ^{88}Sr$(d, n\tilde{p})$ cross section obtained. The total cross section is compared with results of coupled-channel Born approximation calculations using both empirical and shell-model-reaction-theory form factors to describe the decaying isobaric analog state. It is shown also that the new data and calculations are consistent with earlier ^{88}Sr$(d, p)^{89}$Sr data.

1. Introduction

The coupling of analogous (d, p) and (d, n) reaction channels by (p, n), (n, p) charge-exchange in the final state is now a familiar phenomenon [1–10]. The study of such reactions has to date generally been carried out by measuring the (d, p) or (p, d) cross section as a function of energy, across the charge-exchange threshold. The direct population of isobaric analog states (IAS) by (d, n), (p, d), and $(^3\mathrm{He}, d)$ has also been of considerable recent experimental interest [11, 12]. However, the measurement of decay protons $(\tilde{p})$ from the residual IAS, after population via (d, n) or $(^3\mathrm{He}, d)$ has very seldom been carried out [1, 13, 14]. This is surprising, because the $(d, n\tilde{p})$ cross section provides data directly complementary to the (d, p)-excitation-function studies of the charge-exchange coupling [15]. The $(p, n\tilde{p})$ reaction has also been somewhat neglected until recently [16].

In this paper we present results of a study of the ^{88}Sr$(d, n\tilde{p})^{88}$Sr excitation function from threshold to 10.0 MeV, including an analysis of the $(d, n\tilde{p})$ data together with ^{88}Sr$(d, p)^{89}$Sr data [8], in terms of the coupled channel Born approximation (CCBA) [15] with a simple shell-model-reaction-theory form factor [17] to describe the residual IAS. This constitutes the first successful CCBA calculation for the charge-exchange cusp using a realistic form factor, as far as we know.

2. Experimental Method

Self-supporting targets of natural strontium were fabricated by evaporating the metal in high vacuum onto detergent-coated glass

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Spin Determinations with α–Heavy-Ion Angular Correlations*

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A new reaction-mechanism–independent method is proposed for determining spins of nuclear levels from angular correlations between α particles and heavy ions. This is an alternative approach to the well-known Method II of Litherland and Ferguson, permitting geometry other than 0° or 180° for the detection of the reaction particle.

Recently it has been found[1] that certain heavy-ion reactions have large cross sections for populating continuum states with relatively large α-decay widths, via the transfer of four or eight nucleons. This has produced a revival of interest in using particle-α angular correlations to determine the spins of such states. The usual method employed in performing such spin determinations has been the Litherland-Ferguson Method II,[2] which involves a coincidence angular correlation between the decay-particle (α) detector and the reaction-particle (e.g., heavy ion) detector located at 0° or 180°, the latter employing an annular detector, a magnetic analyzer, or a beam-stopping foil in front of the counter. However, in some experiments, particle detection at 0° or 180° is either not possible or highly undesirable.

The present work proposes an alternative method of spin determination which is independent of reaction mechanism. This approach does not require any specific position for the reaction-parti-

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Decays of ^{26}Na and ^{27}Na†

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^{26}Na and ^{27}Na were produced in the $^{10}B(^{18}O,2p)^{26}Na$ and $^{11}B(^{18}O,2p)^{27}Na$ reactions by bombarding pellets of boron with 42-MeV ^{18}O ions. ^{26}Na was also studied using the $^{18}O(^{13}C,p\alpha)$-^{26}Na reaction at a ^{13}C beam energy of 35 MeV. After transfer of the target in a rabbit the β and γ rays were measured with NE102 and Ge(Li) detectors. ^{26}Na decays with $T_{1/2}=1.087 \pm 0.012$ sec and emits 10 γ rays involving 7 excited states of ^{26}Mg. From the end-point energy of β rays in coincidence with 1809-keV γ rays the mass excess of ^{26}Na is found to be -7004 ± 200 keV in agreement with the more accurate data of reaction Q values. ^{27}Na decays with $T_{1/2}=280\pm 20$ msec in agreement with a previous measurement. γ rays of 984.77 ± 0.20 and 1698.5 ± 0.5 keV are emitted with relative intensities of 86.0 ± 2.9 and 14.0 ± 2.3, respectively. The spin of ^{27}Na is established as $J^\pi=\frac{3}{2}^+$ or $\frac{5}{2}^+$ from these data. From the end-point energy of ^{27}Na β rays in coincidence with 985-keV γ rays, compared with ^{26}Na β rays, the mass excess of ^{27}Na is -5650 ± 180 keV based on the ^{26}Na mass. This result is in fair agreement with a recent direct determination of the ^{27}Na mass.

I. INTRODUCTION

In a recent series of experiments[1-5] at Brookhaven several new $T_z=+\frac{5}{2}$ nuclides have been formed by heavy-ion compound reactions and their masses, half-lives, and decay schemes have been measured. The purposes of this work have been (1) to compare the spectroscopic observations with the predictions of various theoretical models, (2) to compare the masses of these nuclides with the predictions of theoretical mass formulations, and (3) to provide new input mass data which may lead to refinements of the mass formulas resulting in more reliable predictions of nuclear masses even further from the line of β stability. Among the 2*s*-1*d* shell members of the $T_z=+\frac{5}{2}$ sequence ^{21}O, ^{23}F, ^{25}Ne, ^{27}Na, ^{29}Mg, ^{31}Al, ^{33}Si, and ^{35}P, the previously unknown nuclides ^{31}Al, ^{33}Si, and ^{35}P have been established and their decay properties studied.[1-3,5] Details of the decay scheme of ^{25}Ne were obtained,[4] this nuclide having been first identified elsewhere[6] by means of different techniques.

As a continuation of this program we have undertaken an investigation[7] of ^{27}Na. This activity, along with a number of other new isotopes of sodium, was reported by Klapisch *et al.*[8] who bombarded U with high-energy protons and observed resultant sodium isotopes with an on-line mass spectrometer. A half-life of 295 ± 10 msec[9] was obtained for ^{27}Na and its mass excess was determined[10] to be -5880 ± 140 keV. β rays with an end-point energy of 7.6 ± 0.5 MeV were also reported,[8] but there has been no other information of the ^{27}Na decay scheme.

^{26}Na is a known radioactivity having a half-life of 1.04 ± 0.03 sec[11] from earlier measurements and 1.07 ± 0.03 sec[9] according to more recent work. Only one β-ray branch, to the 1809-keV first excited state of ^{26}Mg, has been reported in the literature,[11] although there are many other states to which allowed β-ray branches could take place. When ^{26}Na was observed in some early experiments on the $^{18}O+^{13}C$ reaction we decided to check its half-life and search for β-ray branches not previously reported.[7] During later work on ^{27}Na it became clear that a knowledge of the ^{26}Na decay scheme would help in providing a more accurate mass value for ^{27}Na. This is due to the proximity of the end-point energies of the ^{27}Na β rays feeding the 985-keV state of ^{27}Mg and the ^{26}Na β rays feeding the 1809-keV state of ^{26}Mg. Since the energy of the latter can be calculated on the basis of accurate reaction Q values it can be used as an internal calibrator when both ^{26}Na and ^{27}Na are produced simultaneously as in some of the present experiments. In order to use ^{26}Na most effectively as a calibrator the shape of the β-ray spectrum leading to the 1809-keV state must be well defined. This means that the contributions to the total spectrum of pulses in the NE102 scintillator in coincidence with 1809-keV γ rays due to β rays feeding higher states that γ cascade through the 1809-keV state (amounting to ~12% of all decays) must be subtracted out along with effects due to γ-ray summing. In turn these corrections

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Decays of ^{72}Kr and ^{73}Kr†

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Delayed γ rays following the decay of two new proton-rich Kr isotopes have been observed. These isotopes were produced by the bombardment of ^{58}Ni with ^{16}O ions, and were separated from contaminant activities by a gas-transfer system. ^{72}Kr decays with a half-life of 17.4 ± 0.4 sec to states in ^{72}Br, with the subsequent emission of six γ rays. ^{73}Kr decays with a half-life of 25.9 ± 0.6 sec to states in ^{73}Br, and emits eight γ rays. Identification of the Kr isotopes was based both on the buildup of their daughters, and on relative intensities of decay γ rays observed at two different ^{16}O bombarding energies. Decay schemes are presented, and the astrophysical significance of ^{72}Kr is discussed.

I. INTRODUCTION

Recent interest in the properties of proton-rich isotopes with regard to their role in explosive nucleosynthesis[1,2] has prompted a search for such nuclides, especially for the even-even $T_z = 0$ (α-particle) nuclei. The heaviest one known until recently, ^{64}Ge, has been shown to be relatively tightly bound,[2] suggesting that the even heavier isotopes ^{68}Se, ^{72}Kr, ^{76}Sr, and ^{80}Zr may possibly play a role in determining abundances of the chemical elements in the $60 < A < 80$ region of the periodic table. Such studies also contribute to an understanding of the systematics of proton-rich nuclei in this mass region, helping to define the boundaries of proton particle stability and providing tests of mass formulas.

The original purpose of the present experiment was to search for ^{72}Kr. During the course of the investigation it became evident that ^{73}Kr was being made as well. In this article we report the observation of ^{72}Kr and ^{73}Kr, and present data on the half-lives and decay properties of these nuclides. Preliminary results have been reported in Ref. 3. Schmeing *et al.*[4] have independently observed ^{72}Kr and ^{73}Kr at Chalk River.

II. EXPERIMENTAL METHOD

The Kr isotopes were produced via the ^{58}Ni(^{16}O, $2n$) and ^{58}Ni(^{16}O, n) reactions at incident energies of 52 and 53 MeV, using ^{16}O^{5+} beams from one of the Brookhaven National Laboratory MP tandem accelerators. Figure 1 shows the experimental arrangement. A self-supporting ^{58}Ni foil of thickness either 1.5, 2.1, or 3.0 mg/cm^2 served both as target and as isolation foil between the beam-line vacuum and a helium-filled cell. This cell, 10 cm long and 1.6 cm in diameter, was used to thermalize Kr and other reaction products emerging from the target, preparatory to their transfer to a remote counting station in an adjoining room. The use of a gas-transfer system[5] instead of a target shuttle system is particularly useful in this instance, because of the possibility of employing various chemical and/or physical separation techniques to eliminate from the helium gas stream any undesirable reaction products. Contaminant activities such as ^{72}Br, ^{72}Se, ^{71}Se, and ^{69}As are copiously produced by the (^{16}O, pn), (^{16}O, $2p$), (^{16}O, $2pn$), and (^{16}O, αp) reactions at these bombarding energies.[6] Since the desired Kr isotopes were expected to behave as noble gas atoms, it was decided to use a cold trap cooled to dry ice temperature to condense bromine. In addition, the trap and transfer tube were made of copper, and a small volume of powdered Ascarite (KOH) was inserted in the line. Both measures hopefully increased the chemical absorptivity for all elements except for krypton.

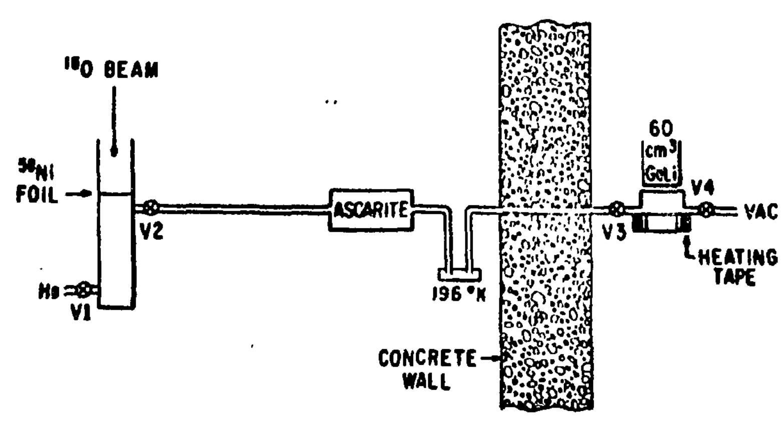

FIG. 1. Experimental arrangement of the gas-transfer system. Copper tubing of 1.6-mm inner diameter was used between *V2* and *V3*.

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Mass and β Decay of the New Isotope ^{29}Mg: Systematics of Masses of $T_z = \frac{5}{2}$ Nuclides in the 2s-1d Shell*

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Measurements of the mass, half-life, and β decay of the new isotope ^{29}Mg are reported. Produced by the ^{18}O(^{13}C, 2p)^{29}Mg reaction, this activity was periodically transferred to remotely located Ge(Li) and NE 102 detectors. γ-ray energies (in keV) and relative intensities for the ^{29}Al daughter transitions are 960.3 ± 0.4 (52 ± 18), 1397.7 ± 0.4 (64^{+30}_{-20}), 1430 ± 1.5 (34 ± 17), 1753.8 ± 0.4 (22 ± 5), and 2223.7 ± 0.4 (100 ± 6). The ^{29}Al excitation energies (in keV) and relative β branching intensities are 1397.7 ± 0.4 (64^{+35}_{-28}), 1753.8 ± 0.4 (<10), 2223.8 ± 0.4 (55 ± 22), and 3184.0 ± 0.6 (100 ± 35). Upper limits on other possible transitions are given. ^{29}Mg decays with a half-life of 1.20 ± 0.13 sec, measured by the decay of the prominent 2224-keV γ ray. The decay of ^{29}Mg is discussed in terms of the Nilsson model. By measuring the spectrum of pulses in the NE 102 detector coincident with 2224-keV γ rays, the mass excess for ^{29}Mg has been determined to be −10 590 ± 400 keV, disagreeing by 1.7 ± 0.5 MeV from a previous report. The present mass for ^{29}Mg is combined with all other information concerning masses of $T_z = \frac{5}{2}$ nuclides in the 2s-1d shell, and the results are compared with predictions based upon measured masses closer to stability using the transverse relationship of Garvey. When the differences between the measured and predicted values are plotted against atomic weight, systematic effects are evident.

I. INTRODUCTION

Nuclei far from the valley of stability are important to study because they not only provide masses to test various predictions, but also lend insight, via β-decay matrix elements, to the structure of very high isospin ground states.

This article is a continuation of a program to search for neutron-rich species in the 2s-1d shell and to measure their masses. Previous work in this region has been summarized by Goosman and Alburger,[1] and Alburger, Goosman, and Davids.[2]

^{29}Mg was shown to be nucleon stable by Artukh *et al.*,[3] who showed that this nuclide lived at least 10^{-7} sec, after having been produced by bombardment of ^{232}Th with 290-MeV ^{40}Ar ions. No information on the decay scheme or half-life of ^{29}Mg has been published. However, a report by Scott *et al.*,[4] who sought the mass of ^{29}Mg via the ^{26}Mg(^{11}B, ^{8}B)-^{29}Mg reaction, indicates from their highest-energy ^{8}B peak a possible mass excess for ^{29}Mg of −12.33 ± 0.16 MeV.

In the present work, ^{29}Mg has been produced in the ^{13}C(^{18}O, 2p)^{29}Mg reaction, and has been identified via the β-delayed γ-ray transitions in ^{29}Al. The half-life and mass have been measured, and the latter differs by 1.7 ± 0.5 MeV from the value suggested in Ref. 4.

II. METHOD AND RESULTS

A. γ-Ray and β-Ray Intensities

As explained in detail in Ref. 1, new activities are sought by looking for γ-ray transitions in the daughter nucleus following the β decay of the parent nuclide at a remotely located counting station. The experimental equipment and electronics were almost identical to that described in Ref. 1, except that a beam of 100 nA (electrical) of the +4 charge state of 35-MeV ^{13}C ions was used to bombard a target of Ta_2O_5 enriched to 99% in ^{18}O. The ^{18}O weight was 3 mg/cm^2 on each side of the thick Ta strip. An on-line computer stored β-ray spectra in an NE 102 scintillator coincident with digital gates set on the γ-ray spectrum as well as storing singles γ rays in four successive 0.9-sec bins, and γ-ray spectra coincident with pulses in the NE 102 detector above about 2.5 MeV. The latter

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Accurate Masses and β-Decay Schemes for ^{34}P and ^{33}Si†

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By using delayed β-γ coincidence techniques, the mass excesses of ^{34}P and ^{33}Si have been measured to be $-24\,546 \pm 45$ and $-20\,569 \pm 50$ keV, respectively, representing improvements in precision of a factor of 2 for ^{34}P and a factor of 4 for ^{33}Si over previous measurements. The first measurements of the high-energy γ rays from ^{34}P decay with a Ge(Li) detector are presented, revealing three new β branches. γ-ray energies (in keV) and relative intensities for the ^{34}S daughter transitions are 1787 ± 1 (0.30 ± 0.10), 1947.1 ± 1.5 (0.28 ± 0.10), 1987.2 ± 1.0 (1.0 ± 0.2), 2127.4 (100.0 ± 0.3), 4073.4 ± 1.5 (0.46 ± 0.06), and 4114.0 ± 1.5 (1.2 ± 0.2). The ^{34}S excitation energies and relative β branches are 2127.4 (100 ± 0.3), 3303.7 (<0.26), 3914.2 (0.30 ± 0.10), 4073.0 (0.76 ± 0.12), and 4114.5 (2.2 ± 0.3). For the decay of ^{33}Si, energies and relative intensities of γ rays were measured to be 415.8 ± 0.6 (6.7 ± 0.6), 1431.4 (13.1 ± 1.0), 1847.5 (100 ± 1), and 2537.5 (9.3 ± 0.8), representing excitation energies and relative β-ray intensities to the ^{33}P daughter states of 1431.4 ($5.1^{+1.0}_{-2.4}$), 1847.5 ($100^{+1.0}_{-2.8}$), and 2537.6 (10.5 ± 1.0). The half-lives of ^{34}P and ^{33}Si were determined by multiscaling γ-ray yields to be 12.45 ± 0.10 and 6.11 ± 0.21 sec, respectively. Combined with an earlier result, a half-life of 6.18 ± 0.18 sec is adopted for ^{33}Si. The transverse mass relationship of Garvey, using the present measurements for ^{34}P and ^{33}Si, predicts a mass excess of $-20\,251 \pm 90$ keV for the $T_z = 3$ nuclide ^{34}Si.

I. INTRODUCTION

A large amount of information has been reported[1,2] recently at various laboratories regarding the properties of exotic nuclei far from the valley of stability. Perhaps the most important reason for this is to test nuclidic mass relationships that have been proposed, although the structure information resulting from β-decay matrix elements connecting high-isospin states is certainly of interest in its own right. Mass measurements have now been reported for seven of the eight $T_z = \frac{5}{2}$ nuclides in the $2s$-$1d$ shell.[2] One of the most successful relationships connecting these masses with those of lower-isospin nuclei is the transverse relationship of Garvey *et al.*[3] The masses of the $T_z = 2$ nuclei required for the comparison of experiment with prediction are all known accurately with one exception, ^{34}P, which has been previously reported with a precision of 90 keV.[1] This previous measurement resulted as a by-product of the measurement of the mass of ^{31}Al, using a system tuned to the half-life of ^{31}Al (0.64 sec), which actually discriminates against ^{34}P ($T_{1/2} = 12$ sec).

A recent measurement[2] of the mass of ^{29}Mg revealed an interesting regular trend in the differences between measured and predicted $T_z = \frac{5}{2}$ masses. However, the ^{33}Si mass was known to a precision[4] of only about 250 keV, and with significant improvements in the experimental facility at this laboratory it was possible to remeasure both the ^{34}P and ^{33}Si masses to a precision of 50 keV.

The β decay of ^{34}P has been reported by Bleuler and Zünti,[5] Morinaga and Bleuler,[6] and Ward and Kuroda.[7] The only Ge(Li) measurements were made by Ref. 7, but their 4.00-MeV γ ray could not be measured with a Ge(Li) detector due to its weak counting rate. They quote an intensity of $0.7 \pm 0.4\%$ for the 4.00-MeV γ ray relative to the strong 2127-keV γ ray. We show in the present work that this 4-MeV line is a triplet, corresponding to three β-ray groups. Reference 7 also reports that $85 \pm 2\%$ of the ^{34}P β decay proceeds to the ^{34}S ground state with $15 \pm 2\%$ terminating at the 2127-keV level. Reference 5 reports values of 75 and 25% for these quantities, but unfortunately

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II. B-11

Sodium Satellite Structure*

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A sample of sodium was bombarded by proton, helium, and oxygen beams and the subsequent K X-ray spectra measured. The spectra exhibit a preponderance of structure which is speculated upon in light of HFS calculations. The strongest lines are ascertained to be the normal $K\alpha$ satellite spectra produced by multiple electron vacancies in single ion-atom collisions.

Recent work[1] has etablished that heavy ion bombardment of Mg, Al, and Si produce X-ray spectra dominated by transitions from multiple inner-shell vacancies. The present work verifies that the same is true in Na. This work, however, shows that there is in addition a host of weaker lines, associated with the highly ionizing process of heavy ion X-ray excitation. The origin of many of these weaker lines is probably associated with transitions which would normally be forbidden as single electron radiative transitions, and thus two-electron transitions are involved. The structure in the spectra ends on the high-energy end near the point for hydrogen-like $K\alpha$ transitions in sodium. Consequently, the Na atom after collision is in a highly ionized and highly excited state whose deexcitation is measured in this experiment by its decay.

The projectiles used were 0.8 Mev protons, 3.2 Mev helium ions and 30 Mev oxygen ions. They were produced using electrostatic accelerators (models KN and EN–High Voltage Engineering Corporation). The X-rays were analyzed using a KAP crystal spectrometer with a resolution equal to 2 eV. The experimental techniques used were similar to those in Ref. 1. Runs were made and repeated until good statistics were obtained. The target was a slice cut from a metallic block of sodium. To a degree, the surface oxidized before it could be placed into the vacuum chamber and pumped out (a time of perhaps three minutes). Several different runs were made on different sodium samples. The

1 McCrary, D. G., Richard, P.: Phys. Rev. A5, 1249 (1972).—Knudson, A. R., Nagel, D. J., Burkhalter, P. G., Dunning, K. T.: Phys. Rev. Letters 36, 1149 (1971).—McCrary, D. G., Senglaub, M., Richard, P.: Phys. Rev. A6, 263 (1972).

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II. B-12

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CHEMICAL ANALYSIS OF HEAVY ELEMENTS BY IDENTIFICATION OF FISSION FRAGMENTS THROUGH X-RAY COINCIDENCE MEASUREMENTS

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A two-parameter coincident (X-ray, X-ray) measurement was made using a Si(Li) X-ray detector and a Ge(Li) X-ray detector to study the X-ray production in the ^{252}Cf fission process. *K* X-ray peaks from adjacent *Z* fission products for elements Y through Rh and I through Pr are well resolved in both detectors. The measurement yields the result that there is a large number of coincident events with X-rays from the same *Z* element as well as with X-rays from the complementary fission product (e.g. Cs *K* X-rays are in coincidence with both the complementary Tc *K* X-rays and the Cs *K* X-rays). The various possibilities one may consider are: (1) *K* X-ray production by the primary fission process followed by internal conversion, (2) multiple *K* X-ray production in the stopping process of the fission products, (3) *K* shell ionization resulting from β-decay of the fission fragments followed by internal conversion in the same fragment, and (4) multiple internal conversion processes from cascading transitions. Each of these four possible causes for self-coincident X-ray production is explored. Further two-parameter measurements were made of low-energy γ-rays in coincidence with characteristic *K* X-rays from the individual elements formed in the fission. Combined with previous mass determinations, it was possible to identify many of the observed γ-rays with individual isotopes. However, a large number of low-energy transitions were observed and identified as to elemental charge, but which had not been seen previously so that no mass determination was possible.

Introduction

This paper reports a method of chemical analysis to study fission yields by observing the X-ray production and other end products in processes involving fission of actinides. Associated with fission fragments are X-rays whose energies are characteristic of the decaying atomic species. Studies of fission products and their yields have long been important for a better understanding of the fission process. Of course these studies are significant with respect to environmental issues as well as power resource problems.

The complete task of measuring fission phenomena in detail is complex and in order to limit this paper to a well defined problem, we will focus our attention on the subjects of (X-ray, X-ray) and (X-ray, γ-ray) coincident measurements. The

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II. B-13

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LETTER TO THE EDITOR

High resolution of K x ray spectrum of 30 MeV chlorine ion beam

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Abstract. The K x ray spectrum from a 30 MeV chlorine ion beam was measured as it was stopped in aluminium. The spectrum exhibits six lines located approximately half way between the $K\alpha_{1,2}$ and $K\beta_{1,3}$ lines of chlorine. These lines can be interpreted as Kα transitions with various 2p shell vacancies and with the M shell electrons partially stripped.

The x ray spectra from highly ionized species have long been of interest for a variety of reasons. This communication reports the spectrum of chlorine at 30 MeV as it impinges upon a metallic aluminium slab. The spectra are measured with a Bragg crystal spectrometer at ninety degrees to the beam axis and the aluminium target was set at forty-five degrees to both the beam and detector. The chlorine ions are expected to reach charge equilibrium after a few collisions and should have an average charge state of plus twelve as they penetrate the first few layers of the aluminium metal (Dmitriev *et al* 1965). Since the K-shell ionization falls off drastically as the ion energy decreases and since absorption further reduces the intensity, it should be reasonable to assume that the bulk of the K x ray yield results from collisions near the surface of the aluminium.

Table 1. Chlorine K x ray transitions

Wavelength (Å) (±0·008)	Energy (keV) (±0·004)	Vacancies in the electronic configuration	HFS (keV)
4·729	2·621	$(K\alpha_{1,2})$	2·621
4·702	2·637	2p	2·636
4·690	2·644	$2p^13p^5$	2·644
4·654	2·664	$2p^23p^6$	2·663
4·617	2·685	$2p^33p^6$	2·684
4·583	2·705	$2p^43p^6$	2·706
4·550	2·725	$2p^53p^6$	2·731
4·514	2·747	$2s^12p^63p^6$	2·752
(4·464)	(2·777)	$2s^22p^63p^6$	2·775
4·403	2·815	(K_β)	2·816

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‡ On leave from the University of Notre Dame.

II. B-14

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ANOMALOUS LOW ENERGY Kα LINES IN Al AND Si FROM HIGH ENERGY OXYGEN BOMBARDMENTS*

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Three prominant peaks are observed in Kα X-ray spectra of both Al and Si at energies below the characteristic $K\alpha_{1,2}$ lines. These emission lines were produced by 30 MeV oxygen bombardment and recorded with a crystal spectrometer. The exact origin of these lines is not understood.

The lowest energy characteristic K X-ray that can occur from a transition involving a single electron is the 2p → 1s ($K\alpha_{1,2}$) transition**. In the present paper we present the observation of three prominent peaks in the spectra of Al and Si which fall below but very near the $K\alpha_{1,2}$ transition energy. These emission spectra follow the excitation of Al and Si by 30 MeV *oxygen bombardment*. From energy considerations these anomalous peaks must be associated with photon emission involving a primary K-shell vacancy produced in the ion-atom collision and also most likely must involve a two electron transition process. The second electron in the two electron process is excited to a higher energy state thus giving rise to a lower energy X-ray emission.

Åberg and Utriainen [1] have reported low-energy structure in the Kα *fluorescence* spectra of Al and Si. These observed transitions were interpreted as being due to a "Radiative Auger Effect" (RAE) [2,3]. In this process a photon is emitted as the result of an L electron falling into the K vacancy and a second L electron promoted to the continuum. From energy conservation, $h\nu + E_{\mathrm{kin}}(\mathrm{L}) = E(\mathrm{KLL})$ where $h\nu$ is the photon energy, $E_{\mathrm{kin}}(\mathrm{L})$ is the energy of the ejected electron and $E(\mathrm{KLL})$ is the corresponding Auger electron energy. The maximum photon energy therefore occurs when $E_{\mathrm{kin}}(\mathrm{L}) = 0$.

Recent studies of Ar $L_{2,3}$ X-ray emission by Cooper and LaVilla [4] and Werme et al. [5] demonstrate that low energy Ar $L_{2,3}$ satellites are present in *fluorescence* and *electron excitation*, and are also due to transitions involving two electrons.

The present experiment was performed with the University of Texas EN tandem Van de Graaff accelerator. A vacuum crystal spectrometer equipped with an ADP crystal was used for obtaining the X-ray spectra produced from 30.0 MeV oxygen bombardment

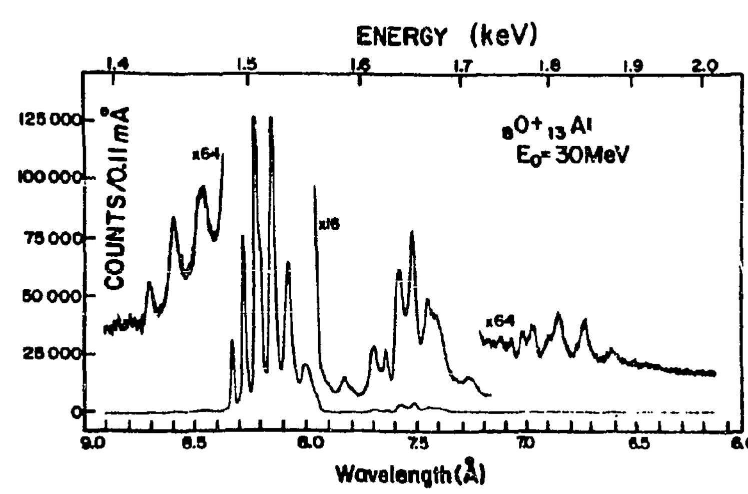

Fig. 1. Depicted is the energy region of the K X-rays of Al excited by 30 MeV oxygen ions. Energy region below 1.49 keV contains the three prominent peaks discussed in the text. The higher energy peaks can be identified as Kα and Kβ satellites, and Kα and Kβ hypersatellites.

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** The term characteristic X-rays generally refers to allowed E1 transitions and the unobserved forbidden 2s → 1s transition, which energetically falls below the 2p → 1s transition, is eliminated in this discussion.

II. B-15

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K X-Ray Spectra from Si and SiO_2 after Oxygen Excitation*

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A beam of 30 MeV oxygen ions was used to excite silicon atoms in both a silicon crystal and in a silicon dioxide crystal. The resulting K X-ray spectra show marked deviation from one another.

It has been recently observed[1] that ion excitation produces a marked difference in the $K\beta$ spectra resulting from chemical bonding effects. In the present work, K X-ray spectra, produced by oxygen excitation, were studied. The amount of inner-shell ionization in this case is many times greater than in proton or alpha particle excitation. Consequently the satellite K X-ray transitions completely dominate the spectrum. Since these satellite transitions are a direct measure of the amount of inner-shell ionization it is obvious that the electron vacancies in the $2p$ shell is near fifty percent after oxygen ion excitation. In a chemical compound the molecule is normally neutral, and an equilibrium is usually reached which has the two or more atoms bound with a few eV, much less than the K X-ray transition energy. Thus, the molecular structure of a substance with a high degree of inner-shell ionization must be indeed a curious entity. The inner-shells normally shield the molecular forces from the strong nuclear Coulomb force. Since these inner electrons are ripped off in the reaction process, the resulting molecular bonding may be changed. In any case, it substantially changes the X-ray spectrum as is seen in Fig. 1.

A 30 MeV oxygen beam produced by a tandem electrostatic accelerator, bombarded targets consisting of a silicon crystal and a quartz crystal. The X-rays were detected with an ADP crystal spectrometer that was computer controlled. The resolution (FWHM) was 2.7 eV and the data were taken in .00011 Å intervals several times and stored in a 12,288 block of memory. Due to the vast quantity of data points, Fig. 1 is a line through the data points. The uncertainties in the data are due only to counting statistics.

The results presented in Fig. 1 show a significant difference between the K X-rays of Si and SiO_2. The data for the Si crystal is not well understood beyond the satellite lines in the $K\alpha$ band. The spectra in the region of the $K\beta$ satellite lines are more complex due to the presence of the $K\alpha$ hypersatellite structure. The multiplets due to spin-spin coupling are barely resolved in the $K\alpha$ spectra. Perhaps the splittings are larger in the $K\beta$ band and further complicates the structure in this region. The $K\beta$ transitions originate from electrons in the valence shell, consequently the host environment must play a major role in the $K\beta$ transition and causes the large discrepancies in the spectra from Si to SiO_2. The effects of the chemical bonding plays a duel role in this measurement, since self absorption will be different for Si and SiO_2. The dE/dx for 30 MeV oxygen is very large and the energy dependance of K-shell ionization is rapidly decreasing as the oxygen ion loses energy. Thus, most of the X-rays occur so near the surface that the self absorption should not be the dominant reason for the observed effects.

It is, however, interesting to note the large differences in the intensities in the $K\alpha$ groups

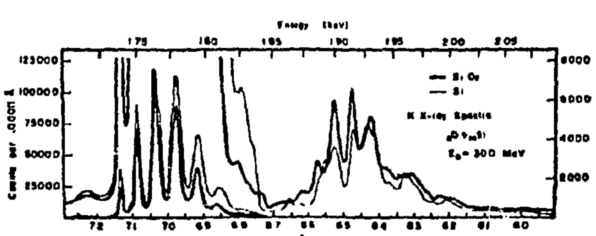

Fig. 1. The 12,288 data pints are represented by a continuous line through the data. The $K\alpha$ spectra have the structure $K\alpha(2p)^6$, $K\alpha(2p)^5$, $K\alpha(2p)^4$, $K\alpha(2p)^3$, $K\alpha(2p)^2$, and $K\alpha(2p)^1$. These assignments are in agreement with Hartree-Fock calculations. The most intense line is the $K\alpha(2p)^4$. The $K\alpha(2p)^6$ is the normal $K_{1,2}$ transition. The notation uses the structure of the initial state and labels by the number of $2p$-subshell electrons. These spectra were calibrated using proton excitation and the known wave lengths for the $K\alpha_{1,2}$ and $K\beta_{1,3}$.

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PHYSICAL REVIEW A VOLUME 7, NUMBER 4 APRIL 1973

$K\beta$ Hypersatellite Observation in Magnesium*

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The K x-ray spectrum of Mg produced by 30-MeV oxygen ions is observed to consist of four regions of K x-ray excitations. These regions consist of the $K\alpha$ satellite lines, the $K\beta$ satellite lines, the $K\alpha$ hypersatellite lines, and the $K\beta$ hypersatellite lines. The last region is observed for the first time and corresponds to $1s \rightarrow 3p$ transitions in an atom consisting of double K-shell vacancies as well as multiple L-shell vacancies.

The observable K x-ray transitions from single-collision events have undergone a revolutionary change in the last three years with the use of high-energy heavy-ion beams. Multiple-ionization states dominate the spectra and lead to many new transitions. In this paper we present the observation of a group of x-ray transitions near the high-energy limit for K x rays in Mg. As will be shown, these x rays are $K\beta$ hypersatellites, that is, $1s-3p$ transitions in atoms with double K-shell ionization and a varying number of L-shell ionization states.

A 30-MeV oxygen beam from the University of Texas tandem electrostatic accelerator was bombarded on a 99.9%-pure Mg foil. The x rays were analyzed in a vacuum x-ray crystal (ADP) spectrometer placed at 90° to the beam line. A stepping motor interfaced to a PDP-7 computer controlled the crystal and detector movement. The pulses from a flow-proportional counter were histogrammed in a 20480-channel array in the computer. The step size was 0.00011 Å.

TABLE I. Magnesium K x-ray transitions.

Label	Observed energies (keV)	Calculated energies (keV)	Configuration	Structure designation
$K\alpha_{1,2}$	1.254	1.254	$K\alpha(2p)^6$	
$K\alpha_3$	1.262	1.262	$K\alpha(2p)^5$	
$K\alpha_4$	1.264			
$K\alpha_8$	1.269			
$K\alpha_5$	1.271	1.272	$K\alpha(2p)^4$	$K\alpha$
$K\alpha_7$	1.272			satellites
$K\alpha_6$	1.274			
$K\alpha_9$	1.281	1.284	$K\alpha(2p)^3$	
$K\alpha_{10}$	1.284			
$K\alpha_{13}$	1.296	1.298	$K\alpha(2p)^2$	
	1.307	1.313	$K\alpha(2p)^1$	
$K\beta$	···	1.295	$K\beta(2p)^6$	$K\beta$
	1.322–1.324	1.321	$K\beta(2p)^5$	satellites
	1.348	1.349	$K\beta(2p)^4$	
	1.357			
	1.373	1.364	$(K\alpha)^h(2p)^4$	
	1.378			
	1.388	1.378	$(K\alpha)^h(2p)^3$	$K\alpha$
	1.390			hypersatellites
	1.401	1.392	$(K\alpha)^h(2p)^2$	
	1.410	1.409	$(K\alpha)^h(2p)^1$	
	1.414			
	1.424–1.427			
	1.502	1.471	$(K\beta)^h(2p)^4$	
	1.520			$K\beta$
	1.531	1.506	$(K\beta)^h(2p)^3$	hypersatellites
	1.560	1.542	$(K\beta)^h(2p)^2$	
	1.589	1.581	$(K\beta)^h(2p)^1$	
	1.620	1.625	$(K\beta)^h(2p)^0$	

The observed K x-ray transitions in the range of 10.0 to 7.2 Å are given in Fig. 1. The data are presented on a linear plot with three different scales in order to emphasize the various types of transitions. The long-wavelength or low-energy region of Mg is easily understood and has recently been discussed in detail.[1] This region, from about 9.5 to 9.9 Å, contains the $K\alpha$ satellites consisting of the $K\alpha$ transitions from initial states with the L-shell configurations $(2p)^n$ for $n=6$, 5, 4, ..., 1 and are thus designated as $K\alpha(2p)^n$. The observed energies, Hartree–Fock–Slater calculated energies, the configurations, and the structure designation are given in Table I. It is noted that the $K\alpha_4$ line is seen here where it was not seen in Ref. 1. The observed energy, 1264 eV, is the same as seen by Kunzl.[2] The reason that this line is observed here is that better statistics have been obtained. As discussed in Ref. 1, the absorption edge (1305 eV) falls below the $K\alpha(2p)^1$ transition which substantially decreases its intensity relative to the other $K\alpha$ satellites. The observed resolution is 1.1 eV.

The second region, from about 9.5 to 9.1 Å, of K x-ray transitions is the $K\beta$ satellite region. The transitions in this region do not lie in a self-contained energy range but rather overlap the $K\alpha$ satellites on the low-energy end and overlap the $K\alpha$ hypersatellites on the high-energy end. The characteristic $K\beta$ transition $K\beta(2p)^6$ is, in fact, buried beneath the $K\alpha(2p)^2$ peak and therefore not clearly defined. The two peaks above $K\alpha(2p)^1$ at energies of 1.322–1.324 keV (doublet) and 1.348–1.357 keV (resolved doublet) are, respectively, the $K\beta(2p)^5$ and $K\beta(2p)^4$ satellite transitions. The results are summarized in Table I. The observed resolution of these lines is about 4 eV.

The third region of excitation, from about 9.1 to 8.6 Å, consists of five closely spaced transitions

PHYSICAL REVIEW A VOLUME 7, NUMBER 4 APRIL 1973

Characteristic L X-Ray Spectra from Proton, α-Particle, and Oxygen Bombardment of Sn[†]

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Spectra have been measured [using a crystal (LiF;200) spectrometer] of L x rays produced by 2.0-MeV proton, 3.2-MeV α-particle, and 30.0-MeV oxygen bombardment of thick tin targets. L x-ray lines are observed in the α-particle-produced spectrum from initial configurations with up to four additional M-shell electron vacancies. The energy resolution of 8 eV (full width at half-maximum) did not allow any detailed structure to be resolved in the oxygen bombardment; an almost continuous structure is observed from multiply ionized tin. The ratios of x-ray yields from $L+M$ vacancies to yields from L vacancies are shown to have the correct order of magnitude for a simultaneous direct Coulomb ionization process for proton and α-particle impact.

I. INTRODUCTION

Several experiments have been reported in which K x-ray lines[1] and L x-ray lines[2] produced by heavy-ion bombardment have been observed to be broadened and shifted to higher energies than the corresponding lines produced by proton and electron bombardment. For heavy-ion beams in the 1-MeV/amu range, these energy shifts have been attributed to multiple inner-shell electron vacancies of the initial atomic configurations produced by the atom–heavy-ion collisions. Recently high-resolution experiments using crystal spectrometers have resolved the shifted $K\alpha$ and $K\beta$ lines into parent and satellite components.[3] These satellite lines result from initial atomic configurations in which the heavy-ion collisions have removed from one to six $2p$ electrons. Little high-resolution work has been done for heavy-ion-produced L x-ray transitions.[4,5]

Herein we report the measurement of L x-ray spectra produced from 2.0-MeV proton, 3.2-MeV α-particle, and 30.0-MeV oxygen bombardment of thick tin targets. Using a crystal (LiF; 200) spectrometer, an energy resolution of 8 eV (full width at half-maximum) is obtained. All of the LN x-ray lines produced by the α-particle bombardment are clearly observed to have satellite transitions resulting from M-shell electron vacancies. In particular, the intense $L\beta_{2,15}$ transition is observed with zero to four electron vacancies in the M shell. A nearly continuous spectrum was observed from the oxygen bombardment where no detailed satellite structure could be resolved.

It is expected that if atom-atom collision effects[6,7] are not present, multiple inner-shell ionization can be explained by direct simultaneous Coulomb ionization of the atom by the incident projectile. Indeed, much work involving $K\alpha$ x-ray satellite transitions has been reported which supports this assumption.[8–10] Der *et al.*[5] have shown that the L x-ray energy shifts of highly ionized Ni, Cu, and Zn produced by oxygen bombardment decrease with increasing oxygen energy as do the M-shell Coulomb-ionization cross sections of the same energies. In this paper we show that the ratios of proton- and α-particle-produced x-ray yields from $L+M$ initial vacancies to yields from L-only initial vacancies have the correct order of magnitude for a simultaneous direct Coulomb reaction mechanism.

II. EXPERIMENT

Beams of 30.0-MeV oxygen ions, 2.0-MeV protons and 3.2-MeV α particles from The University of Texas at Austin EN tandem and KN Van de Graaff accelerators were focused into thick tin targets at an incidence angle of 45°. The resulting x rays were wavelength-analyzed by a Bragg crystal spectrometer positioned at 90° to the beam direction. The diffracted x rays from a LiF (200) crystal were detected in a flow-proportional counter operating at 2000 V using a 10% argon and 90% methane gas mixture. The spectrometer shared a common vacuum system with the beam line.

For each setting of the spectrometer, x rays were counted for a fixed amount of beam current. The number of x rays counted was then recorded and the angle of the spectrometer was changed by a stepping motor, so that the x-ray wavelength was incremented by a constant amount of 0.00123 Å. The data-accumulation system was automatic and was controlled by a PDP-7 computer. Each 1024-channel spectrum consists of many short data accumulations added together in order to reduce possible systematic errors. For the $^1H^+$-, $^4He^+$-, and $^{16}O^{5+}$-produced spectra a total of approximately 25, 250, and 8 μC of charge, respectively, was collected for each spectral datum.

III. RESULTS AND DISCUSSION OF ENERGIES

The spectra produced by the proton, α-particle, and oxygen bombardments are shown in Fig. 1,

II. B-18

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LETTER TO THE EDITOR

Observation of chlorine Kα satellite and hypersatellite and Kβ satellite transitions

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MS received 2 April 1973

Abstract. X ray measurements from highly ionized chlorine yield lines from the few electron atomic system with nuclear charge seventeen. The 1s–2p Lyman Kα transition in hydrogenic chlorine is observed. Other transitions in chlorine XII through XVII are identified.

X ray emission lines measured using a Bragg crystal spectrometer from highly ionized chlorine beams have recently been reported (Moore *et al* 1973). These data were taken with an insufficient beam energy to produce adequate electron stripping from the chlorine projectile to reach the few electron system. Further, the beam was stopped in a thick slab. The present data were obtained at a chlorine energy near the maximum which can be produced by a model EN tandem (55 MeV) and the x rays were emitted from chlorine transmitted through a thin carbon (approximately 10 μg cm^{-2}) foil. These conditions produced a spectrum as shown in figure 1. The resulting chlorine

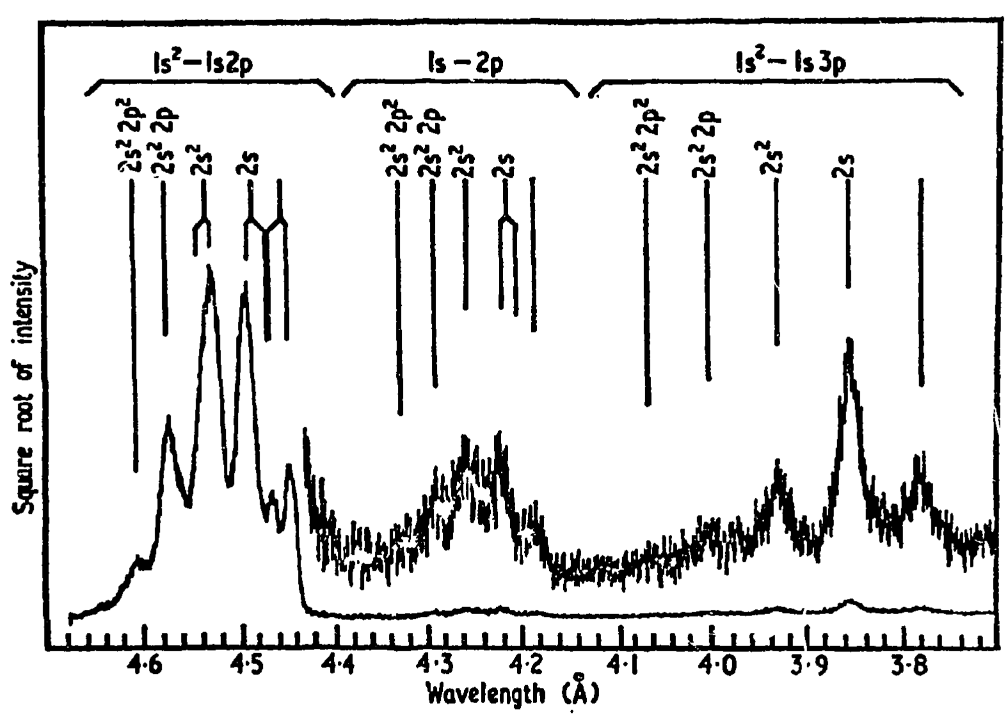

Figure 1. The chlorine photon spectrum at a beam energy of 55 MeV. The vertical scale is the square root of the number of counts in 1·1 mA intervals. The intensity is plotted as the square root in order to make visual recognition of the peaks easy. The spectrum is linear in wavelength. The spectrum was repeated seventeen times and summed together. The transitions arrays are explained in the text.

EXPERIMENTAL ENERGY DEPENDENCE OF ALUMINIUM MULTIPLE INNER-SHELL IONIZATION FROM 3.0 TO 30.0 MeV OXYGEN BOMBARDMENT☆

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Aluminium, Kα, relative-satellite, X-ray yields for initial ionization states with 0, 1, 2, 3, 4, and 5 additional L-shell vacancies produced from 3.0 to 30.0 MeV oxygen bombardment are shown to be consistent with a multiple-Coulomb reaction mechanism.

It has been proposed that if atom-atom collision effects [1] are not present, multiple inner-shell ionization from swift heavy charged particles can be explained by a simple extension of Coulomb, single-vacancy production formalisms [2–5] assuming uncorrelated electrons [5–11]. With such an assumption and using an impact-parameter formalism, the cross sections for simultaneous single K and multiple L-shell ionization can be written as [8]

$$\sigma_{1\mathrm{K},n\mathrm{L}}(E) = \int_0^\infty 2P_\mathrm{K}(E,b)\binom{8}{n}P_\mathrm{L}^n(E,b)(1-P_\mathrm{L}^n(E,b))^{8-n}\,2\pi b\,db, \tag{1}$$

where $P_\mathrm{K}(E, b)$ and $P_\mathrm{L}(E, b)$ are the probabilities per electron at incident E and impact parameter b for removing K and L-shell electrons respectively. Furthermore, if one approximates $P_\mathrm{L}(E, b)$ by a constant $P_\mathrm{L}(E)$ for all impact parameters for which $P_\mathrm{K}(E, b)$ is nonzero then the fraction of the total K-shell ionization cross section with n additional L-shell vacancies can be written as

$$\frac{\sigma_{1\mathrm{K},n\mathrm{L}}}{\sigma_\mathrm{tot}} = \binom{8}{n}P_\mathrm{L}^n(E)(1-P_\mathrm{L})^{8-n}\,. \tag{2}$$

In addition, $P_\mathrm{L}(E)$ can be estimated from the equation [6]

$$P_\mathrm{L}(E) \approx \sigma_\mathrm{L}(E)/2\pi\langle r_\mathrm{L}^2\rangle\,, \tag{3}$$

where $\langle r_\mathrm{L}^2\rangle$ is the main-square radius of the L-shell and $\sigma_\mathrm{L}(E)$ is the L-shell cross section per electron.

☆ Supported in part by the United States Atomic Energy Commission and the Robert A. Welch Foundation.

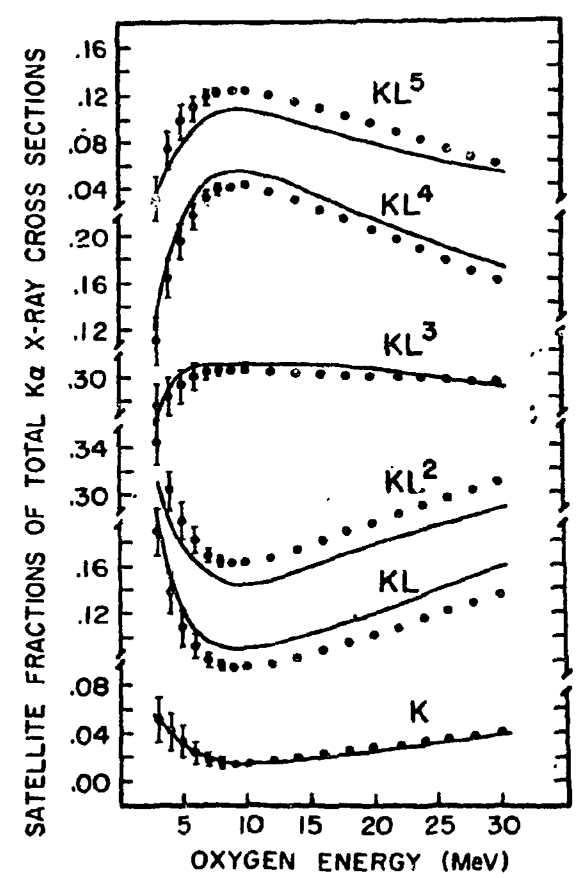

Fig. 1. Satellite fractions of the total Kα X-ray production cross section. At 9.0-MeV the fractions are 0.015, 0.075, 0.0242, 0.305, 0.241, and 0.122 for 0, 1, 2, 3, 4, and 5 additional L-shell vacancies respectively. The smooth curves are from a least squares fit to the fractions with $P_\mathrm{L}(E)$ a variable at each energy.

Many workers have shown this model to be in qualitative agreement with experimental X-ray energy shifts and satellite yield ratios [6–11]. In this letter, calculations from eqs. (1), (2) and (3) are compared to expermentally measured Al Kα X-ray satellite fractions for

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LIFETIME MEASUREMENTS OF HELIUM-LIKE AND LITHIUM-LIKE OXYGEN

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A high resolution Bragg crystal spectrometer has been used to measure the decay times of the transitions: $1s^2-1s\,2p$ ($1\,^1S-2\,^3P$) and $1s^2-1s\,2s\,2p$ ($1\,^2S-2\,^4P$). They are 1.47 ± 0.08 and 3.48 ± 0.08 ns, respectively. Delayed decay has been observed from states with much shorter lifetimes. These result in non-linear curves on a semilogarithmic graph that are all similar to each other. Thus, more than one delayed decay contributes to the formation of these states.

The original measurement of the lifetime of the $2\,^3P_1$ intercombination line in the two electron oxygen system was made by Sellin et al. [1]. The technique used by this group is quite similar to the present work. The result of their mean life measurement for the $2\,^3P_1$ is 1.45 ± 0.06 ns which compares favorably with the 1.47 ± 0.08 ns measurement reported in this manuscript.

The mean life was measured nine times, twice at 8 MeV, four times at 16 MeV, and two times at 35 MeV beam energy for the oxygen ions. Several different geometries were used with the same essential result. The uncertainties in counting statistics were at most less than one percent and usually less than one-tenth of one percent. The ± 0.08 ns uncertainty in the mean life reflects the self consistency of the measurements and rough estimates of feeding effects from more highly excited states.

The tail of the decay curve was smoothly fit by a straight line on a semi-log plot. This aspect of the present work merely confirms the previous measurement with better resolution and better statistics.

The previously unmeasured $2\,^4P_{1/2}$ quartet state in the three-electron oxygen system is found to have a mean life of 3.48 ± 0.08 ns. The chosen transition $1s^2\,2s-1s\,2s\,2p$ ($^2S-^4P$) is fairly difficult to measure due to its very weak intensity. As a result, measurements were made only at 8 MeV and 16 MeV incident beam energies, since at the higher energies the gamma radiation background becomes orders of magnitude larger, making a 35 MeV run marginal. Fig. 1 shows that the transitions from the quartet P state in O VI and from the triplet P state in O VII are enhanced over the fast transitions, as the distance is increased between

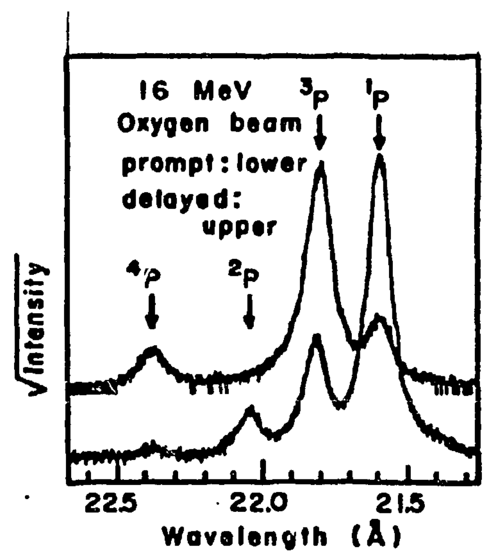

Fig. 1. These spectra were taken with an X-ray crystal spectrometer positioned at 90° with respect to the beam axis at a variable downstream distance from a thin carbon foil. The lower (PROMPT) and upper (DELAYED) spectra were taken at distances of about 0 and 10 mm, respectively.

the beam foil and the downstream acceptance aperture of the detector. Fig. 2 shows the decay curves as a function of flight path for the particular region containing the doublet and quartet P states of the lithium-like system and the triplet and singlet P states of the helium-like system.

In the study of metastable autoionizing levels of the lithium-like oxygen sequence Sellin [2] has measured the lifetime of the $^4P_{5/2}$ state to be 25 ± 3 ns. This $J = 5/2$ component of the ^4P state is supposed to have a long lifetime since it can decay only through spin-spin interaction with the adjacent continuum. However, the $^4P_{3/2,1/2}$ components are expected to have much shorter lifetimes since they may decay via the spin-orbit interaction as well. Recent scaling arguments by Sellin

II. B-21

Z. Physik 261, 413–421 (1973)

Potassium and Titanium KX-Ray De-Excitation Induced by Ion Bombardment*

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KX-ray de-excitation spectra have been produced for K and Ti by proton, alpha and oxygen ion beam bombardment. These spectra have been measured with a crystal spectrometer of resolution (FWHM) of 10 and 13 ev for the $K\alpha_{1,2}$ line in K and Ti respectively. The additional lines not found in the normal X-ray spectra are attributed to multiple inner shell ionization. The energy shifts and relative intensities of these lines are compared to theoretical predictions.

I. Introduction

Heavy ion bombardment has been shown to produce X-ray lines from multiple inner shell ionization states [1, 2]. The observance of multiple inner shell ionization induced by bombardment of a titanium target with proton, alpha, and oxygen ion beams has been reported [3]. These beams produce different degrees of ionization of the target atom resulting in varying numbers of additional X-ray lines with different relative intensities. In this paper the energies and energy shifts of the X-ray lines produced by ion bombardment of Ti and K are tabulated.

The experimental energy shifts observed are correlated to the predictions of Hartree-Fock-Slater calculations performed using a computer program which incorporates calculations detailed by Herman and Skillman [4]. These calculations are consistent with the explanation that the additional X-ray lines are a result of multiple inner shell ionization. Good agreement is obtained for the proton and alpha beam induced spectra by assuming simultaneous holes in only the $1s$ and $2p$ electronic subshells prior to de-excitation.

The oxygen ion beam induced spectra show corresponding X-ray lines shifted higher in energy than the proton and alpha induced lines. This is interpreted as being due to additional inner shell vacancies caused by the much higher nuclear charge of oxygen. The HFS calcula-

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II. B-22

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Calcium K X-Ray Spectra Produced by Oxygen, Alpha-Particle, and Proton Bombardment*

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$K\alpha$ and $K\beta$ X-rays of calcium were produced by bombarding a thick calcium wafer with oxygen, helium and hydrogen ions. These reactions produce a substantial amount of inner shell ionization. The K X-ray spectra contain X-ray lines from calcium which emanate from initial states with a varying degree of K or L shell vacancies. The initial configurations were assigned on the basis of Hartree-Fock-Slater calculated energies. Related intensity ratio of $1s \rightarrow 2p$ ($K\alpha$) transitions and of $1s \rightarrow 3p$ ($K\beta$) transitions of H plus Ca, He plus Ca and O plus Ca were obtained. In addition to observing many new transitions due to multiple K and/or multiple L shell vacancies, energy shifts relative to the H plus Ca spectrum were observed in the O plus Ca spectrum due to M shell vacancies.

I. Introduction

The detection and identification of X-ray lines emanating from calcium with multiple inner shell ionization is the subject of this paper. Measurements were made of X-rays emitted from a thick calcium target when bombarded by ion beams of 30 MeV oxygen, 3.2 MeV helium and 0.8 MeV hydrogen (velocities of proton and helium were the same). The so-called satellite and hypersatellite X-ray lines were observed. Satellite X-ray lines are due to the de-excitation of multiply ionized atoms, A hypersatellite X-ray line results from the de-excitation of an atom with two electron vacancies in the K-shell [1]. Preliminary results of the observation of $K\alpha$ hypersatellite lines in ion-atom scattering have recently been reported [2].

II. Experiment Procedure

The experiment was conducted using a (LiF; 200) crystal spectrometer with a flow proportional counter to serve as a detector. The spectra obtained in these measurements are given in Fig. 1. Resolution, Full Width Half Maximum (FWHM) was 7.7 eV. The 30 MeV oxygen beam was provided by a High Voltage Engineering Corporation (HVEC)

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Lyman x rays from a highly stripped nitrogen beam

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Abstract. The Lyman series has been observed for the hydrogen-like system of bare nitrogen (+7) plus an electron. The experimental resolution for these x ray lines is about 2 eV.

X rays from hydrogen-like nitrogen have been identified by their agreement in energy with the calculated energies for Lyman transitions between the eigenstates of $Z = 7$, A = 14 'hydrogen'.

Many spectral lines for hydrogen-like ions have been measured for higher nuclear charge Z, up to O VIII (Moore 1949). However, due to the short wavelengths associated with Lyman series transitions for $Z > 4$ hydrogenic ions, high resolution measurements with large energy range have been restricted to observations of the Balmer and higher order hydrogenic series. This, then, is the first reported measurement of the Lyman series with high resolution techniques ($E/\Delta E = 300$) for $Z = 7$ hydrogenic nitrogen.

The present work shows that observation of the most energetic transitions in a heavy-ion beam is possible. The present work permits one to suggest that even higher-Z beams may be studied in a similar fashion. Supporting this, Marion and Young (1968) provide graphs of the various charge-state ionization probabilities versus incident beam energy, for projectiles from hydrogen through neon. The two most important experimental limitations to the size of the Z that may be studied are due to the limit in available *beam energy* from the heavy ion accelerator and the limit in smallness of the *atomic spacing* in the analysing crystal.

In this experiment, a beam of 30-MeV N^{5+} is passed through a thin carbon foil (about 2 μg cm^{-2}) which is used to remove electrons from the nitrogen. A Bragg Crystal Spectrometer was used to look for photons in the energy region of the Lyman transitions from hydrogen-like nitrogen. At the incident energy of 30 MeV, about 50% of the transitions are expected to be of this character (Marion and Young 1968).

The nitrogen Lyman series is shown in figure 1. The 1s–2p transition is not shown since geometrical considerations with the KAP analysing crystal did not permit detection of such a soft x ray. Beyond the 1s–6p transitions, the lines are unresolved and there are few counts. Nevertheless, the calculated series limit has been marked on the figure. This point marks a drop in the yield that is consistent with such an assignment.

It is no surprise that the eigenenergies of the $N^{(7+)}+e$ system are in agreement with those of hydrogen—scaled up by the factor $Z^2(1+1/1836)/(1+1/A^*1836)$, where A is atomic mass number. What is surprising, and, indeed, exciting, is that x rays from this process have such a high yield when measured by so inefficient a device as a Bragg Spectrometer. As a result, many associated processes such as He-like, Li-like, etc, transitions might also be studied at very high resolution. Further, one might hope that

II. B-24

Volume 45A, number 1 PHYSICS LETTERS 27 August 1973

OBSERVATION OF PLASMON EXCITATIONS IN X-RAY PRODUCTION FOLLOWING HEAVY ION BOMBARDMENT ☆

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Four equidistant peaks are observed below the $K\alpha_{1,2}$ line in the X-ray spectra of Na, Al, Si, SiO_2, Ca, Sc and Ti, produced by oxygen bombardment. With much weaker intensity, these lines are also seen in proton excitation. The lines are interpreted to be due to the excitation of one or more volume plasmons in the target material by the $K\alpha_{1,2}$ X-ray decay.

After heavy ion bombardment the X-ray emission spectra for various elements were measured in the energy region below the characteristic $K\alpha_{1,2}$ transition. In each of the proton induced spectra one or two transitions are observed below the $K\alpha_{1,2}$ line, whereas in oxygen induced spectra four such lines are observed (see fig. 1). Peaks below the $K\alpha_{1,2}$ line have been measured previously for Al and Si and their origin was attributed to enhanced two electron processes resulting from multiple ionization states [1]. Hartree-Fock calculations were performed for the energies of such radiative Auger transitions, but a consistent explanation for all the observed lines could not be obtained. We therefore propose an alternative explanation, namely, that these lines arise from simultaneous excitation of the $K\alpha_{1,2}$ and volume plasmons, which result in multiple discrete energy losses of the characteristic X-ray [2].

The present experiment was performed using the University of Texas EN Tandem Van de Graaff Accelerator. A vacuum curved crystal spectrometer (equipped, at different times, with a LiF, EDDT, and an ADP crystal) was used for obtaining the X-ray spectra produced by 3.0 MeV proton, and 13.0 MeV to 30.0 MeV oxygen beams incident upon thick targets of high purity Na, Al, Si, SiO_2, Ca, Sc and Ti.

Table 1 lists the experimental values of the low energy lines for target K X-rays. We found no influence of the energy or the charge state of the oxygen beam on either line shape or its location in the spectrum. However, the intensity of the plasmon X-ray lines decreased as the oxygen beam energy was increased. Further indication of a strong energy dependence is given in the observation by Garcia and Oona [3] of proton induced plasmon X-ray lines in carbon. While several lines are seen at proton energies of 100 keV, they disappear completely at 2 MeV. Fig. 1 shows the spectra obtained by oxygen bombardment of Ti. The four lines observed in oxygen excitation are equally spaced (~ 42 eV) within experimental

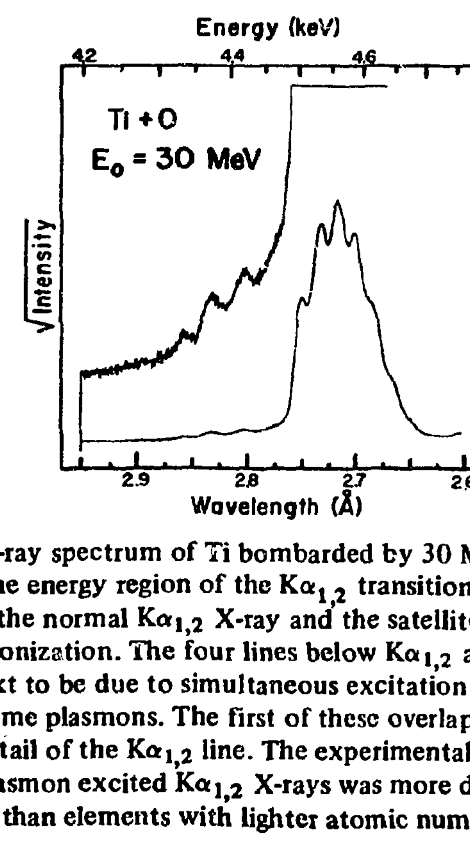

Fig. 1. X-ray spectrum of Ti bombarded by 30 MeV oxygen ions in the energy region of the $K\alpha_{1,2}$ transition. The strong lines are the normal $K\alpha_{1,2}$ X-ray and the satellites due to 2p-shell ionization. The four lines below $K\alpha_{1,2}$ are interpreted in the text to be due to simultaneous excitation of one to four volume plasmons. The first of these overlaps strongly with the tail of the $K\alpha_{1,2}$ line. The experimental observation of the plasmon excited $K\alpha_{1,2}$ X-rays was more difficult for titanium than elements with lighter atomic number.

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PHYSICAL REVIEW A VOLUME 8, NUMBER 3 SEPTEMBER 1973

Projectile and Target Dependence of the $K\alpha$ Satellite Structure*

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Proton, α-particle, and oxygen-ion beams are used to induce $K\alpha$ x-ray spectra in the elements Ca, Sc, Ti, V, Cr, and Mn. The target dependence of the satellite structure for $Z = 20$ to $Z = 25$ is studied. The relative intensity ratios for the production of one K-shell and multiple L-shell vacancies are measured. These ratios are compared with the predictions of the binary-encounter approximation (BEA) and the semiclassical approximation (SCA) for multiple ionization. The data strongly reflect the statistical approach used in the theories. The BEA theory agrees well with the proton and α-particle data but does not give good agreement with the oxygen data.

I. INTRODUCTION

Recently, there has been much interest in inner-shell ionization by heavy-ion bombardment. In the 1-MeV/amu range, the cross section for K-shell ionization has been predicted with some success by the modified Born approximation or by the binary-encounter model.[1-4] In recent experiments the x rays resulting from inner-shell ionization have been resolved into a number of satellite peaks,[5-8] which are due to single K-shell, multiple L-shell ionization. The intensities of these satellite peaks have been predicted in the semiclassical-approximation (SCA) formulation.[9] The results are expressed as an integral over the impact parameter of a product of single-ionization probabilities. The prediction of the peak intensities has also been done in the same manner using the binary-encounter approximation (BEA) to obtain values of the single-ionization probabilities.[10] In this paper a study is made of the dependence of the relative intensity of the multiple ionization produced as a function of the target for three projectiles. The $K\alpha$ satellite lines produced by proton, α-particle, and oxygen beams on targets of Ca through Mn are measured in high resolution. The measured intensities are examined to test the assumption that the multiple-ionization intensities can be expressed as a product of single-ionization probabilities.[11] In addition, the data are compared with the particular predictions of the SCA and BEA approximations.

II. EXPERIMENT

In the experiment the 0.8-MeV proton and 3.2-MeV α particles were produced by the University of Texas, model KN particle accelerator. The current of each beam was about 1 μA. The O^{5+} beam was produced by the University of Texas model EN tandem Van de Graaff accelerator. The beam energy for the Ca, Sc, Ti, V, Cr, and Mn targets was 30 MeV with a current between 10 and 100 nA. The targets of the various elements used were either foils or metal plates. Their thicknesses ranged from 0.5 to 800 mils. All targets were thick enough to stop the beam, and each was placed at an angle of 45° with the beam.

To analyze the spectrum a Bragg crystal spectrometer equipped with a LiF crystal was used. It was placed perpendicular to the beam at a 45° angle to the target. A flow proportional counter was used to detect the x rays. The pulses from the detector after amplification were sent through a single-channel analyzer. An energy gate was set to minimize the background in each spectrum and the data were collected in a PDP-7 computer which stepped the spectrometer. The counting time for each spectrometer setting was controlled by a current integrator. In this way effects due to beam fluctuations were minimized, and the same amount of charge struck the target for each setting.

In Fig. 1 the $K\alpha$ spectra are shown for oxygen bombarded on each element. The peaks are labeled according to the primary L-shell electron configuration of the initial state. The proton- and α-induced spectra are not shown here. The resolution ranges from about 7-eV full width at half-maximum (FWHM) for calcium to about 34-eV FWHM for manganese. The relative intensities are determined by fitting each peak to a Gaussian distribution and calculating the area under each curve. The uncorrected intensities are normalized to the total intensity of the $K\alpha$ spectrum. These are listed in Table I. The labeling of the columns, KL^n, corresponds to the number of vacancies in the K and L shell (e.g., KL^2 designates one K-

PHYSICAL REVIEW A VOLUME 8, NUMBER 3 SEPTEMBER 1973

Multiply Excited States in the Two- and Three-Electron Oxygen Ion*

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(Received 23 April 1973)

High-resolution measurements of x-ray decay from excited states in highly stripped oxygen ions have yielded many transitions not attributable to the Lyman series in hydrogenic oxygen or to the analogous heliumlike oxygen series. These additional transitions are explained by considering the "screening" effects associated with adding a $2s$, $2p$, or $3p$ "spectator" electron to configurations governing the single-electron decays in excited heliumlike and lithiumlike oxygen. By comparing Hartree-Fock calculations for term energies, many of the observed transitions can be assigned to the doubly excited configurations $2pnp$ and $1smsnp$ in the heliumlike and lithiumlike sequencies, respectively.

I. INTRODUCTION

Experimental studies of photon and electron decays from excited states in highly stripped ions have been a popular subject in recent years.[1] Spectroscopic measurements on these systems are of prime importance in confirming theoretical atomic-structure calculations as well as in determining the collision mechanisms governing excited-state populations. One of the developments in this field has been the measurement and description of those transitions[2] in heliumlike and lithiumlike ions which clearly do not stem from singly excited atomic states. These transitions have been attributed to decays of doubly (or multiply) excited levels. In fact, using the beam-foil technique, Berry *et al.*[3] successfully made lifetime measurements on doubly excited states in neutral helium.

Measurements of these doubly (multiply) excited configurations are not restricted to radiative transitions or even to the use of beam-foil techniques. For instance, measurements of electron decay from multiply excited metastable autoionization states in O VI and F VII by Sellin *et al.*[4] demonstrated the importance of spin-orbit and spin-spin interactions in determining the transition probabilities for excited states (in simple ions) which are metastable against autoionization by the Coulomb interaction. Other methods for observing doubly excited doublet and quartet levels in lithiumlike ions have also been reported in papers on measurements of plasma discharges[5] and on observations of the solar corona[6] (where the levels have high excitation energies of about 500 keV). Holøien[7] has suggested that many doubly excited configurations will be observed for the He-like and Li-like isoelectronic sequences. However, there are no reported measurements of x-ray decays from multiply excited states in systems such as O VI and O VII. The purpose of this experiment, then, was to measure the radiative decay from a highly stripped beam of oxygen ions in the relatively soft x-ray region 14.0–24.5 Å. This region includes the entire Lyman-series spectra for hydrogenlike and heliumlike oxygen. For this wavelength region the resolution was sufficient to clearly separate singlet and triplet heliumlike doubly excited states and doublet and quartet lithiumlike doubly excited states. Sellin *et al.*[8] have reported x-ray measurements in oxygen in this wavelength region; however, their experimental apparatus had insufficient energy resolution and efficiency to permit observation of most of the presently reported transitions.

II. EXPERIMENTAL PROCEDURE

Using the beam-foil excitation technique the x rays from an energetic oxygen-ion beam were measured at a lab angle of 90° using a curved-crystal vacuum spectrometer. The spectrometer was equipped with a rubidium-acid-plate (RAP) analyzing crystal and a gas-flow proportional counter (operated at 2 kV, with 10% methane, 90% argon gas flowing at a rate of 0.5 l/hr.) utilizing a 2.0-μ Mackrofol[9] entrance window. The Bragg angle of the analyzing crystal and the position of the proportional counter were varied simultaneously using a stepping motor, controlled by a PDP-7 computer. Data were taken at each detector-crystal position for the same amount of integrated oxygen-ion beam current. The resulting data, for $\lambda = 14.0-24.5$ Å, were stored in histogram form, using a 36 684-channel grid of computer memory.

The oxygen-ion beam was provided by the University of Texas tandem Van de Graaff accelerator. Measurements were made at incident O^{n+} ion energies from 5.3 to 32.3 MeV (n depends on the maximum yield for a charge state given by MeV/amu curves by Marion and Young[10]). Thin carbon foils, typically about 10 $\mu g/cm^2$, were used to excite the ion beam near the primary entrance slit to the

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LETTERS TO THE EDITOR

IN-BEAM AXIAL β-RAY SPECTROMETER FOR THE MEASUREMENT OF INTERNAL CONVERSION ELECTRONS*

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An axial beta-ray spectrometer for in-beam internal conversion measurements is described. Spectra taken for electrons from $p+{}^{90}Zr$ reactions at 11.2 MeV bombarding energy demonstrate the high transmission and low background provided by this instrument.

In-beam studies of internal conversion (IC) constitute a relatively unexplored area of experimental nuclear physics[1–4]). Such conversion electron studies allow investigation of short-lived levels in nuclei that are not normally populated by long-lived radioactive decay, but only by nuclear reactions. In-beam measurements also are advantageous because nuclear reactions provide large effective source strength, and allow control of the thickness, size and uniformity of the source. Besides giving the usual information on spins and parities of nuclear levels, in-beam IC studies also may be exploited to measure nuclear lifetimes directly.

A major problem associated with any attempt at in-beam detection of electrons is the necessity of separating the electrons from the gamma-rays in order to minimize background levels arising from Compton scattering in the electron detector, while still obtaining high transmission of electrons to the detector[1–3]). An axial β-ray spectrometer was designed and built for use with the University of Texas EN tandem Van de Graaff accelerator. To test its usefulness for in-beam conversion electron studies a ${}^{90}Zr$ target was bombarded with 11.2 MeV protons at a current of 300 nA, and the conversion electron spectra were studied. These spectra demonstrate that the transmission (3.5%)

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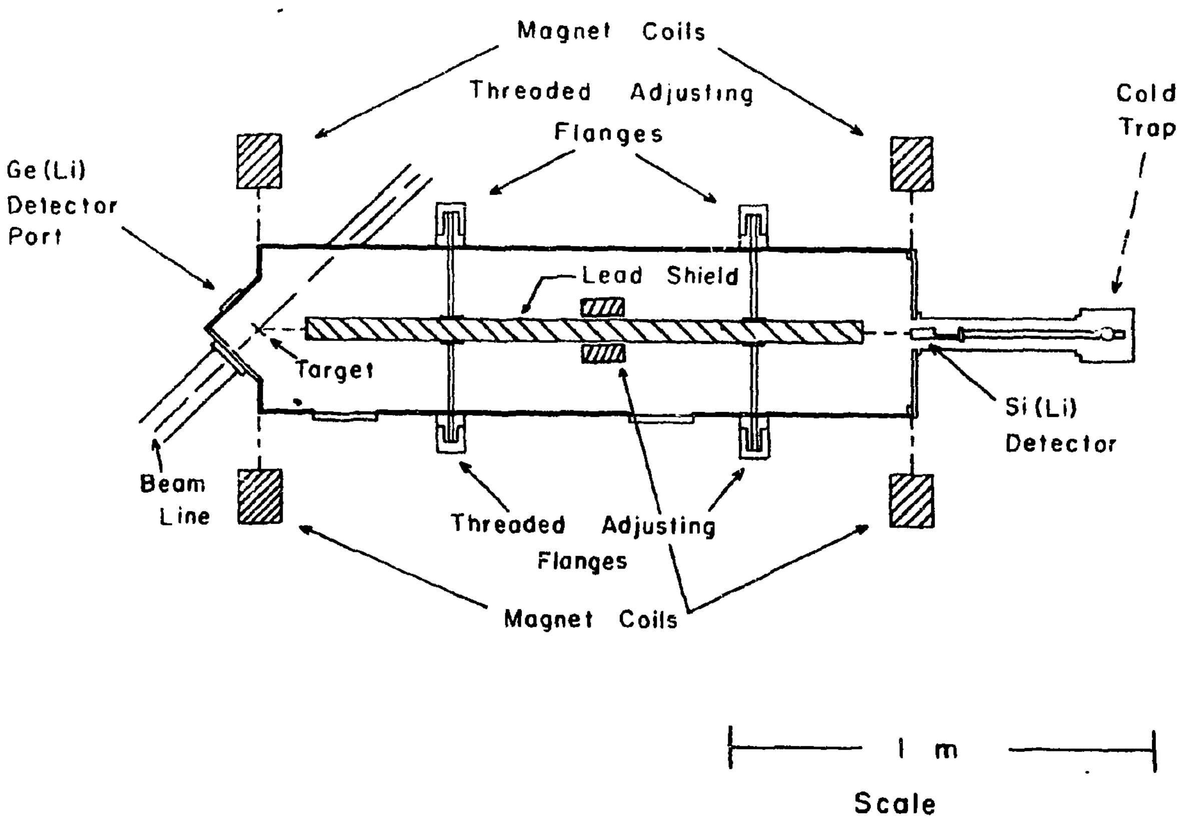

Fig. 1. Schematic drawing of axial β-ray spectrometer used for in-beam internal conversion measurements.

II. B-28

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A NEW TECHNIQUE FOR HIGH-RESOLUTION CHARGED-PARTICLE MASS IDENTIFICATION*

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Received 12 February 1973

A simple technique is described which exploits an electrostatic particle guide to transport charged particles and permit time-of-flight measurements over quite long flight paths. Where excellent mass resolution, together with the best energy resolution from charged particle detectors is desired this single-detector energy-mass identifier is far superior to conventional particle telescope systems.

Research in the field of low energy nuclear physics has generated a variety of techniques for charged particle mass identification, such as conventional particle telescopes, magnetic spectrographs, and time-of-flight. A simple technique is reported here which exploits an electrostatic particle guide similar to that described by Oakey and Macfarlane[1]) to transport charged particles and permit time-of-flight measurements over quite long flight paths. By placing a single high-resolution charged-particle detector at the end of the guide, the mass may be determined from the obvious relation $m = 2Et^2/L^2$, where E is the energy deposited in the detector and t is the time for the particle to traverse the guide of length L. Where excellent mass resolution together with the best energy resolution from charged particle detectors is desired this single-detector energy-mass-identifier' is far superior to conventional particle telescope systems, because for these telescopes two or more detectors must be used, and also by virtue of the fact that the detector for the guide system is safely far from the region of the target and the beam. Since ions, once trapped by the logarithmic potential[2]) of the electrostatic guide, continue to traverse the guide no matter what its length (except for those colliding with the very thin, high-voltage wire along the guide's center), the guide may be made almost arbitrarily long, so that any desired velocity resolution may be obtained, while still maintaining a relatively large collection efficiency[1]). The mass resolution of such a system is then given by

$$\left\langle\frac{\Delta M}{M}\right\rangle = \left(\left\langle\frac{\Delta E}{E}\right\rangle^2 + \left\langle\frac{2\Delta t}{t}\right\rangle^2 + \langle 2\Delta\theta\rangle^2\right)^{\frac{1}{2}},$$

where $\Delta E/E$ represents the resolution of the energy measurement, $\Delta t/t$ represents the resolution of the time measurement, and $\Delta\theta$ is the angle of the cone of acceptance of the guide. For the system and test to be described $\Delta M \ll 1$ amu.

The device consists of a 7.1 m long stainless steel tube of inside diameter 5.08 cm with a 20 mil. tungsten wire along its center. A standard high-voltage feed-through provides up to 20 keV negative voltage to the wire. The wire is terminated about 5 cm from the target, and the detector is placed about 2.5 cm from the other end of the wire. The guide is mounted on a rotating arm, radial to the center of a 10.0 cm scattering chamber. The present system can cover scattering angles between 0° and 60°. The beam is stopped on a small Faraday cup located 2 cm behind the target, in the scattering chamber.

To test the usefulness of this system for mass identification, a thin carbon foil was bombarded with a 9.0 MeV pulsed deuteron beam from the University of Texas EN Tandem Accelerator. Beam pulses of about 4 ns width occur every 400 ns. A Sherman–Roddick preamplifier[3]) was used with an Ortec 2 mm surface barrier detector of active area 100 mm^2 to generate the linear energy signal for the energy amplifier as well as a fast (rise time about 2 ns) timing signal. The fast signal was taken as the start and a fast pulse generated from the source oscillator wave train was used as the stop for input to an Ortec time to amplitude convertor (TAC) to generate a signal proportional to the time for the particle to traverse the guide. The output of the TAC and the linear energy signal were fed to a PDP-15 computer where the data was accumulated in the two-parameter mode of our on-line data acquisition program SUPERVISOR. A total of 21 on-line windows were selected on the time-of-flight spectrum so that the performance of the system as a high resolution mass identifier could be

* Supported in part by the U.S. Atomic Energy Commission underc ontract AT-(40-1)-2972.

COMPUTER PHYSICS COMMUNICATIONS 5 (1973) 390–394. NORTH-HOLLAND PUBLISHING COMPANY

ASSOCIATED LEGENDRE POLYNOMIALS, ORDINARY AND MODIFIED SPHERICAL HARMONICS*

W.J. BRAITHWAITE
University of Texas, Austin, Texas; Princeton University, Princeton, N.J,
and
University of Washington, Seattle, Washington, USA

Received 18 July 1972

PROGRAM SUMMARY

Title of program: LEGENDRE

Catalogue: ABME

Program obtainable from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue).

Computer: CDC 6600; *Installation*: University of Texas, Austin, Texas, USA

Operating system: CDC Scope

Programming language used: FORTRAN IV

High speed storage required: 4928 words. *No. of bits in a word*: 60

Is the program overlaid? No

No. of magnetic tapes required: None

What other peripherals are used? Card reader, line printer

No. of cards in combined program and test deck: 160

Card punching code: CDC

Keywords: General, Expansion, Representation, Rotation, Deformed, Correlations, Symmetry, Legendre Polynomial, Spherical Harmonic, Partial Wave, Fourier.

Nature of physical problem

The package LEGENDRE contains three FUNCTION subprograms which calculate, respectively, Legendre polynomials, ordinary and modified spherical harmonics for partial wave or Fourier expansions.

Method of solution

The method of calculation is a forward recurrence in $l (l = m, m+1, \ldots, l_{max})$ for each m, from $m = 0, 1, \ldots, m_{max}$.

* Supported in part by the U.S. Atomic Energy Commission.

II. C. ABSTRACTS OF PAPERS SUBMITTED FOR PUBLICATION

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1. The β Decay of $^{22}F^{*}$

(C. N. Davids[†], D. R. Goosman[††], D. E. Alburger[††], A. Gallmann[††], G. Guillaume[††], D. H. Wilkinson[††], and W. A. Lanford[***])

^{22}F was produced in the $^{18}O(^{6}Li,2p)^{22}F$ reaction using 26 MeV $^{6}Li^{3+}$ ions. Following transfer of the target in a shuttle system, delayed γ and β rays were observed with Ge(Li) and NE102 plastic detectors. Several γ rays from ^{22}F decay were observed, decaying with a half-life of 4.23 ± 0.04 sec. γ-γ coincidence measurements have established that a 1900.0-keV transition terminates on a level in ^{22}Ne at 5523.4 keV, contrary to a previous study. The ground state of ^{22}F is of $J^{\pi} = 4^{+}$ (with 3^{+} as a remote possibility) disagreeing with a previous assignment of 5^{+}. Accurate excitation energies are presented for 7 states in ^{22}Ne. Experimental results compare favorably with full (2s,1d) basis shell-model calculations of the A = 22 system.

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*Research performed at Brookhaven National Laboratory under the auspices of the U. S. Atomic Energy Commission
†Alfred P. Sloan Foundation Fellow on leave from the University of Texas
††Brookhaven National Laboratory, Upton, New York
***Research supported in part by National Science Foundation. Present address: Wright Nuclear Structure Laboratory, Yale Univ., New Haven, Conn. 06520

(Phys. Rev. C, to be published)

2. States in ^{85}Kr from the $^{84}Kr(d,p)^{85}Kr$ Reaction*

(C. P. Browne[†], D. K. Olsen, J. Chao, and P. J. Riley)

Thirty states in ^{85}Kr were investigated via the $^{84}Kr(d,p)^{85}Kr$ reaction using 11.0 MeV deuterons. At least 22 of these states have not been previously reported. Angular distributions were measured from 20° to 160° for transitions to 25 of these states, and were fitted with finite-range DWBA calculations. Excitation energies, ℓ-values, spectroscopic factors and the implied values of J^{π} are given. Comparisons are made with

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states of other nuclei having both one neutron less and one neutron more than the N = 50 shell closure.

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*Work supported in part by the U. S. Atomic Energy Commission.
†Visiting Professor; permanent address: University of Notre Dame, Notre Dame, Indiana.

(Submitted to Phys. Rev. C)

3. Interference Between Coulomb and Nuclear Excitation in the Inelastic Scattering of ^{11}B Ions from ^{208}Pb*

(J. L. C. Ford, Jr.+, K. S. Toth+, D. C. Hensley+, R. M. Gaedke++, P. J. Riley+++, and S. T. Thornton++++)

The elastic and inelastic scattering of 72.2 MeV ^{11}B ions from ^{208}Pb was studied. The angular distributions for transitions to the 3^-, 5^-, 2^+, and 4^+ states at 2.61, 3.20, 4.10 and 4.31 MeV, respectively, show pronounced effects due to interference between Coulomb and nuclear excitation. The data are well reproduced by distorted wave calculations provided that the phase of the nuclear excitation form factor is altered by 5^o from that given by the collective model.

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*Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.
+Oak Ridge National Laboratory, Oak Ridge, Tennessee
++Trinity University at San Antonio, Texas
+++The University of Texas at Austin, Texas. Then research participation at Oak Ridge National Laboratory sponsored by Oak Ridge Associated Universities.
++++University of Virginia, Charlottesville, Virginia

(Accepted for publication in Physical Review)

4. High Resolution Ne KLL Auger Spectra Produced by H^+ and He^+ Bombardment*

(D. L. Matthews, B. M. Johnson, J. J. Mackey and C. F. Moore)

Ne KLL Auger satellite lines are measured with an energy resolution of 0.02% FWHM. The relative intensities of initial 2p vacancy satellite lines are observed to be 4 times larger with He^{+} than with H^{+} bombardment. The He^{+} beam also produces new satellite lines which are assigned to double initial 2p vacancies.

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*This work supported by the U. S. Air Force Office of Scientific Research and the U. S. Atomic Energy Commission.

(Accepted in Phys. Letters A)

5. A High Resolution Study of Ar LMM Auger Electrons Produced by Ion Bombardment

(B. M. Johnson, D. L. Matthews, L. E. Smith, and C. F. Moore)

Ar LMM Auger electron lines produced by H^{+}, He^{+}, O^{4+}, and O^{5+} bombardment are measured with high instrumental resolution (0.02% FWHM). Individual heavy ion induce Auger satellite lines are resolved for the first time. Two strong lines are observed at 221 and 223 eV in the oxygen induced spectra. The ratio of satellite to normal line production is given for each projectile.

(Submitted to Journal of Physics B as a letter to the editor)

6. High Resolution K-Auger Spectra for Multiply-Ionized Neon*

(D. L. Matthews, B. M. Johnson, J. J. Mackey, and C. F. Moore)

K-Auger transitions of Neon produced by 33 MeV O^{5+} bombardment are clearly resolved above a broad peaked background. Besides the 5 normal transitions, 58 satellite lines stemming from initial configurations having single K shell, multiple L shell (up to 6) vacancies are observed. Transition energies, relative intensities, and line widths are measured and compared to that obtained with 1.5 keV electron bombardment. Hartree Fock calculations of transition energies (including term splittings) are used to identify observed lines.

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*Work supported by the Robert A. Welch Foundation, the Air Force Office of Scientific Research, and The U. S. Atomic Energy Commission.

(Submitted to Phys. Rev. Letters)

7. Excitation of Multiplet Configurations in Neon*

(C. P. Bhalla+, D. L. Matthews and C. F. Moore)

High resolution Auger electron measurements of Neon have been made using electron, proton, alpha and oxygen ion excitation. Energies and intensities have been extracted for transitions with initial states ^3P and ^1P (with configuration $1s^1\ 2s^2\ 2p^5$). In general, the population ratio of triplet P to singlet P is independent of the type of incident ion, but this ratio is seen to differ significantly from the statistical expectation.

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*Supported in part by the U. S. Army Research Office (Durham, N. C.), in part by the Air Force Office of Scientific Research and in part by the Robert A. Welch Foundation.
+FOM- Institute for Atomic and Molecular Physics, Amsterdam, The Netherlands

(Submitted to Phys. Letters A)

8. Silicon and Silicon-Dioxide K X-Ray Spectra from Hydrogen, Helium, and Oxygen Bombardment

(J. McWherter, D. K. Olsen, H. H. Wolter, and C. F. Moore)

Silicon and silicon-dioxide K X-ray spectra produced by 0.8-MeV hydrogen, 3.2-MeV helium, and 13.0- and 35.0-MeV oxygen bombardment were measured with a high-resolution crystal spectrometer. The resulting Kα and Kβ, diagram and satellite, chemical energy shifts observed with these ions and those from electron excitation are compared and discussed. In general, the chemical shifts obtained from the different projectiles are similar and are dependent upon the amount of additional L-shell ionization. However, the oxygen-produced Kβ satellite shifts are anomalously large. The spectra indicate that perhaps these shifts are due to transitions from the conduction band of silicon dioxide.

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*Work supported in part by the U. S. Atomic Energy Commission. Contract Number AT-(40-1)2972.

(Submitted to Phys. Rev. A)

9. Auger Decay of Multiply-Ionized Neon*

(D. L. Matthews, B. M. Johnson, J. J. Mackey, L. E. Smith, W. Hodge, and C. F. Moore)

A high resolution double focussing electrostatic electron analyzer has been used to resolve Ne Auger electrons produced by 0.15 - 6.0 MeV H^+, 1.0 MeV He^+, and 33 MeV O^{5+} bombardment. Individual K-Auger satellite lines stemming from the decay of multiply-ionized neon have been observed. The energies, relative intensities, and production probabilities of these satellite lines were measured as a function of the projectile Z and as a function of proton bombarding energy. Tentative identifications for all observed lines were made by comparison with calculated Auger satellite transition energies. The reliability of the Hartree Fock calculations used was demonstrated by comparison with e^- + Ne data and by comparing calculated x-ray transition energies for multiply-ionized neon to recent measurements of O + Ne x-ray lines. A rough estimate of the probability of single and double orbital vacancy production as a function of L-shell defect was obtained. With proton bombardment, the satellite production probability Q_s was observed to decrease smoothly with increasing proton energy. The observation that Q_s for 6 MeV proton bombardment was less than that obtained with equal velocity electrons is believed to imply that electron shakeoff is not the dominant collision mechanism in high energy proton bombardment. Measured quantities are compared to previous determinations when possible.

(Submitted to Physical Review A)

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II. D. ABSTRACTS OF TALKS PRESENTED AT MEETINGS

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APS Washington Meeting Apr. 1973

AO 11 Experimental Energy Dependence of Al Multiple Inner-Shell Ionization From 3.0 to 30.0-MeV Oxygen Bombardment.* DAVID K. OLSEN, C. FRED MOORE, and ROBERT L. KAUFFMAN, University of Texas at Austin.-- Aluminum Kα X-ray spectra have been measured from 3.0 to 30.0-MeV oxygen bombardment of thick targets and 10.0 to 30.0-MeV oxygen bombardment of thin targets. The Kα X-ray yields were resolved by a high-resolution, Bragg, crystal spectrometer into six satellite groups resulting from additional L-shell electron vacancies. From these satellite X-ray yields, satellite fractions of the total K-shell ionization cross section are estimated and shown to be consistent with a simultaneous, direct, multiple, Coulomb reaction mechanism.

*Supported in part by the U. S. Atomic Energy Comm. and the Robert A. Welch Foundation.

APS Washington Meeting Apr. 1973

AO 12 Projectile and Target Dependence of the Kα Satellite Structure.* ROBERT L. KAUFFMAN, JAMES H. MCGUIRE, and PATRICK RICHARD, Kansas State University at Manhattan, and C. FRED MOORE, University of Texas at Austin.--Proton, alpha, and oxygen ion beams are used to induce Kα X-ray spectra in thick targets of Ca, Sc, Ti, V, Cr, and Mn. After correcting for the thick target, the relative intensities of the Kα diagram and the 5 satellite lines from single K-shell multiple L-shell ionization are obtained. These intensities are found to fit fairly well with a binomial distribution in a parameter, P_L, which is interpreted as an average probability of ionization of the L-shell. A prediction of the probabilities

APS Washington Meeting Apr. 1973

EO 4 Anomalous X-Ray Transitions Above the Lyman-like Series Limit in $O^{7+} + e^-$.* DENNIS L. MATTHEWS, W. J. BRAITHWAITE, CLAUDE CAMP, and C. FRED MOORE, University of Texas at Austin.--Observation of the X-ray decay from a highly-stripped beam of oxygen ions has yielded several anomalous X-ray transitions not directly attributable to helium-like or lithium-like oxygen. One particular set of these transitions are located just above the $O^{7+} + e^-$ Lyman-like series limit. There are five of these transitions having energies at 744.0, 747.3, 751.8, 757.4, and 765.3 ± 0.4 eV. Identification of the origin of these transitions is presently underway and descriptions for several of them will be given.

*Supported in part by the Robert A. Welch Foundation.

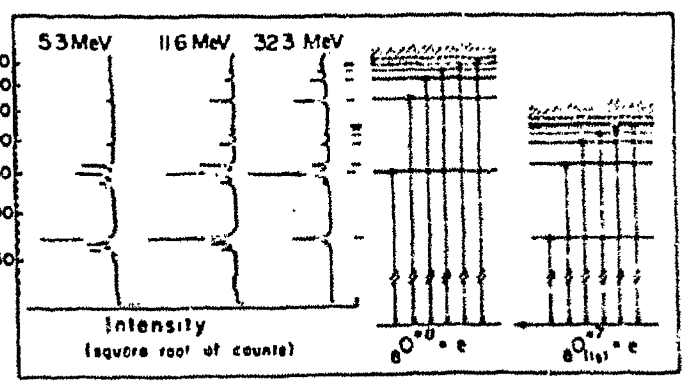
APS Washington Meeting Apr. 1973

EE 10 A New Technique for High Resolution Charged-Particle Mass Identification.* G. W. HOFFMANN, C. F. MOORE, F. PIPITONE, and J. R. WHITE, Center for Nuclear Studies, Univ. of Texas.--A simple technique has been developed which exploits an electrostatic particle guide similar to that described by Oakey and Mcfarlane[1] to transport charged particles and permit time-of-flight measurements over quite long flight paths. Where excellent mass resolution, together with the best energy resolution from charged particle detectors is desired this single-detector energy-mass-identifier is far superior to conventional particle telescope systems.

*Work supported in part by the U. S. Atomic Energy Comm.
[1] N. S. Oakey and R. D. Macfarlane, Nucl. Instr. Methods 49 (1967) 220.

APS Washington Meeting Apr. 1973

EO 3 The Lyman Series in Hydrogenic Oxygen and Lyman-like Series in Helium-like Oxygen.* C. FRED MOORE and JOSEPH E. BOLGER, University of Texas at Austin. -- Oxygen beams from an electrostatic accelerator were used to produce a few electron system of Oxygen. X-ray decay of this system was measured. The Rydberg constant for Oxygen was measured to be 10.973 ± .006 μ^{-1}.



*Supported in part by the Robert A. Welch Foundation, the Research Corporation and the Air Force Office of Scientific Research.

APS Washington Meeting Apr. 1973

JK 7 In-Beam Conversion Electron Studies of p + Pb.* L. L. LYNN, G. W. HOFFMANN, J. FITCH, and C. FRED MOORE, University of Texas.-- An axial β-ray spectrometer was used to make in-beam studies of internal conversion electrons resulting from the proton bombardment of lead isotopes. A large number of previously unreported internal conversion transitions have been observed. The placement of these transitions within the appropriate energy level schemes of Pb and Bi isotope will be discussed.

*Research supported in part by the U. S. Atomic Energy Comm.

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APS Washington Meeting Apr. 1973

KE 14
Single-Nucleon Transfer Reactions Induced by ^{11}B Ions Incident on ^{208}Pb., K. S. TOTH, J. L. C. FORD, Jr., D. C. HENSLEY, Oak Ridge Nat. Lab.† R. M. GAEDKE, Trinity Univ., and P. J. RILEY, Univ. Texas.--^{208}Pb was bombarded with 72-MeV ^{11}B ions accelerated in the Oak Ridge isochronous cyclotron. With the use of a 60-cm long position sensitive proportional detector placed in the focal plane of a broad-range magnetic spectrograph all four single-nucleon transfer reaction products were identified. At this time angular distribution measurements have been completed for five final states in ^{209}Bi populated in the reaction ^{208}Pb(^{11}B,^{10}Be) and for three states in ^{207}Pb populated in the reaction ^{208}Pb(^{11}B,^{12}C). The differential cross sections are single peaked and smooth. Once again, as reported earlier[1] for the analagous reaction ^{208}Pb(^{12}C,^{11}B)^{209}Bi, the indication is that for the proton stripping reaction the peak angles remain constant with increasing excitation energy in ^{209}Bi. Experiments are underway to complete the study by obtaining angular distribtuions for the (^{11}B,^{10}B) and (^{11}B,^{12}C) reactions.

†Operated by Union Carbide Corp. for the ASAEC
[1]J. S. Larsen et al, Phys. Letters 42B, 205 (1972).

APS Washington Meeting Apr. 1973

KL 3 New Proton-Rich Activities Near ^{72}Kr.* CARY N. DAVIDS† and DAVID R. GOOSMAN, Brookhaven National Laboratory, Upton, New York 11973-- The alpha-particle nuclide ^{72}Kr has been produced via the ^{58}Ni(^{16}O,2n)^{72}Kr reaction with 52-MeV ^{16}O ions. Recoils were thermalized in He gas, and krypton activities were enhanced by expanding the gas through Ascarite and copper traps into a remotely-located γ-ray counting chamber. γ rays with energies (± 0.4 keV) of 162.8, 257.5, 310.0, and 414.9 keV were observed, decaying with an average half-life of 17.3 ± 0.3 sec, which we attribute to ^{72}Kr from the observed buildup of the ^{72}Br daughter activity. This half-life is consistent with that of an earlier experiment[1]. The astrophysical significance of ^{72}Kr will be presented. Two other activities with half-lives of 25.9 ± 0.6 and 41.6 ± 1.8 sec were observed, and their identification will be discussed.

*Work performed under the auspices of the U.S.A.E.C.
†Alfred P. Sloan Foundation Fellow, on leave from the University of Texas at Austin.
[1]J. C. Hardy, private communication.

APS Washington Meeting Apr. 1973

KL 8 The ^{84}Kr(d,p)^{85}Kr Reaction.* C. P. BROWNE,** D. K. OLSEN, and P. J. RILEY, University of Texas at Austin, Texas.—States of ^{85}Kr have been investigated via the ^{84}Kr(d,p)^{85}Kr reaction at an incident deuteron energy of 11.0 MeV, and with an overall experimental energy resolution of 30 keV. Krypton gas isotopically enriched to 90.1% of ^{84}Kr and contained in a thin walled gas cell was used. Proton groups leading to approximately 30 states in ^{85}Kr with excitation energies up to 3.0 MeV have been identified. The angular distribution data have been analyzed in the framework of the distorted-wave Born-approximation (DWBA) with corrections for non-locality and finite-range in the local-energy-approximation. Spin and parity assignments and spectroscopic factors have been extracted and will be presented.

*Work supported in part by the U. S. Atomic Energy Comm.
**Visiting Professor from the Univ. of Notre Dame, Notre Dame, Indiana.

APS Washington Meeting Apr. 1973

KL 9 Proton-Induced Reactions on Y^{89} at 28 MeV.* J. R. COMFORT, Ohio U., W. J. BRAITHWAITE, U. Texas, and A. NATHAN and J. R. DURAY, Princeton U.--A 27.8-MeV proton beam from the Princeton AVF cyclotron bombarded an Y^{89} target and initiated (p,d), (p,t) and (p,α) reactions leading to Y^{88}, Y^{87} and Sr^{86}, respectively. The resolution was typically about 35 keV. In Y^{88}, cross-section ratios for some low-lying states are in excellent agreement with their expected configurations. Of special interest is an apparent ℓ_n = 2 angular distribution for a level near 706 keV, in agreement with a recent 2^- assignment.[1] The (p,t) data have enabled unambiguous J^π assignments for states in Y^{87} previously observed as ℓ_p = 1 transitions in the Sr^{86}(He^3,d)Y^{87} reaction.[2] The (p,α) spectra reveal the population of many states in Sr^{86}. The angular distributions have characteristic patterns, but generally do not show much structure.

*Work supported in part by the U.S.A.E.C. and the N.S.F.
[1]F. Gebbard et al., Phys. Rev. C6, 2167 (1972).
[2]J. V. Maher et al., Phys. Rev. C3, 1162 (1971).

APS Washington Meeting Apr. 1973

KL 10 Direct-Reaction Study of High-Excitation Bound States and Neutron Resonances in the Zr Isotopes.* W. E. COKER, G. W. HOFFMANN, F. FIPITONE, and J. R. WHITE, Center for Nuclear Studies, Univ. of Texas.--A new electrostatic particle guide permitting high-resolution energy-mass identification for charged particles has been used to study bound states at high excitation, and neutron resonances in the Zr isotopes via the (d,p) reaction at 9 to 12 MeV incident deuteron energy. DWBA analyses of the bound-state and resonance angular distributions are presented, with complex-energy eigenstates as resonance form factors. Comparison with results of earlier neutron capture, and other, experiments is provided.

*Research supported in part by the U. S. Atomic Energy Comm.

Munich Conference Aug. 1973

Proc. of Internat. Conf.
on Nucl. Physics, Aug. 1973

4.164

MASS AND β DECAY OF ^{29}Mg: SYSTEMATICS OF MASSES OF T_z = 5/2 NUCLIDES IN THE 2s-1d SHELL*

D. R. Goosman, C. N. Davids†, and D. E. Alburger
Brookhaven National Laboratory, Upton, New York, U.S.A.

The new isotope ^{29}Mg has been produced in the $^{18}O(^{13}C,2p)^{29}Mg$ reaction using 35-MeV ^{13}C ions from one of the Brookhaven National Laboratory MP Tandem Van de Graaffs. Targets of $Ta_2{}^{18}O_5$ were transferred in a rabbit to remote Ge(Li) and NE102 γ- and β-ray detectors. ^{29}Mg decays with a half-life of 1.20 ± 0.13 sec and emits γ rays with the following energies (in keV) and relative intensities: 960.3 ± 0.4 (52 ± 18), 1397.7 ± 0.4 (64 $^{+30}_{-20}$), 1430.0 ± 1.5 (34 ± 17), 1753.8 ± 0.4 (22 ± 5), and 2223.7 ± 0.4 (100 ± 6). The ^{29}Al excitation energies (in keV) and relative β branching intensities are 1397.7 ± 0.4 (64 $^{+35}_{-28}$), 1753.8 ± 0.4 (<10), 2223.8 ± 0.4 (55 ± 22), and 3184.0 ± 0.6 (100 ± 35). By measuring the spectrum of β-ray pulses in the NE102 detector in coincidence with 2224-keV γ rays the mass excess for ^{29}Mg has been determined to be -10,590 ± 400 keV, disagreeing by 1.7 ± 0.5 MeV with a previous report (Scott, Cardinal, Fisher, Hudson, and Anyas-Weiss, Atomic Masses and Fundamental Constants, ed. by Sanders and Wapstra, Plenum Press, London-New York, 1972, p.54).

Similar techniques have been used to re-measure the masses of ^{33}Si and ^{34}P formed in the $^{18}O(^{18}O,2pn)^{33}Si$ and $^{18}O(^{18}O,pn)^{34}P$ reactions, respectively. Mass excesses are -20,569 ± 50 keV for ^{33}Si, and -24,546 ± 45 keV for ^{34}P.

The masses of the relevant T_z < 5/2 nuclides, including the new value for ^{34}P, have been used to predict the masses of the T_z = +5/2 nuclides by using the transverse relationship of Garvey, Gerace, Jaffe, Talmi, and Kelson, Rev. Mod. Phys. **41** (1969) S1. Measured masses are compared with these predictions in Fig. 1 which includes the present results for ^{29}Mg and ^{33}Si but omits the ^{29}Mg value reported by Scott et al. (ibid.). A systematic trend in the differences between the predicted and measured masses is evident. It is curious to note in Fig. 1 that the differences are closest to zero at masses 27 and 35, which is where the $s_{1/2}$ and $d_{3/2}$ neutron shell closures occur, respectively. The $d_{5/2}$ neutron shell closure occurs at mass 23. Thus far we have been unable to find ^{23}F, the only missing member of this series.

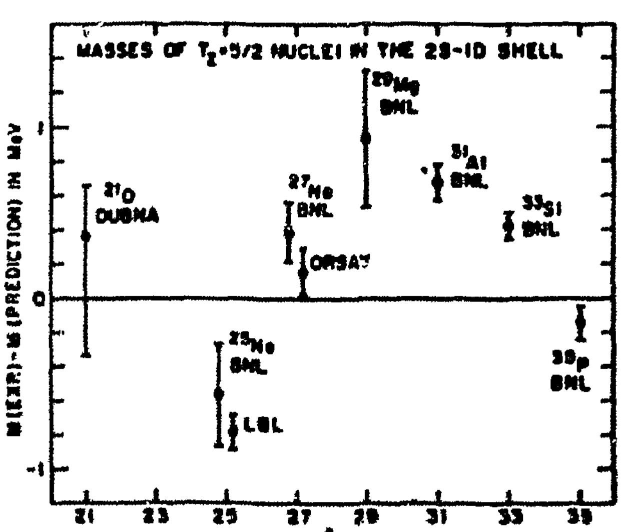


Fig. 1 Measured masses of T_z = +5/2 nuclei compared with predictions.

*Research carried out under the auspices of the U.S. Atomic Energy Commission.

†Alfred P. Sloan Foundation Fellow on leave from the University of Texas at Austin, Texas.

Munich Conference Aug. 1973

4.55 Proc. of Internat. Conf. on Nucl. Physics, Aug. 1973

SPECTROSCOPIC STUDIES OF ^{84}Kr AND ^{85}Kr*

P. J. Riley, C. P. Browne,** and D. K. Olsen,
Center for Nuclear Studies, University of Texas at Austin, Texas

E*(MeV)	ℓ	J^{π}	S
0.000	4	$9/2^+$	0.17
0.303	1	$1/2^-$	0.067
1.136	2	$5/2^+$	0.47
1.427	0	$1/2^+$	0.40
1.868	2	$(5/2^+)$	0.011
2.043	2	$(5/2^+)$	0.043
2.369			
2.514	2	$(5/2^+)$	0.015
2.598			
2.736	0	$1/2^+$	0.088
2.848	0	$1/2^+$	0.137
3.055	2	$(3/2^+)$	0.243
3.109	0	$1/2^+$	0.117
3.277	0	$1/2^+$	0.076
3.326	2	$(3/2^+)$	0.036
3.390	4	$1/2^+$	0.054
3.456			
3.565	2	$(3/2^+)$	0.060
3.628	0	$(1/2^+)$	0.026
3.717	2	$(3/2^+)$	0.073
3.787	2	$(3/2^+)$	0.034
3.896	2	$(3/2^+)$	0.029
3.928	0	$1/2^+$	0.024
4.027	2	$(3/2^+)$	0.037
4.146	0	$1/2^+$	0.038
4.335	2	$(3/2^+)$	0.020
4.450	2	$(3/2^+)$	0.027
4.547	2	$(3/2^+)$	0.032
4.623			

Table 1. DWBA Analysis of the 84Kr(d,p)85Kr Reaction.

There has been little previous information available on the states of 84Kr and 85Kr because of the difficulty of obtaining isotopically enriched targets. Using 90.1% isotopically enriched 84Kr gas, only recently available, we have studied states of 85Kr with the 84Kr(d,p)85Kr reaction, and states of 84Kr via the 84Kr(p,p') reaction. An experimental energy resolution of 30 keV was obtained by using a thin walled gas cell. The incident beam energy was 11 MeV in the (d,p) work, and 12 MeV in the (p,p') measurements. In the (d,p) work, proton groups leading to approximately 30 states in 85Kr with excitation energies up to 5 MeV were identified. The differential cross section data were analyzed with the distorted-wave Born Approximation (DWBA), with a non-locality correction. Orbital angular momentum transfer values, spin and parity assignments, and spectroscopic factors have been extracted and are summarized in Table 1.

A typical 84Kr(p,p') spectrum, showing about 30 excited states in 84Kr, is shown in Figure 1. A comparison spectrum using natural krypton to identify the lines due to 83Kr and 86Kr in the 84Kr gas is also given. The excitation energies of the states of 84Kr are in good agreement with previous decay measurements of Hill and Wang (Phys. Rev. C5, (1972),806). The one-phonon, 2+ (0.88 MeV) and 3^- (2.70 MeV), and the 0^+ (1.84 MeV), 2^+ (1.90 MeV), and 4^+ (2.10 MeV) members of the two-phonon triplet states have been fitted using both the DWBA and the coupled-channel code JUPITOR-1. Much better agreement between the experimental and theoretical cross section data has been obtained with the coupled-channel analysis.

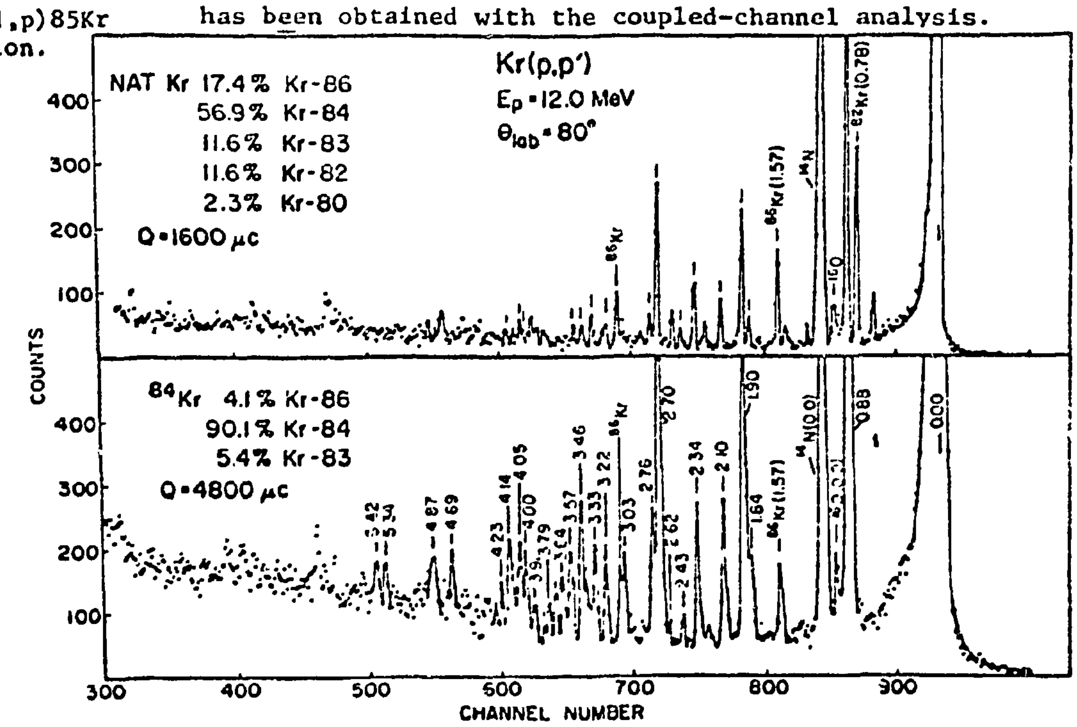


Figure 1. A 84Kr(p,p')84Kr spectrum.

* Work supported in part by the U. S. Atomic Energy Commission.
** Visiting Professor from the University of Notre Dame, Notre Dame, Indiana.

Munich Conference Aug. 1973

Proc. of Internat. Conf.
on Nucl. Physics, Aug. 1973

4.75

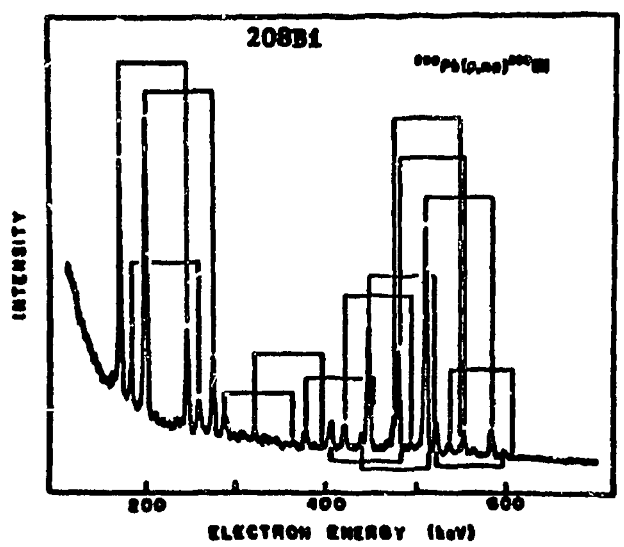
INTERNAL CONVERSION ELECTRONS FROM THE PROTON BOMBARDMENT OF $^{206,208}Pb$*

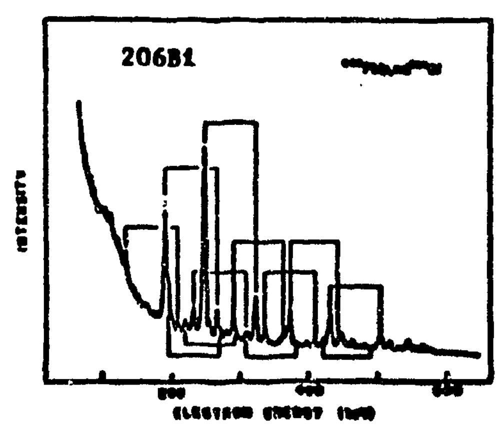
C. Fred Moore, Larry L. Lynn, and G. W. Hoffmann
CENTER FOR NUCLEAR STUDIES, UNIVERSITY OF TEXAS, AUSTIN, TEXAS, USA

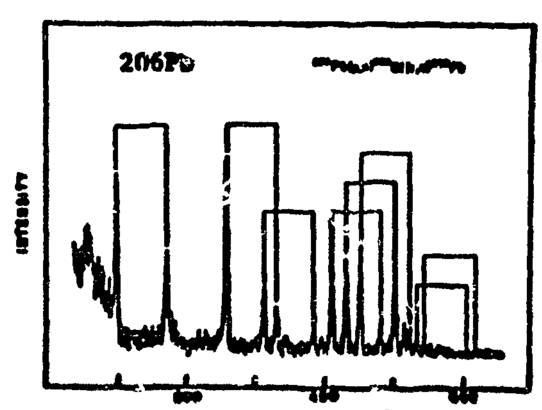
Enriched targets of 206,208Pb were bombarded by 9 MeV protons. In-beam measurements of the resulting internal conversion electrons were made using an axial β-ray spectrometer. Electrons with kinetic energies in the 100-600 keV range were detected with a resolution (FWHM) of 3 keV. Groups corresponding to the ejection of K,L, and M electrons were observed in 206,208Bi populated by the (p,n) reaction and in 206Pb populated by the beta decay of 206Bi. The electron spectra accumulated by sweeping the spectrometer's coil current are shown in the figures. The K- and L-electron groups for each nuclear transition have been connected in the figures. The 208Bi data are in good agreement with previous 208Pb(p,nγ)208Bi results [Proetel et al., Nucl. Phys. A161 (1971)565]; in addition, a number of new electron groups were observed. Several new transitions were observed in 206Bi, and the 206Pb data are in good agreement with previous results [Kanbe et al., Nucl. Phys. A192 (1972)151] for the internal conversion electrons observed after the β-decay of 206Bi.

Observed Transition Energies (keV)

^{208}Bi	^{206}Bi	^{206}Pb
262.7	226	184.1
275.4	282.1	(262.8)
291.7	286.5	343.4
(338.2)	311.5	398.1
(375.7)	(325)	497.1
(413.0)	328.4	516.1
467.6	380.7	537.5
496.2	(425)	(620.6)
510.6	463.5	(632.2)
530.5	511.4	
538.5	522.4	
565.3	(554.8)	
570.1	(649.6)	
601.5		
(603.3)		
(614.4)		
(627.2)		







*Work supported in part by the U. S. Atomic Energy Commission and in part by the Research Corporation.

Munich Conference Aug. 1973

Proc. of Internat. Conf.
on Nucl. Physics, Aug. 1973 **5.52**

INELASTIC SCATTERING AND SINGLE NUCLEON TRANSFER REACTIONS WITH ^{11}B IONS INCIDENT ON ^{208}Pb

J. L. C. Ford, Jr., K. S. Toth, D. C. Hensley, R. M. Gaedke,[1]
P. J. Riley,[2] and S. T. Thornton[3]

Oak Ridge National Laboratory*
Oak Ridge, Tennessee, U.S.A.

Inelastic scattering of ^{11}B ions from ^{208}Pb and the single nucleon transfer reactions (^{11}B,^{12}C), (^{11}B,^{12}B), (^{11}B,^{10}B), and (^{11}B,^{10}Be) on ^{208}Pb leading to the residual nuclei ^{207}Tl, ^{207}Pb, ^{209}Pb, and ^{209}Bi, respectively, have been observed. The 72.2 MeV incident ^{11}B ions were accelerated by the Oak Ridge isochronous cyclotron, and the reaction products were detected in a 60 cm-long, position-sensitive proportional detector placed in the focal plane of a broad-range spectrograph. The energy loss in the counter furnished a ΔE signal distinguishing the various reaction products.

All four transfer reactions selectively populate the known single particle or hole states. Angular distributions were measured for excited states observed in each of the single nucleon transfer reactions.

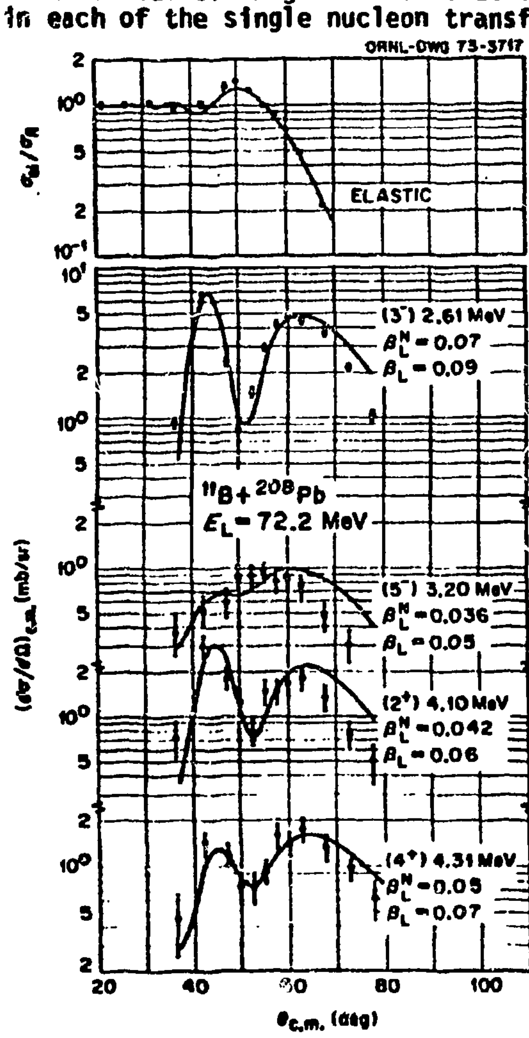


Fig. 1. Elastic and Inelastic scattering of ^{11}B ions from ^{208}Pb. The curves are optical model and DWBA fits.

Inelastic scattering was observed to the 3^-, 5^-, 2^+, and 4^+ states at 2.61, 3.20, 4.10, and 4.31 MeV, respectively, in ^{208}Pb. The angular distributions for all four levels show marked interference patterns due to interference between Coulomb and nuclear excitation. The observed inelastic angular distributions along with the elastic data are shown in fig. 1. At a center-of-mass angle near 51°, where nucleon absorption begins to depress the elastic data below the Rutherford value, a pronounced minimum is seen in the angular distributions of the 3^-, 2^+, and 4^+ states, and change in slope in that of the 5^- state.

The solid curve drawn through the elastic scattering data was calculated with the following parameters: V = 21.6 MeV, W = 5.7 MeV, r_0 = 1.34 fm, and a = 0.42 fm. The calculations for the inelastic groups were made with these same parameters for both the entrance and exit channels of the reaction, and for the form factor, except that W was increased to 8.1 MeV in the form factor.

Shown on fig. 1 are the optical model deformation parameter, β_L^N, obtained by matching the theoretical curves to the data, as well as the deduced target deformation, β_L. The deformation values for β_L are in good agreement with those obtained with other light and heavy projectiles.

*Operated by Union Carbide Corp. for the USAEC.

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Munich Conference Aug. 1973

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5.81

A NEW METHOD FOR SPIN DETERMINATIONS USING HEAVY IONS*

W. J. Braithwaite, Center for Nuclear Studies, University of Texas at Austin, and
J. G. Cramer, Nuclear Physics Laboratory, University of Washington, Seattle, USA.

A new reaction-mechanism-independent method is proposed for determining spins of nuclear states from angular correlations, when spinless particles are used to populate and de-excite those states, formed in the bombardment of even-even target nuclei. This method is based on a fortuitous grouping of the zeros of the reduced rotation matrix which lie nearest to 90 degrees.

It is worth pointing out that, recently, heavy-ion reactions have been found with relatively large cross sections for the transfer of four or eight nucleons, populating continuum states with relatively large alpha widths. This has led to a revival of interest in using [Heavy-Ion]-Alpha angular-correlations to determine the spins of such states.

The z-axis is taken in the $\vec{k}_i \times \vec{k}_f$ direction and reflection symmetry is invoked resulting in the following correlation function for the decay particle, in terms of the nuclear substate population amplitudes $\{A(J,M)\}$ of the nuclear excited states:

$$W_J(\theta,\phi) = |\Sigma\, A(J,M)\, \exp(-iM\phi)\, C(J,M,\theta)|^2 \text{ , where } C(J,M,\theta) \equiv d^J_{M0}(\theta)$$

(the reduced rotation matrix) and where the sum is over $J + M$ = even.

Since $C(J,-M,\theta) = (-)^M\, C(J,M,\theta)$, a state of spin J has a truncated $(J/2) + 1$ number of different C-functions in its correlation function. For J = 2 or 3 there are, thus, only two C-functions in the correlation function; so by choosing $\theta = \theta(J-2)$ where the function $C(J,J-2,\theta(J-2)) = 0$, only the following simple ϕ-dependence is retained in the correlation function: $W_J(\theta,\phi) = A + B\,\sin^2(J\phi + \delta)$.

Simplicity in the correlation function would be unexpected for states with $J > 3$, since it involves sums of three or more C-functions and only one of these C-functions could be set to zero at any time. However, one-term simplicity is retained, approximately, since all of the C-functions can be set approximately to zero, simultaneously, except for $C(J,J,\theta)$, by the same choice of $\theta = \langle\theta(M)\rangle$. Table 1 is a list of $\{\theta(M)\}$ and $\langle\theta(M)\rangle$ for all integer values of J between 2 and 8. To an excellent approximation (tested numerically), the slope-weighted average of the $\theta(M)$ values may be written as follows:

$$\langle\theta(M)\rangle \doteq \sum_M \theta(M)\,(J^2 - M^2)^{1/2} / \sum_M (J^2 - M^2)^{1/2} \text{ , where } M \neq J.$$

This means that the derivative weighting factor de-enhances the importance of the higher M values, since they have the shallowest slopes through zero. This is fortunate, since Table 1 shows that those $\theta(M)$s with the largest M values deviate the most from the mean.

J^π	M= 0/1	2/3	4/5	6/7	$\langle\theta(M)\rangle$
2^+	54.7°		$\{\theta(M)\}$		54.7°
3^-	63.4°				63.4°
4^+	70.1°	67.8°			68.9°
5^-	73.4°	70.5°			72.1°
6^+	76.2°	75.5°	72.5°		74.8°
7^-	77.9°	76.9°	73.9°		76.3°
8^+	79.4°	79.1°	78.0°	75.0°	77.8°

Table 1. The zeros of $C(J,M,\theta)$, $\{\theta(M)\}$, and their mean values, $\langle\theta(M)\rangle$, for (J^π).

Setting the detector for the decay particle at $\theta = \langle\theta(M)\rangle$ allows the correlation function to be written, approximately, as follows:

$$W_J(\langle\theta(M)\rangle,\phi) \doteq A + B\,\sin^2(J\phi + \delta) \text{ ,}$$

where both θ and ϕ are center of mass angles. θ = a constant leads to a trajectory of (θ,ϕ)-values in the lab frame. Experimentally this means that a goniometer is needed to position the detector for the decay particle.

The spin, J, is easy to extract from this correlation function.

*Work supported in part by the United States Atomic Energy Commission.

Munich Conference Aug. 1973

Proc. of Internat. Conf.
on Nucl. Physics, Aug. 1973

6.6

DECAYS OF NEW PROTON-RICH NUCLIDES ^{72}Kr AND ^{73}Kr*

Cary N. Davids+, Center for Nuclear Studies, University of Texas at Austin, USA, and Brookhaven National Laboratory, Upton, N.Y., USA, and David R. Goosman, Brookhaven National Laboratory, Upton, N.Y.,USA.

Delayed gamma rays following the decay of two new proton-rich Kr isotopes, ^{72}Kr and ^{73}Kr, have been observed with a Ge(Li) detector. These isotopes were produced by the bombardment of ^{58}Ni with ^{16}O ions, using a 53 MeV beam from one of the Brookhaven National Laboratory MP Tandem Accelerators. Contaminant activities such as ^{72}Br, ^{72}Se, ^{71}Se, and ^{69}As were eliminated by means of a gas-transfer system, copper cold trap, and Ascarite(KOH) filter. Identification of the Kr isotopes was based both on the buildup of their daughter nuclides, and on relative intensities of decay gamma rays observed at two different ^{16}O bombarding energies. ^{72}Kr decays with a half-life of 17.4 ± 0.4 sec to states in ^{72}Br, with the emission of six gamma rays. The half-life of ^{73}Kr is 25.9 ± 0.6 sec, and eight gamma rays have been observed.

Decay schemes for ^{72}Kr and ^{73}Kr are shown in figures 1 and 2. They have been constructed by using observed energy sums and intensities. Positron decay branches have been calculated using the gamma-ray intensities and the total number of decays obtained from the buildup of the daughter nuclides. The results are consistent with a ^{72}Br ground-state spin greater than 1, but do not rule out a spin of 0^+ or 1^+. For ^{73}Kr, our results are consistent with a ground-state spin and parity of $(5/2)^-$.

^{72}Kr is possibly of astrophysical importance since it is an even-even $T_z = 0$ nuclide. Clarification of its role in explosive nucleosynthesis must await the measurement of its mass as well as the mass of ^{68}Se.

*Work performed under the Auspices of the U.S. Atomic Energy Commission
+Alfred P. Sloan Foundation Fellow

Figure 1

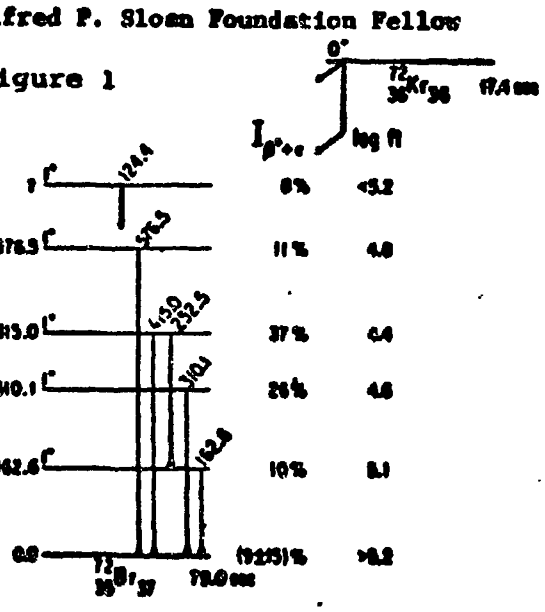
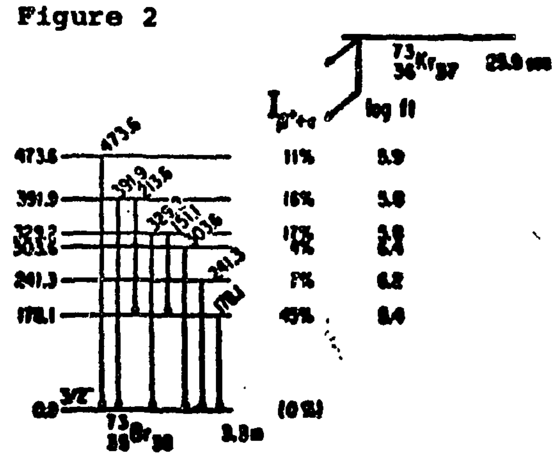


Figure 2



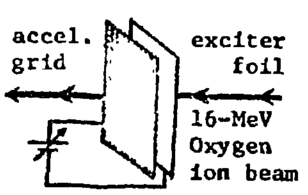
APS Bloomington Meeting Oct. 1973

BC13. Spin and Beta Decay of the $T_z = 2$ Nuclide ^{22}F.* C. N. DAVIDS†, D. R. GOOSMAN, and D. E. ALBURGER, Brookhaven National Laboratory.--^{22}F was produced in the $^{18}O(^6Li,2p)^{22}F$ reaction using 26 MeV $^6Li^{3+}$ ions. Following transfer of the target in a shuttle system, delayed γ and β rays were observed with Ge(Li) and NE102 plastic detectors. Seven γ rays from ^{22}F decay were observed, decaying with a half-life of 4.23 ± 0.04 sec. γ-γ coincidence measurements have established that a 1900.0-keV transition terminates on a level in ^{22}Ne at 5523.4 keV, contrary to a previous study. The ground-state spin and parity of ^{22}F is either 3^+ or 4^+, disagreeing with a recent assignment of 5^+. β-γ coincidences show direct β-feeding to 5 states in ^{22}Ne, for which accurate excitation energies are presented. Experimental results compare favorably with shell-model β-decay calculations for $J^\pi(^{22}F) = 4^+$ and compare poorly for $J^\pi = 3^+$.

*Work performed under the auspices of the U.S. A.E.C.
†Alfred P. Sloan Foundation Fellow, on leave from the University of Texas at Austin.

APS Bloomington Meeting Oct. 1973

DE13. Possible Electron Resonances in Highly-Ionized Oxygen.* C. FRED MOORE, W. J. BRAITHWAITE, and D. L. MATTHEWS, University of Texas.--Each 16-MeV oxygen ion that passes through the exciter foil "knocks out" many electrons in its immediate path. These electrons are post-accelerated (see fig), striking the fast-moving, highly-stripped oxygen ion that produced them. As the accelerating grid voltage is varied from -400 V to +400 V, several peaks are seen in the Lyman X-ray yield, with widths as narrow as 30 eV. These peaks may be due to some sort of resonant excitation, leading to a final state where only one electron is bound to the bare oxygen nucleus.



*Work supported in part by the U. S. Air Force Office of Scientific Research, the Robert A. Welch Foundation and the U. S. Atomic Energy Commission.

APS Bloomington Meeting Oct. 1973

DC14. Decays of ^{74}Kr and ^{75}Kr.* CARY N. DAVIDS†, LEWIS A. PARKS, ANN SCHMIEDEKAMP, and DANIEL P. WHITMIRE, University of Texas at Austin.--The nuclides ^{74}Kr and ^{75}Kr have been produced via the $^{60}Ni(^{16}O,2n)^{74}Kr$ and $^{60}Ni(^{16}O,n)^{75}Kr$ reactions, using 42 MeV ^{16}O ions. A gas transfer system was used to separate Kr isotopes from contaminant activities, and delayed gamma rays were observed with a Ge(Li) detector at a remote location. Nine gamma rays are attributed to ^{74}Kr decay, with energies (±0.3 keV) of 62.8, 89.6, 93.4, 123.2, 140.2, 203.1, 217.1, 296.6, and 306.5 keV. Their average half-life is 11.6 ± 0.4 min. Two gamma rays are associated with the decay of ^{75}Kr having energies (±0.3 keV) of 132.4 and 154.9 keV. Their average half-life is 4.2 ± 0.2 min. Decay schemes will be presented, along with comparisons with other work.

*Work supported by the U.S.A.E.C., the National Science Foundation, and the Robert A. Welch Foundation.
†Alfred P. Sloan Foundation Fellow.

APS Bloomington Meeting Oct. 1973

FD10. An Anomalous Result for $^9Be(\alpha,t)^{10}B$ at E_α=27 MeV.* K. W. KEMPER, S. COTANCH, G. E. MOORE, A. W. OBST, R. J. PUIGH, and R. L. WHITE, Florida State U.--To further investigate isospin conservation in direct reactions,[1] $^9Be(\alpha,t)^{10}B$ was measured in the range $\theta_{c.m.}$=15°-110° for transitions to the first four states in ^{10}B. Surprisingly, the transition to the 0^+(T=1) state at 1.74 MeV was not observed over the angular range studied. DWBA calculations described the transition to the 3^+ state if a large f-wave contribution was assumed ($p_{3/2}/f_{7/2}$=3). If transfer of a $p_{3/2}$ proton was assumed, then the transition to the 1^+(0.72 MeV) transition was out of phase by 15°, while the transition to the 1^+ (2.15 MeV) state was well described. Neither DWBA nor CCBA calculations provide any clue as to the reason for the lack of population of the 0^+ state. Difficulties describing the (α,t) reaction on 1p shell nuclei have also been encountered in other studies.[2]

*Supported in part by grants NSF-GP-25974, NSF-GP-15855, and NSF-GU-2612.
[1]S. Cotanch and D. Robson, Nucl. Phys. A209, 301 (1973).
[2]D. Dehnhard and R. H. Siemssen, BAPS 12, 17 (1967); H. T. Fortune, D. Dehnhard, R. H. Siemssen, and B. Zeidman, BAPS 14, 487 (1969).

APS Bloomington Meeting Oct. 1973

FC7. Internal Conversion Electrons from Proton Bombardment of ^{121}Sb, ^{103}Rh, and ^{93}Nb.* L. L. LYNN,† J. R. WHITE, G. W. HOFFMANN, and C. FRED MOORE, University of Texas at Austin.-- Internal conversion electrons from the proton bombardment of ^{121}Sb, ^{103}Rh, and ^{93}Nb targets were studied in-beam using an axial β-ray spectrometer. Proton beams having energies of 8 and 9 MeV were used, and electrons in the 70 - 600 keV energy range were detected. A large number of previously unreported internal conversion electrons were observed. Several new transitions in the resultant nuclei (^{121}Te, ^{103}Pd, and ^{93}Mo) were identified also.

*Research supported in part by the U.S. Atomic Energy Commission and the Office of Naval Research
†Present address: Texas Southern University

APS Bloomington Meeting Oct. 1973

EB5. Inelastic Scattering and Single-Nucleon Transfer Reactions with ^{11}B Ions Incident on ^{208}Pb; K. S. TOTH, J. L. C. FORD, JR., D. C. HENSLEY, Oak Ridge Nat. Lab.†, R. M. GAEDKE, Trinity Univ., P. J. RILEY, Univ. Texas, S. T. THORNTON, Univ. Virginia.--^{208}Pb was bombarded with ^{11}B and angular distributions were measured for elastically and inelastically scattered ^{11}B particles and for ^{12}C, ^{12}B, ^{10}B and ^{10}Be particles resulting from single-nucleon transfer reactions. The 72.2-MeV ^{11}B ions were accelerated in the Oak Ridge isochronous cyclotron, and reaction products were detected in a 60 cm-long, position-sensitive proportional detector placed in the focal plane of a broad-range spectrograph. Inelastic scattering was observed to the 3^-, 5^-, 2^+, and 4^+ states at 2.61, 3.20, 4.10, and 4.31 MeV in ^{208}Pb. At $\theta_{c.m.} \approx 51°$ all four angular distributions showed effects due to interference between Coulomb and nuclear excitation. The transfer reactions were found to populate known single particle or hole states in the residual nuclei. Angular distributions were obtained for 5 final states in ^{209}Bi, 4 in ^{207}Pb, 6 in ^{209}Pb and 4 in ^{207}Tl. In the (^{11}B,^{10}Be) reaction a large cross section was also observed for exciting the 3.37-MeV state in ^{10}Be.
†Operated by Union Carbide Corp. for the USAEC.

APS Bloomington Meeting Oct. 1973

DE10. Position Determination of Radiation in a Solid-State Detector using Differences in Pulse Risetimes.* W. J. BRAITHWAITE, C. R. DOSS, and C. FRED MOORE, University of Texas.--The position of radiation striking a silicon surface-barrier detector has been determined from the relative risetimes of the pulses collected at either end of its high-resistance backing. An 8 mm x 25 mm detector, fabricated at the Center for Nuclear Studies, has been used to study this effect. In the preliminary tests this device has been used to detect alpha particles between 6 and 9 MeV with a position resolution of 0.6 mm and an energy resolution of 34 keV. Much larger position-sensitive surface-barrier detectors are nearing completion. These devices will be used in the near future to test the usefulness of this risetime method for determining position when using solid-state detectors of very high capacitance.

*Work supported in part by the U. S. Atomic Energy Commission.

APS New York Meeting Jan. 1973

GI 11 Cross Sections for Multiple Inner Shell Ionization of Al from 0.4 to 3.0-MeV Helium Bombardment.* DAVID K. OLSEN, C. FRED MOORE, and ROBERT L. KAUFFMAN, University of Texas at Austin, and PATRICK RICHARD and JAMES H. MCGUIRE, Kansas State University.--Aluminum Kα X-ray spectra have been measured from a thick target bombarded by Helium ions with energies from 0.4 to 1.0 MeV in 0.1-MeV steps and 1.0 to 3.0 MeV in 0.2-MeV steps. The Kα X-ray yields were resolved by a high-resolution, Bragg, crystal spectrometer into four major satellite groups resulting from zero to three additional L-shell, electron vacancies. These satellite yields were unfolded, correcting for target absorbtion and fluorescence, to give cross sections. These experimental results are in good agreement with a simultaneous, direct, Coulomb excitation model.

*Supported in part by the U. S. Atomic Energy Commission and the Robert A. Welch Foundation.

APS New Haven Meeting Dec. 1973

BC7 High Resolution Ne KLL Auger Spectra Produced by H^+, He^+, and O^{4+} Bombardment.* DENNIS L. MATTHEWS, B. M. JOHNSON, J. J. MACKEY, L. E. SMITH, and C. FRED MOORE, University of Texas at Austin.--The Ne KLL and satellite Auger spectrum has been investigated with an energy resolution of 0.02% FWHM. With 250 keV H^+ bombardment only single 2p vacancy satellite lines are observed. In contrast, 1.0 MeV He^+ bombardment yields many additional lines due to double initial 2p vacancies. Then as expected, 16 MeV O^{4+} bombardment yields many additional satellite lines due to 3 and 4 initial 2p vacancies. Relative intensity and flourescence yield measurements for all observed defect configurations will be discussed.

*Work supported by the U. S. Air Force Office of Scientific Research, the Robert A. Welch Foundation, and the U. S. Atomic Energy Commission.

APS New York Meeting Jan. 1973

GI 12 Anomalous K X-Ray Bands in Fluorine.* C. FRED MOORE, H. H. WOLTER, J. E. BOLGER, R. L. KAUFFMAN, and J. MCWHERTER, University of Texas, Austin, Texas.--Crystals of LiF and CaF_2 were bombarded with proton, alpha, and oxygen beams and the subsequent K X-ray spectrum from fluorine was measured. Except for a group of Kα satellite lines the spectra exhibit two groups of lines at higher energies which cannot be understood in the framework of free atom HFS calculations. With oxygen bombardment these lines as observed are only a factor four less intense than the satellite lines, and they thus represent an important mechanism of excitation and deexcitation. Our present belief is that they are hypersatellite lines of recoil fluorine ions and the calculation need to take into account the electron gas in the crystal.

*Supported in part by the Air Force Office of Sponsored Research and the Robert A. Welch Foundation.

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II. E. Experimental Research in Progress

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1. Nuclear Research in Progress

a. Magnetic Dipole Moment of the $^{20}Ne(2^+, 1.63\ MeV)$ State

(W.J. Braithwaite, D.K. Olsen, A.W. Obst, and C.H. King)

A perturbed angular correlation measurement has been started which should yield the absolute magnitude of the static magnetic dipole moment of the $J^\pi = 2^+$ first excited state in ^{20}Ne at 1.63 MeV. Here a gamma ray is detected from a ^{20}Ne nucleus formed and decayed by the reaction $^{12}C(^{12}C,\alpha)Ne^{20*}_{2+}(\gamma_0)\ Ne^{20}_{gs}$ where only the Ne^{20}_{gs} and the gamma ray are detected.

It is possible in principle to measure the absolute magnetic dipole moments of excited states of light nuclei, with appropriate lifetimes, by using the process of deorientation. Deorientation results from the interaction of the magnetic moment of the nuclear excited state with the hyperfine field at the nucleus due to the surrounding electronic configuration. This interaction changes with time the magnetic substate population of the excited state formed in a nuclear reaction, and thus its effects can be determined by measuring a particle-gamma angular correlation of the de-excitation gamma-ray. In addition to the magnetic moment, deorientation depends upon the lifetime and spin of the nuclear state and the electromagnetic field at the nucleus. Usually knowledge of this field is the main problem in determining the magnetic moment, but for light nuclei situations can be produced where the electromagnetic field can be accurately calculated. In this experiment the Ne^{20} emerges at 0° from the carbon target in a variety of charge states, including--with some probability--bare ^{20}Ne with only one orbital electron. This perturbation de-orients the nucleus in a known fashion, washing out the correlation pattern by an amount that determines the size of the magnetic moment since the lifetime,

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perturbation strength, etc., are known.

Several experimental problems have been encountered in our efforts to measure ^{20}Ne outgoing at 0^{o}, using our double-focussing spectrometer. Two of these problems will be outlined below.

Figure 1 shows two different energy spectra taken with a silicon detector located at the double-focussing point of the spectrometer magnet, for two different settings of the field. The analyzed ions enter the spectrometer at 10^{o} from the 30 MeV ^{12}C-beam that is incident on an enriched ^{12}C target of 50 $\mu gm/cm^2$. Although the only reaction products of interest are ^{20}Ne(+10,+9,+8), several other heavy ions are observed. As indicated in Fig.1, the energy regions for the interesting ^{20}Ne charge states are fairly free of contaminant ions, with the exception of ^{20}Ne(+9) which is difficult to distinguish from ^{16}O(+8). This contaminant is not expected to cause much difficulty in the coincidence spectrum except for a small "true" gamma background. The effects of this background can be investigated by varying the incident beam energy.

The worst experimental problem we encountered was due to "beam tail" that is elastically scattered into the silicon detector located in the double-focussing position of the magnetic spectrometer. Although this tail comes at an energy that distinguishes it from the ^{20}Ne (+10,+9,+8), the counting rate from this process has been extremely high. Pileup rejection has been necessary to remove the "sum peaks" that fall in the energy region of interest and the beam currents have been kept small in order to reduce these effects and to avoid saturation effects in the preamplifier. Although no direct beam can ever hit the pole faces, our tests indicate that small-angle Rutherford scattering onto the pole faces is the main cause of our "beam tail" difficulties. To solve this problem and to improve

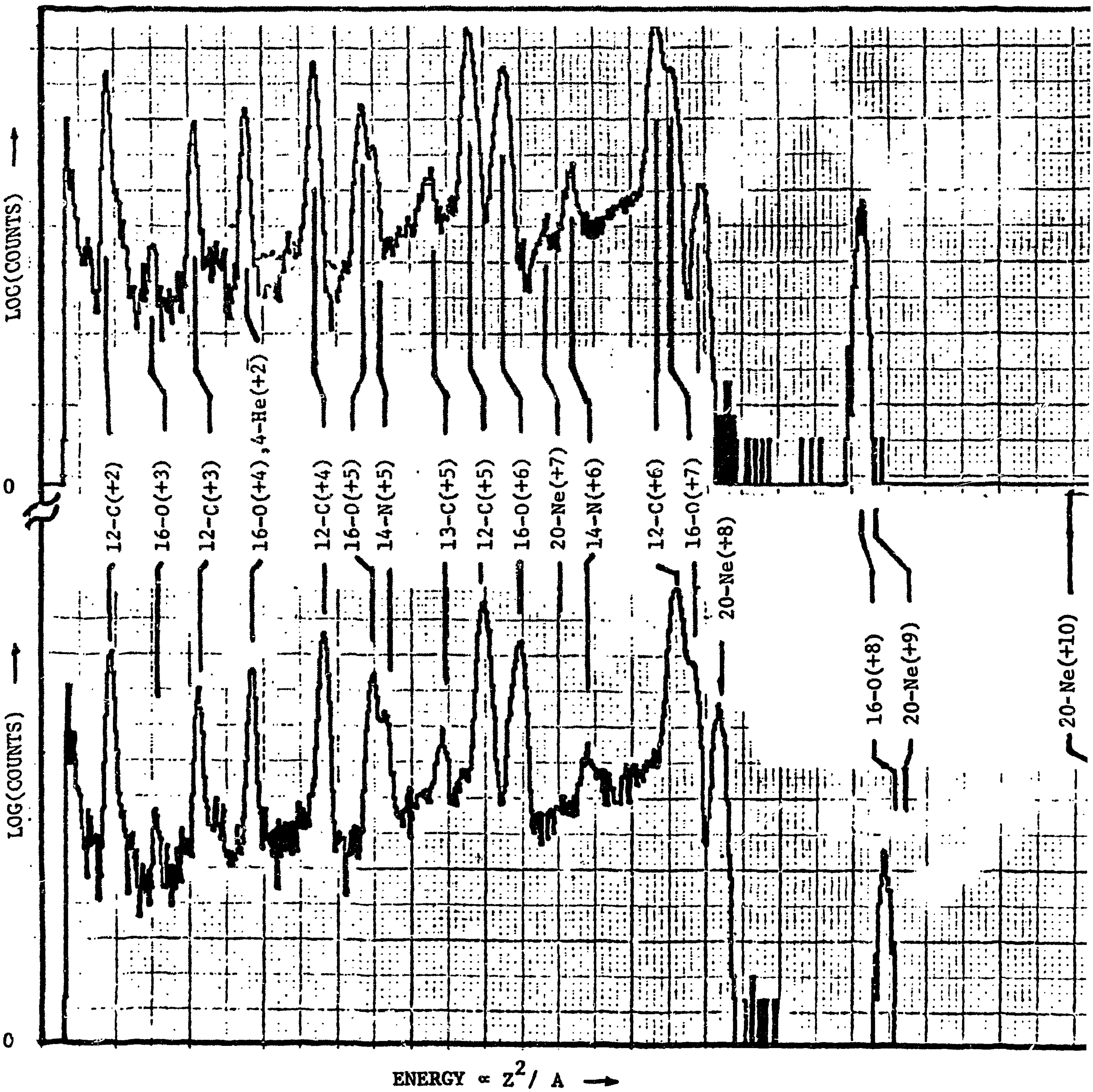

Figure 1 Energy spectra taken at two different field settings show the contributions from several different reaction products. ^{20}Ne(+10) is not seen in these spectra since neither field setting favors this charge state.

our system in general we are presently building a new scattering chamber which includes a carefully designed set of beam-defining apertures and anti-scattering baffles.

It is worth pointing out that for heavy-ion bombardments it is usually not possible, in principle, to avoid some "beam tail" problems when magnet fields are used as the ONLY means to separate the reaction products outgoing at 0^o from the beam. This is because there is always a non-trivial portion of the beam in all possible charge states: $Q/M = 1/A$, $2/A$, ... Z/A. Thus, only particles more rigid than the beam in its $Q/M = 1/A$ state could avoid "beam tail" effects entirely. This condition is impossible to satisfy, except for a few of the very-light ions and only in "luck-Q" reactions, and even for these reactions, when $Z > 1$, the yield of charge state 1 is usually much smaller than that for the higher charge states.

In the $^{20}Ne - \gamma$ coincidence experiment we are measuring de-orientation of the nuclear spin due to the 10^+, 9^+, and 8^+ charge states of ^{20}Ne formed in the reaction $^{12}C + ^{12}C \rightarrow ^{20}Ne$ (2^+, 1.63 MeV) + α at a 30-MeV incident, ^{12}C energy and using the new particle-gamma angular correlation system. Angular distributions are being measured using the magnetic spectrometer set at zero degrees to select ^{20}Ne recoils of selected charge states in coincidence with the de-excitation gamma rays from $^{20}Ne^*(2+)$. De-orientation effects have been investigated for this reaction without charge-state selection.[1] The charge state probabilities for the recoiling ^{20}Ne at zero degrees from 30-MeV ^{12}C on a thin ^{12}C target are 10^+:6%, 9^+:30%, and 8^+:43%.[2] The differential cross section at forward angles for producing the ^{20}Ne, 2^+ state with this reaction is known to be large in this energy region.[3] No deorientation effects should be measured for the gamma-ray angular distribution taken in coincidence with the ^{20}Ne, 10^+, or 8^+ charge states whereas the correlation of the 9^+ charge state should show a strong deorientation effect. From this change in the angular correlation the absolute magnetic moment should be accurately determined using the static magnetic field of a ground-state, hydrogenic, ^{20}Ne atom. If this method is successful magnetic moments of other excited states in the neon region will be investigated.

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[1]M. A. Faessler, B. Borh, and D. Schwalm, Ann. Phys. 63, 577 (1971).
[2]"Nuclear Reaction Analysis, Graphs and Tables", J. B. Marion and F. C. Young, p. 45 (North-Holland, Amsterdam, 1968).
[3]W. J. Courtney and H. T. Fortune, to be published in Phys. Rev. C.

b. The ^{78,80,82}Kr(d,p)^{79,81,83}Kr Reactions

(J. Chao, C. Chang, C. Newson, D. K. Olsen, B. K. Arora, and P. J. Riley)

Very little is known about the level structure of the gaseous Krpton isotopes. As part of a systematic study of these isotopes, ^{78,80,82}Kr (d,p)^{79,81,83}Kr differential cross section measurements are being carried out. These measurements are more difficult than the previous ^{84}Kr(d,p)^{85}Kr (Ref. 1) and ^{86}Kr(d,p)^{87}Kr (Ref. 2) experiments because of the low isotopic enrichment available for the target gas. These enrichments are shown below:

	Kr-78	Kr-80	Kr-82
Kr-78:	56.5%	14.8%	0.2%
Kr-80:	34.2%	50.9%	15.1%
Kr-82:	6.9%	31.8%	76.8%
Kr-83:	1.2%	2.1%	7.7%
Kr-84:	1.1%	0.3%	0.2%

Presently we have measured ^{82}Kr(d,p)^{83}Kr differential cross sections using the 76.8% isotopically enriched ^{82}Kr gas at laboratory angles from 20° to 160° in 5° steps with an incident deuteron energy of 12.0 MeV. A typical pulse height spectrum indicates roughly 30 proton groups from krypton are excited. Identification of proton groups from the ^{83}Kr contaminant in the target gas have been made by comparing these spectra from those produced from material krypton targets (11.55% ^{83}Kr). The excitation energies of the remaining groups are based on the assumption that they are all produced from ^{82}Kr. Spectra produced from the ^{80}Kr target gas will be used to determine the ^{81}Kr proton groups observed in the present measurements. DWBA calculations are being carried out to obtain detailed spectroscopic information. We plan to complete the study of the ^{78,80,82}Kr (d,p)^{79,81,83}Kr reactions using the above gas mixtures.

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[1] C. P. Browne, D. K. Olsen, J. Chao, and P. J. Riley, submitted to Phys. Rev. C.
[2] K. Hazava, C. L. Hollas, P. J. Riley, and W. R. Coker, Phys. Rev. C 1, 938 (1970).

c. The (t,p) Reaction to the Low-Lying Levels of the Even-Even Krypton Isotopes

(D. K. Olsen, P. J. Riley, E. R. Flynn*, N. Stein*, J. D. Sherman*)

The (p,t) reaction provides an excellent spectroscopic tool to study the low-lying levels in even-even nuclei. The transition intensities are very sensitive to the nuclear wave functions of the states involved, and the shapes of the angular distributions provide, in most cases, an unambiguous spin and parity assignment for the final state. The usefulness of this reaction is enhanced when the measurements are performed over a series of isotopes and the trend of the cross sections to particular states are observed. In addition, the (p,t) reaction permits the study of the nucleus two neutrons beyond the last stable isotope. Furthermore, (t,p) measurements compliment (p,p') measurements. Inelastic proton scattering tends to excite the vibrational one-particle-one-hole states, whereas two-particle transfer tends to excite two-particle-two-hole states.

For these reasons we have carried out $^{84}Kr(t,p)^{86}Kr$ and $^{86}Kr(t,p)^{88}Kr$ differential cross section measurements using the Los Alamos Scientific Laboratory triton-beam facility. With an incident triton energy of 17.0 MeV, spectra have been obtained for both isotopes in 6° intervals from 12° to 54°. The target gases were contained in a thin-walled gas cell, and the charged-particle reaction products were momentum analyzed in a broad range magnetic spectrometer and detected by photographic plates.

Although most of these plates are in the process of being scanned, a preliminary $^{84}Kr(t,p)^{86}Kr$ spectrum at 24° allowed us to assign excitation energies and some probable spin.
It appears that the one-phonon, 0^+, pairing vibration in ^{86}Kr is at 3.535 MeV of excitation, whereas the one-phonon, 2^+, pairing vibration is split into two states at 4.106 and 4.185 MeV of excitation. It is planned to extend these (t,p) measurements to the remaining even-even krypton isotopes.

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d. Study of ^{84}Kr and ^{86}Kr from 12.0 MeV Inelastic Proton Scattering

(B. K. Arora, D. K. Olsen, C. Newson, J. Chao, and P. J. Riley)

Differential cross sections for elastic and inelastic proton scattering from ^{84}Kr and ^{86}Kr have been measured. The purpose of this work is to investigate the low-lying collective vibrational states of these nuclei and to help establish their level structure.

A 12.0-MeV proton beam from the EN Tandem Van de Graaff was carefully focused onto the target gas contained in a thin-walled, three-inch-diameter gas cell. The resultant elastic and inelastic proton groups were detected in four detector assemblies which were separated by 20^{o}. Each detector assembly defined a gas-target G-value using the usual two-slit arrangement before the detectors. The G values were typically 5.2×10^{-4} cm, and 2 mm lithium-drifted-silicon solid state detectors were used. An overall energy resolution (full with at half maximum) of roughly 30 keV was obtained with a gas pressure of about ten inches of water. In addition a fixed monitor detector at 110^{o} was employed to help insure consistency in the data.

Spectra were obtained in 5^{o} intervals from 30^{o} to 150^{o} with 90.1% and 99.9% isotropically pure ^{84}Kr and ^{86}Kr gas respectively. Figure 1 shows a typical ^{84}Kr spectrum at 80^{o} and also a spectrum obtained with natural krypton gas at the same angle to facilitate the identification of proton groups from other krypton isotopes. Figure 2 shows a ^{86}Kr spectrum at 120^{o}. Elastic proton groups from oxygen and nitrogen contamination were observed on all spectra. The excitation energies of excited states are shown on the figures.

The ratio-to-Rutherford, elastic differential cross sections for both ^{84}Kr and ^{86}Kr are shown in Fig. 3 where the smooth curves are the best optical model fits to the experimental data. These fits were obtained using the computer code of Smith[1] starting with the average parameters of Perey[2]. The average radii ($r_s=r_I=r_c=1.25$) and spin orbit ($r_{so}=1.25, a_{so}=.65, V_{so}=7.5$) parameters of Perey[2] were held constant and only the real well depth V_o, real diffuseness a_o, surface imaginary well depth W_D, and imaginary diffuseness a_I were allowed to vary. The best fits gave V_o = 53.2 and 53.5, W_D = 14.9 and 10.6, a_o = .646 and .604, and a_I = .467 and .565 for ^{84}Kr and

^{86}Kr respectively with chi-squared per points of about one assuming 3.0% error bars for the experimental data.

Figures 4 and 5 show differential cross sections to the lowest energy 2^+ and 3^- states in ^{84}Kr and ^{86}Kr. From these data deformation parameters β_2 and β_3 have been extracted assuming these states to be one-phonon quadrupole and octupole surface vibrations respectively. Both distorted-wave Born-approximation (DWBA) and coupled-channel (CC) calculations using the computer JUPITER 1[3] were performed. The calculations used the best-fit, optical-model parameters given above with imaginary form factors. Coulomb excitation was not considered. The smooth curves of Figs. 4 and 5 are the DWBA results. They give reasonable fits to the experimental data with β_2 = .131 and .106 for the 2^+ states and β_3 = .157 and .142 for the 3^- states for ^{84}Kr and ^{86}Kr respectively.

The CC calculations were more complicated; however, they gave almost identical fits and deformation parameters as the DWBA calculations. A $0^+ - 2^+ - 3^-$ coupling was considered, and again the best-fit optical model parameters were used. However, with CC part of the imaginary absorption for the elastic channel is implicitly accounted for by the coupling to the excited 2^+ and 3^- states. Hence we found that for CC a reduction of the surface imaginary well depth by 13% and 12% respectively for ^{84}Kr and ^{86}Kr almost exactly reproduced the simple optical-model fit to the elastic data. With this procedure we obtained deformation parameters for ^{84}Kr and ^{86}Kr respectively of β_2 = .128 and .105 and β_3 = .155 and .142. Furthermore the CC fits to the 2^+ and 3^- differential cross sections are almost identical to those shown in Figs. 4 and 5.

Presently CC calculations are being performed to fit the "two phonon" states in ^{84}Kr and ^{86}Kr. Furthermore, it is hoped that the shape of the angular distributions to many of the higher excited states will allow

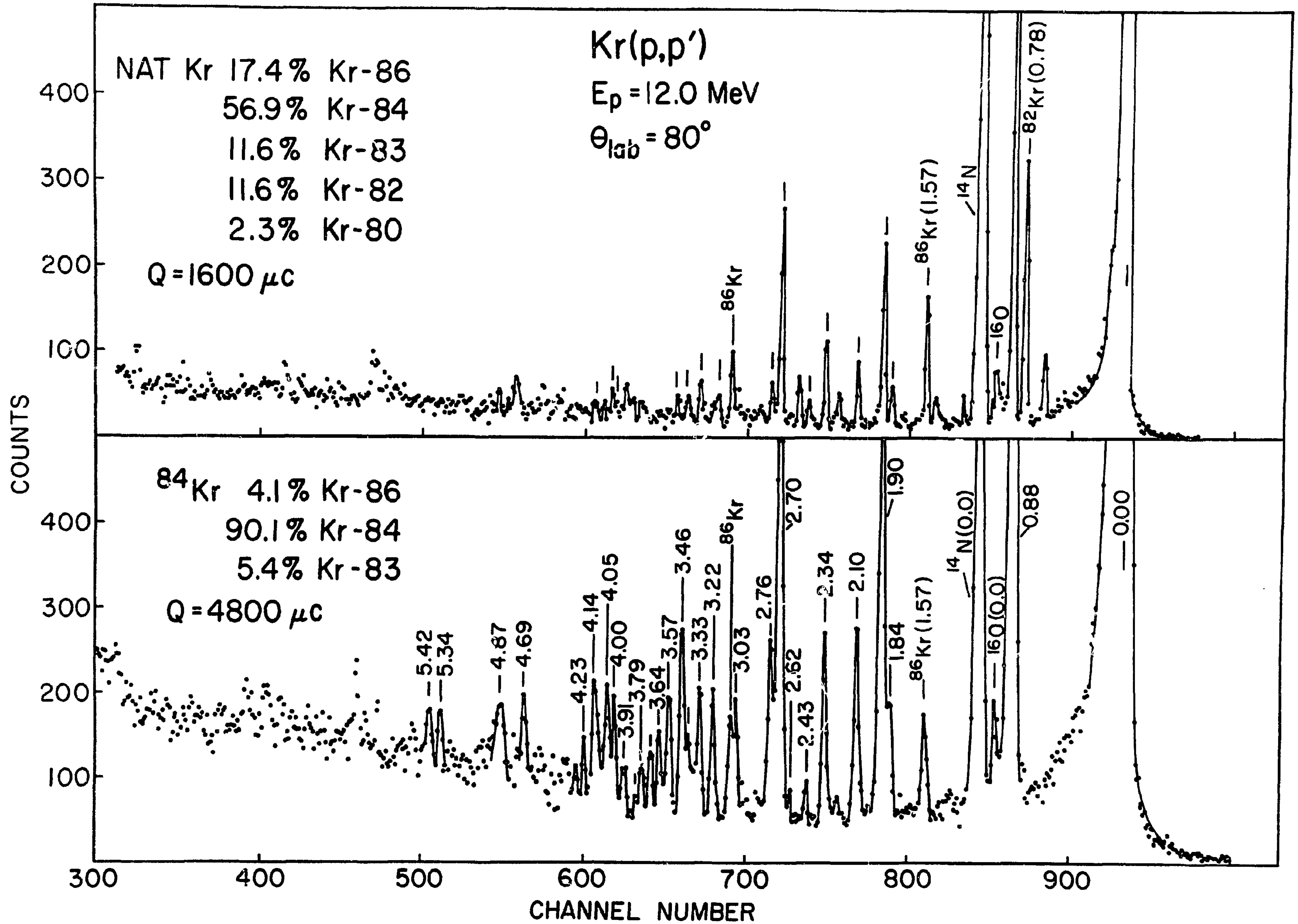
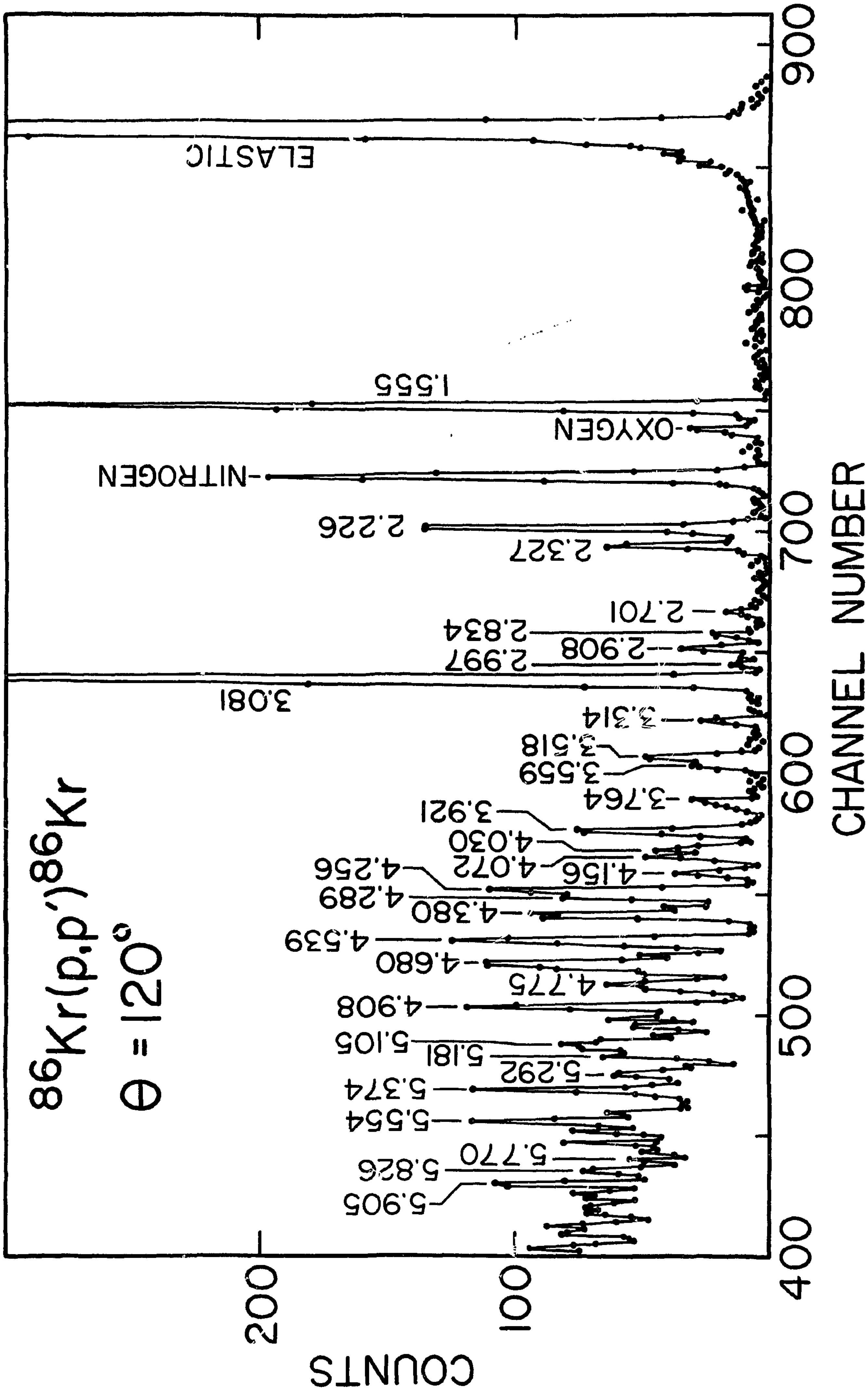

Kr(p,p′)
E_p = 12.0 MeV
θ_{lab} = 80°
NAT Kr 17.4% Kr-86
56.9% Kr-84
11.6% Kr-83
11.6% Kr-82
2.3% Kr-80
Q = 1600 μc
^{84}Kr 4.1% Kr-86
90.1% Kr-84
5.4% Kr-83
Q = 4800 μc
COUNTS
CHANNEL NUMBER
^{86}Kr
^{86}Kr (1.57)
^{14}N
^{16}O
^{82}Kr (0.78)
5.42
5.34
4.87
4.69
4.23
4.14
4.05
4.00
3.91
3.79
3.64
3.57
3.46
3.33
3.22
3.03
2.76
2.70
2.62
2.43
2.34
2.10
1.90
1.84
^{14}N (0.0)
^{16}O (0.0)
0.88
0.00

Figure 1



$^{86}Kr(p,p')^{86}Kr$
$\Theta = 120°$
COUNTS
100
200
CHANNEL NUMBER
400
500
600
700
800
900
5.905
5.826
5.770
5.554
5.374
5.292
5.181
5.105
4.908
4.775
4.680
4.539
4.380
4.289
4.256
4.156
4.072
4.030
3.921
3.764
3.559
3.518
3.314
3.081
2.997
2.908
2.834
2.701
2.327
2.226
NITROGEN
OXYGEN
1.555
ELASTIC

Figure 2

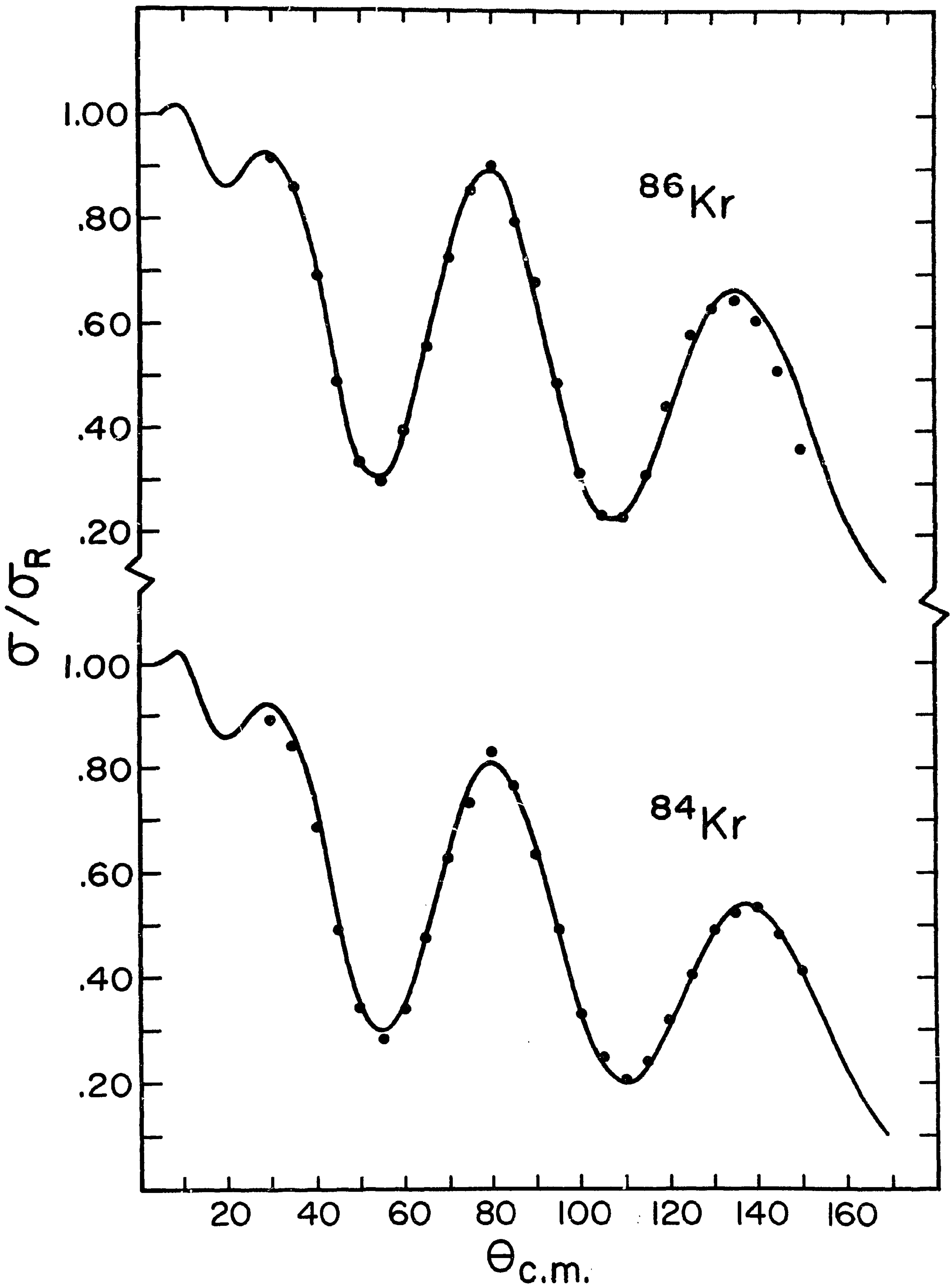
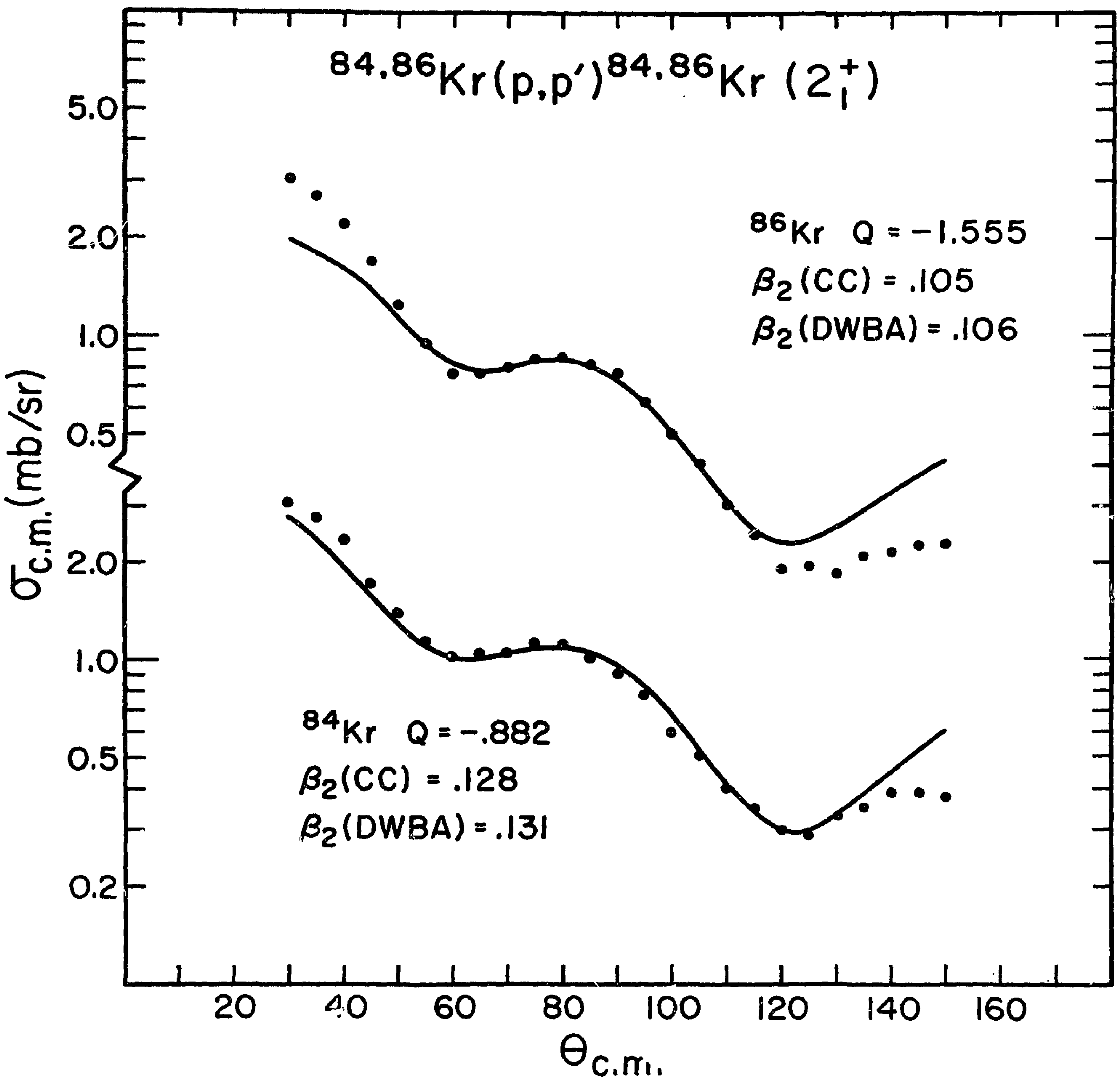
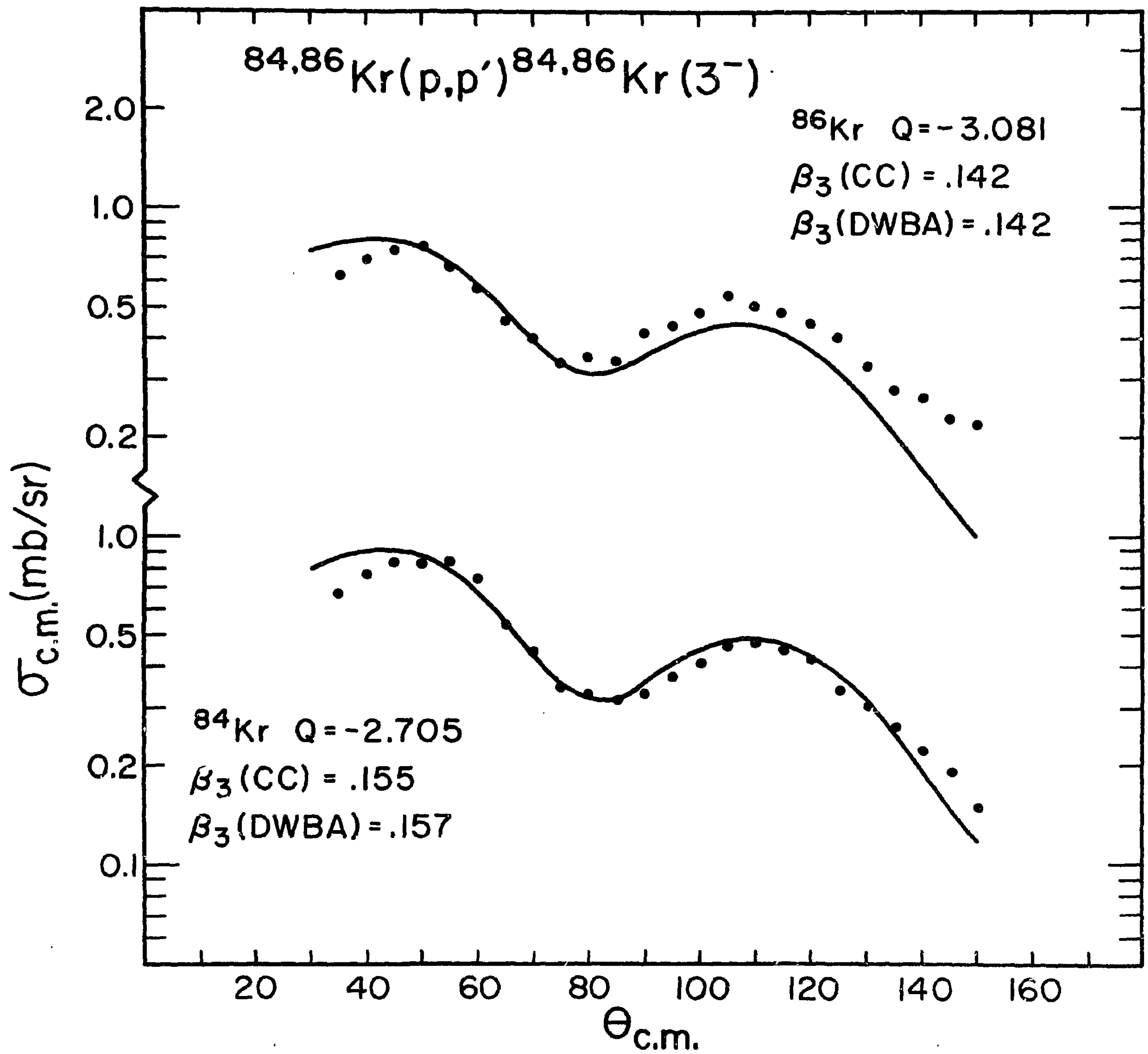

1.00
.80
.60
.40
.20
^{86}Kr
σ/σ_R
1.00
.80
.60
.40
.20
^{84}Kr
20
40
60
80
100
120
140
160
$\Theta_{c.m.}$

Figure 3



$^{84,86}Kr(p,p')^{84,86}Kr\ (2_1^+)$
^{86}Kr Q = −1.555
β_2(CC) = .105
β_2(DWBA) = .106
^{84}Kr Q = −.882
β_2(CC) = .128
β_2(DWBA) = .131
$\sigma_{c.m.}$(mb/sr)
$\theta_{c.m.}$
5.0
2.0
1.0
0.5
2.0
1.0
0.5
0.2
20
40
60
80
100
120
140
160

Figure 4



$^{84,86}Kr(p,p')^{84,86}Kr(3^-)$
^{86}Kr Q=-3.081
β_3(CC) = .142
β_3(DWBA) = .142
^{84}Kr Q=-2.705
β_3(CC) = .155
β_3(DWBA) = .157
2.0
1.0
0.5
0.2
1.0
0.5
0.2
0.1
$\sigma_{c.m.}$(mb/sr)
20
40
60
80
100
120
140
160
$\Theta_{c.m.}$

Figure 5

the spins and parities of these states to be established.

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[1]W. R. Smith, Comput. Phys. Commun. 1, 198 (1969).
[2]F. G. Perey, Phys. Rev. 131, 745 (1963).
[3]T. Tamura, Rev. Mod. Phys. 37, 679 (1965).

e. Single-Neutron States Near Zero Separation Energy

(G. W. Hoffmann, W. R. Coker, J. McIntyre, M. Mahlab, H. Newson, and P. J. Riley)

Using a quadrupole mass spectrometer, described elsewhere, we are studying states of nuclei in the mass 40 and 90 region which lie in the vicinity of zero neutron separation energy, and which have an appreciable component of single-neutron-plus-core configuration. These states are studied via the (d,p) reaction, using the mass spectrometer to remove deuterons without affecting resolution, and offer a unique complement to earlier (n,γ) studies on the same nuclei. The experimental resolution attained is at present 13 keV or better for outgoing protons of 6 to 8 MeV, which proves to be sufficient to pick out the most strongly populated states. Information concerning this region of excitation is necessary to complete our detailed picture of nuclear structure in the most widely studied regions since it fills the gap between the low lying levels studied by conventional direct reaction experiments and neutron strength function data from thermal neutron studies.

The biased magnetic quadrupole spectrometer has been used to study (d,p) stripping to highly excited and neutron-unbound states in ^{31}Si, ^{41}Ar, ^{95}Zr and ^{97}Zr at E_d = 10.0 MeV. Many new levels and resonances have been observed, and angular distributions are in the process of being extracted. Fig. 1 and 2 present some typical spectra. The angular distributions for the unbound states will be analyzed via DWBA using complex energy eigenstates (Gamow states) to provide single particle resonance state functions.

In the earlier study of gaseous targets the particle groups seen at forward angles were difficult to resolve due to the large number of elastically scattered particles observed. In order to conduct studies at forward angles it became necessary to remove the elastically scattered particles. We have been successful at doing this for solid and gas targets using the quadrupole spectrometer. In a (d,p) reaction the deuterons are focused at different points than protons of the same energy. Thus the detector will see only proton reaction products at that energy, when the system is correctly baffled.

In order to accommodate gas targets a larger scattering chamber was designed and built. It has the capabilities to study solid and gaseous targets. In addition, the additional size allows coincidence techniques to be used. Space for more efficient Faraday cups is also available.

f. A New Method for Spin Determinations Using Heavy-Ion-Alpha Angular Correlations

(W. J. Braithwaite and J. G. Cramer)

This new method was reported briefly in last year's progress report; however, it was only a few months old at that time. Our understanding of just how this method works has become considerably more detailed during the past year. Some of our findings have been reported[1] already, so we will concentrate in this report on the new ideas that are not in print at the present time. Thus, the present account is given with the assumption that the reader is somewhat familiar with the results that have been published already.

Briefly reviewing, this method requires that all the particles entering both the formation reaction and the sequential-decay reaction are zero-spin bosons, except for the recoiling nucleus (J^{π}) that subsequently decays (see Figure 1). For definiteness it will be assumed that heavy ions are used to induce the formation reaction and that the excited nucleus decays by alpha emission. The correlation function[2] describing the alpha emission may be written as follows in terms of the nuclear substate population amplitudes $\{a_M^J\}$ and the rotation matrix elements $\{e^{-iM\Phi}\, d_{M0}^J(\Theta)\}$ where Θ and Φ are angular coordinates in the recoil center-of-mass system.

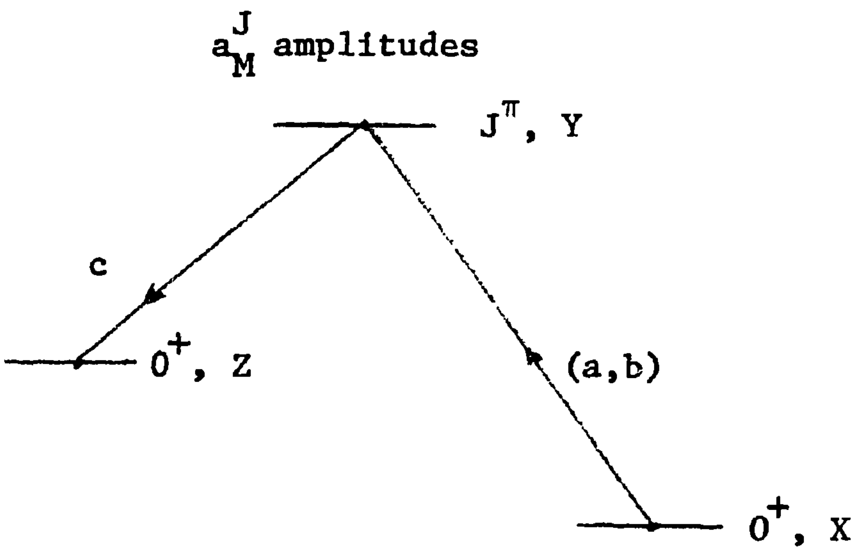

Figure 1 Schematic of the Reaction X(a,b)Y(c)Z.

$$W_J(\Theta,\Phi) = |\Sigma\, a_M^J\, e^{-iM\Phi}\, d_{M0}^J(\Theta)|^2,$$

where J + M = even.

It has been shown[1] that this expression may be written approximately as follows for a particular FIXED choice of $\Theta = \Theta_{ave}$. [Figure 2 shows the validity of this approximation for the case of J = 4.]

$$W_J(\Theta_{ave},\Phi) \simeq |a_J^J\, e^{-iM\Phi} \pm a_{-J}^J\, e^{iM\Phi}|^2\, [d_{M0}^J(\Theta_{ave})]^2$$

This expression, which is a function of Φ only, will differ from a CONSTANT value ONLY if BOTH $A_J \propto |a_J^J|$ and $A_{-J} \propto |a_{-J}^J|$ are non-zero. This is because if either is zero the Φ-dependence becomes part of the overall (unobservable) phase. One might want to view this condition conceptually as a "beat" between the decay radiation from the M = +J and M = -J substates.

Expanding the correlation function in terms of A_J and A_{-J} leads to the following expression:

$$W_J(\Phi) \approx (A_J - A_{-J})^2 + 4\, A_J\, A_{-J}\, \sin^2[J\Phi - \delta].$$

Once again it is easy to see that if either A_J and A_{-J} is zero, the correlation function is isotropic.

The condition that Θ be fixed in the recoil-center-of-mass (RCM) results in the approximate condition $\theta \approx$ constant in the laboratory if the corresponding correlation points in ϕ are taken in the rough vicinity of the recoil direction, providing that the outgoing (formation) particle is emitted in the forward direction. For definiteness, consider the following rather extreme example: 36-MeV ^{12}C is inelastically scattered from ^{12}C exciting its 14.08 MeV state. If its spin is 4, then the correlation should be taken for $\Theta = 68.9^{\circ}$ (RCM). For ϕ angles in the rough vicinity of the recoil direction, this results in the approximate laboratory condition that $\theta \approx 76.4^{\circ}$. This laboratory angle is correct to within $\pm 0.5^{\circ}$ for a 55° range in ϕ (LAB) and for a 90° range in Φ (RCM) around the recoil direction, when the inelastically scattered ^{12}C is emitted at 15° (LAB) from the beam direction.

We found this approximate constancy of θ (LAB) surprising at first because we had expected a much greater kinematic distortion from the RCM $\rightarrow$ LAB when the projectile and target have equal masses. Despite the large excitation energy, little kinetic energy is given to the recoiling (excited) carbon nucleus as a result of the inelastically scattered projectile in the forward direction. Thus, the subsequent alpha decay is from a slow moving nucleus and the kinematic distortion in $\Theta \rightarrow \theta$ is reduced. However, the remarkable insensitivity of θ to varying values of ϕ must partly reflect the fact that when θ is not too far from 90°, the small out-of-plane momentum component of the decaying alpha is nearly proportional to the large in-plane component, for ϕ angles in the rough vicinity of the recoil direction.

An array of 12 alpha detectors has been assembled in order to perform the experiment given as the example in the above two paragraphs. This array is discussed in another section of this report where a photograph of the array is shown. From this picture one can see that the (LAB) θ angle varies quite slowly with ϕ.

The value of Θ to be used in the angular correlation depends on the spin (J) of the state being measured. Table I lists the $\Theta = \Theta_{ave}$ values that should be used for spin values up to 16. Figure 3 shows graphically the dependence of Θ_{ave} on J where we see that as $J \to \infty$, $\Theta_{ave} \to 90^{o}$. That is, as J increases the decay particle detector moves closer-and-closer to being in plane. For the region of ϕ in the general direction of the recoil, the decaying alpha is pushed even closer to the reaction plane by the forward motion of the recoiling (parent) nucleus.

In the following remarks, we would like to comment on how we expect this new method to compare with the well-known method of Litherland and Ferguson[3]. In making these comparisons we will refer to Table II where BC Geometry refers to our correlation method and LF Geometry refers to the correlation method of Litherland and Ferguson.

1. Using our method (BC), the experimenter has a choice of angles at which to place the outgoing particle detector for the PRODUCTION reaction (e.g. it can be set at the maximum of the production differential cross section). This is in contrast to the LF Method where only 0^{o} or 180^{o} are allowed for the production angle.
2. Smaller detector solid angles are required for BC than for LF, since the competing substates enter LINEARLY with $\Delta\Omega$ for BC in contrast to LF where they enter QUADRATICALLY (providing the production detector has circular symmetry). As a result, $\Delta\Omega$ must be drastically reduced for BC detectors compared to that permissible for LF detectors. This reduces

the counting rate and with it much of the advantage gained from setting the production angle at the angle of maximum counting rate (#1). There are some small advantages, however, in using a much smaller $\Delta\Omega$. For example, this reduces the kinematic broadening troubles for BC compared with those encountered by LF, since the latter uses large decay-counter solid angles. As a further plus, the BC method does not require exact circular symmetry in either the formation or decay detectors, as does LF. Relaxing this condition is convenient experimentally.

3. The correlation function for LF has NO useless fitting parameters, since for LF the "A" is determined from $N_{singles}$, Γ/Γ_{tot}, the detector geometry and the kinematics. In contrast, BC requires 3 fitting parameters other than the FREQUENCY of the oscillation pattern (which determines the spin).
4. BC fails if either the M = +J or the M = -J substate is not populated appreciably. LF only requires a non-trivial M = 0 population (of course using a different quantization axis).
5. A model calculation for use in the experimental design is more likely to be meaningful for BC than for LF, since the BC permits the outgoing production angle to be chosen by the experimenter. This angle is likely to be chosen at a point where the production differential cross section is a maximum, the model calculations are apt to be sufficiently reliable for design purposes.
6. The BC requirement that the correlation be taken at $\Theta = \Theta_{ave}$ is fairly inconvenient since this angle depends on the spin of the state. However, it is usually possible to make an educated guess at the J. If the guess is wrong, the correlation function will be strongly modulated in angle. Even so, the oscillation frequency is still a pretty good indication of the spin of the state, so the correlation can be retaken at the appropriate Θ.

It should be noted that the spin dependence of Θ is a fairly slow function of J.

7. When the reaction $T(\alpha, \alpha')T^*(\alpha_o)R$ is used to determine the spin of T^* there can be a confusion due to the identical properties of the outgoing alphas. To analyze this problem, define det#1 as meant for detecting α' and det#2 as meant for detecting α_o. For example, if $^{12}C(\alpha,\alpha')$ $^{12}C^*(\alpha_o)^8Be_{gs}$ were studied with det#2 at 180^o and det#1 at some forward angle, the reversal of emission order corresponds to inelastic scattering to a much higher excited state of ^{12}C which in turn decays to the $^8Be_{gs}$. This can lead to identical energies in the respective detectors as that for the reaction of interest. Since, in this example, both density-of-states considerations and reaction systematics favor inverting the desired order of emission, this measurement would be plagued severly by a "reverse-reaction" background. This problem is reduced for the BC method since the outgoing (formation) angle may be chosen at a forward angle where the differential cross section is maximum and the "forward-reaction" is enhanced over the "reverse reaction".

8. A spectrometer magnet is needed for the LF method at 0^o except for those few cases where a degrader foil may be used to effect separation. A spectrometer or an annular detector is needed by the LF method when the production particle exits at 180^o. In contrast, the special equipment needed for BC measurements will be less demanding than for LF, except for a few special cases.

9. Subject to the restriction that all reaction particles (except for the excited nucleus) are zero spin bosons, unnatural parity states cannot be studied using either BC or LF methods. Thus, all spin measurement carry with them an implicit parity determination. The interdict against unnatural parity states is due to the parity selection rule that forbids

a J^{π} state with $\pi = (-1)^{J+1}$ to decay to a 0^+ state by emission of a 0^+ projectile, since the spin J must all be removed by the orbital angular momentum. As a result, both methods forbid unnatural parity states in the decay channel. In addition to this, the formation channels of the LF system are parity forbidden to unnatural parity states since the formation particle must leave in a direction parallel to the beam (0° or 180°). Although hindered, unnatural parity states may be formed in BC reactions. Recently the Pennsylvania group[4] has pointed out that in the alpha-decay to the 2^+ state it may often be true that the $L = J - 2$ partial wave completely dominates, in which case a spin assignment can be made. If a similar extension can be made to the BC method, then unnatural parity states can be studied since they were forbidden only in the decay channel due to the final state being 0^+.

In closing, it is worth pointing out that in the comparisons made above, the new method of spin determinations was found to follow sufficiently different rules as to complement rather than compete with the method of Litherland and Ferguson.[3]

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[1] W. J. Braithwaite and J. G. Cramer, Phys. Rev. Letters 31, 401 (1973); ibid, Proc. of the Int'l Conf. on Nucl. Phys., Vol. 1, Edited by J. de Boer and H. J. Mang, (North Holland Publ. Co., Amsterdam and Am. Elsevier Pub. Co., N. Y., 1973) p. 238; ibid, Bull. Am. Phys. Soc. 18, 921 (1972).

[2] J. G. Cramer and W. W. Eidson, Nucl. Phys. 55, 593 (1964).

[3] A. E. Litherland and A. J. Ferguson, Can. J. Phys. 39, 788 (1961).

[4] D. P. Balamuth, J. E. Holden, J. W. Noé, and R. W. Zrumühle, Phys. Rev. Letters 26, 795 (1971); R. W. Zrumühle, D. P. Balamuth, L. K. Field and J. W. Noé, Phys. Rev. Lett. 29, 795 (1972); L. K. Fifield, R. W. Zurmühle, D. P. Balamuth, and J. W. Noë, Proc. of the Int'l Conf. on Nucl. Phys., Vol. I, Edited by J. de Boer and H. J. Mang, (North Holland Publ. Co., Amsterdam and Am. Elsevier Publ. Co., N. Y., 1973) p. 168.

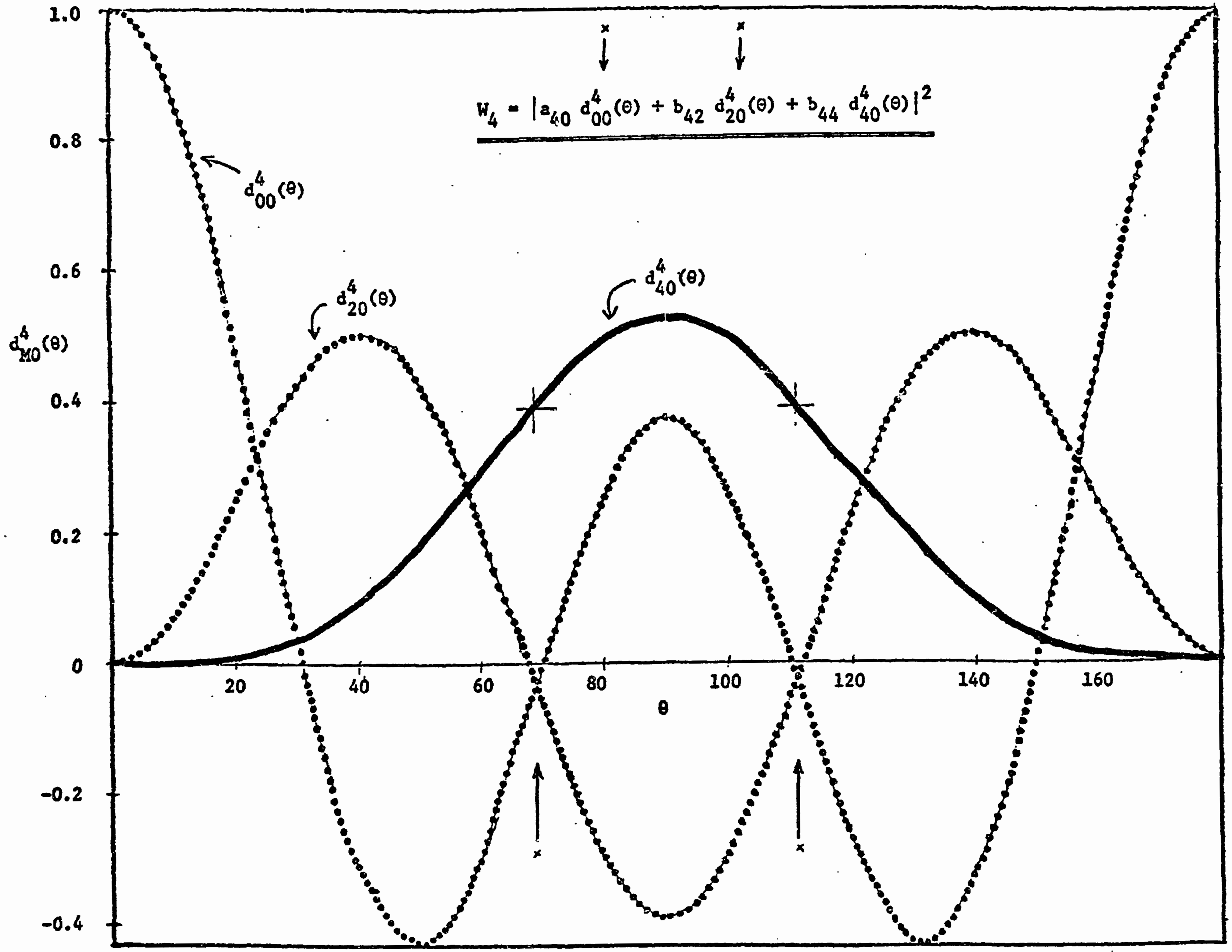

Figure 2 Nearly coincident root angles for the reduced rotation matrix elements of J=4, |M| <4.

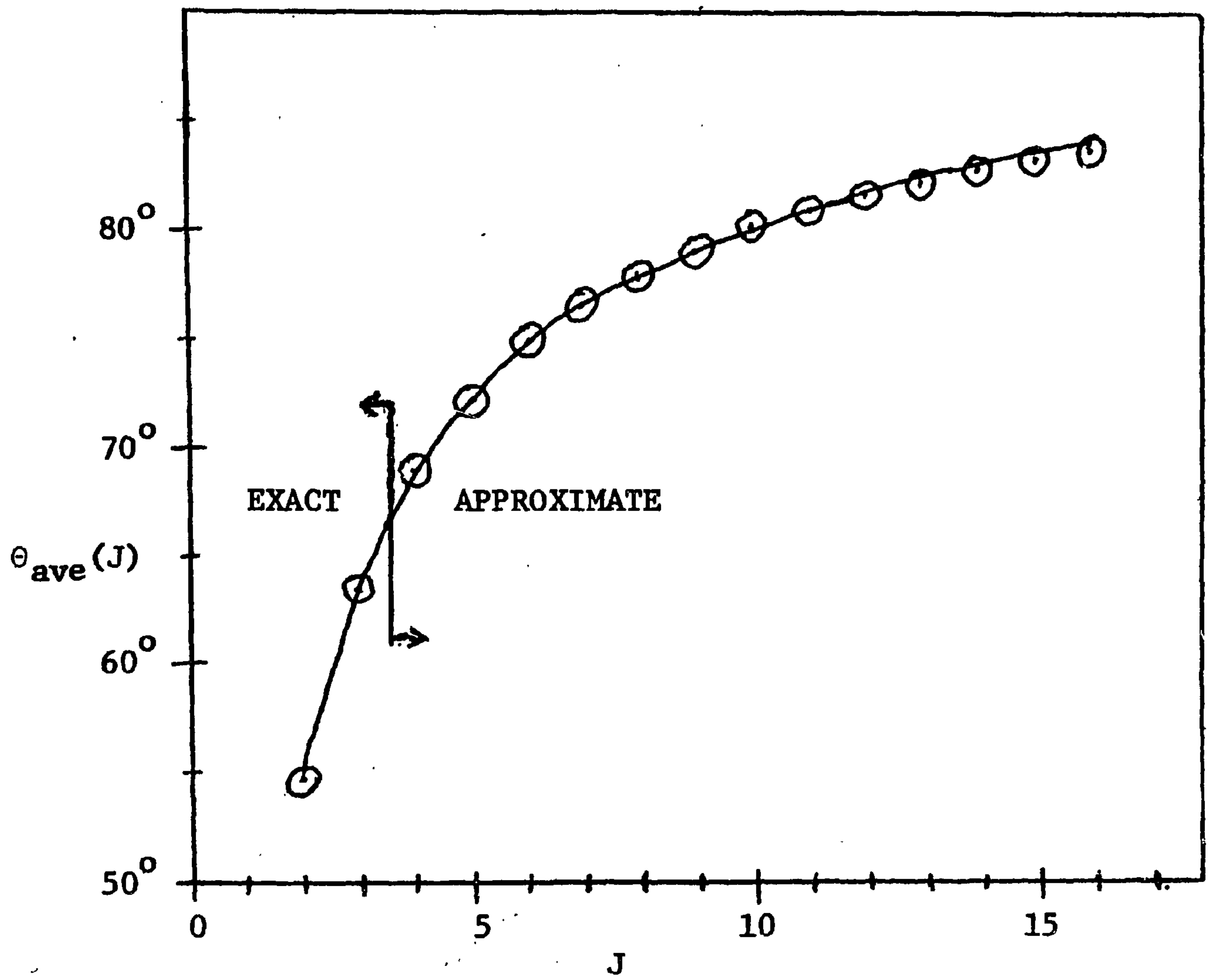

Figure 3 The J-dependence of the average root angle of $d^J_{M0}(\Theta)$, for $|M| < J$.

Table I. Root Angles [Θ(M)]

J^π	M=0/1	M=2/3	M=4/5	M=6/7	M=8/9	M=10/11	M=11/12	M=13/14	Θ_{ave}
0^+	-	-	-	-	-	-	-	-	-
1^-	-	-	-	-	-	-	-	-	-
2^+	54.7°	-	-	-	-	-	-	-	54.7°
3^-	63.4°	-	-	-	-	-	-	-	63.4°
4^+	70.1°	67.8°	-	-	-	-	-	-	68.9°
5^-	73.4°	70.5°	-	-	-	-	-	-	72.1°
6^+	76.2°	75.5°	72.5°	-	-	-	-	-	74.8°
7^-	77.9°	76.9°	73.9°	-	-	-	-	-	76.3°
8^+	79.4°	79.1°	78.0°	75.0°	-	-	-	-	77.8°
9^-	80.5°	80.0°	78.9°	76.0°	-	-	-	-	78.9°
10^+	81.4°	81.3°	80.7°	79.6°	76.7°	-	-	-	80.1°
11^-	82.2°	81.9°	81.3°	80.1°	77.4°	-	-	-	80.7°
12^+	82.8°	82.7°	82.4°	81.8°	80.6°	78.0°	-	-	81.5°
13^-	83.3°	83.2°	82.8°	82.2°	81.1°	78.5°	-	-	82.0°
14^+	83.8°	83.7°	83.6°	83.2°	82.6°	81.4°	78.9°	-	82.6°
15^-	84.2°	84.1°	83.9°	83.5°	82.9°	81.8°	79.3°	-	83.0°
16^+	84.6°	84.5°	84.4°	84.2°	83.8°	83.1°	82.1°	79.7°	83.5°

Table II. A summary of the comparisons between the new method for spin determinations (BC) and the well-known method of Litherland and Ferguson (LF).

	BC Geometry	LF Geometry
1. Production Reaction Angle	Angle may be chosen by experimenter (e.g. to make $d\sigma/d\Omega$ = max)	Angle = 0^{o}, 180^{o}
2. Competing Substates (with $\Delta\Omega$)	Enter Linearly (Axially Symm. Detector NOT Required)	Enter Quadratically (Axially Symm. Detector Required)
3. Correlation Function (Frequency J	$A + B \sin^2(J\phi - C)$	$A[P_J(\cos\phi)]^2$
4. FAILURE Condition	if either $M = +J$ or $M = -J$ is not populated appreciably	if $M = 0$ is not populated appreciably
5. Experimental Design	Model calculations are usually more reliable at maximum $d\sigma/d\Omega$	Production Angle = 0^{o}, 180^{o}
6. Dependence on θ	θ must be fixed at $\bar{\theta}(J)$, which depends weakly on J	independent of θ
7. Identical particles (for production & decay)	Suppresses the effect of "reverse reactions" since $d\sigma/d\Omega$ = maximum	may be swamped by "reverse reactions"
8. Special Equipment	particle goniometer or position-sensitive detector	Magnet or Annular Detector (or lucky reaction)
9. Un-Natural Parity States	Forbidden in decay only	Forbidden in both formation and decay

g. Detection of ^{8}Be Outgoing in a Nuclear Reaction

(W. J. Braithwaite, A. W. Obst, C. H. King, and C. R. Doss)

A large amount of experimental work employing four nucleon transfer reactions has been carried out recently in order to determine whether quartet configurations play an important role in the description of high-lying nuclear states. Several different four-nucleon transfer reactions have been invoked, but in a recent review, Robson[1] has concluded from parentage considerations that the most promising of these reactions is (^{12}C, ^{8}Be).

Although detection of ^{8}Be has been pioneered by several groups[2] some years ago before the recent interest in possible quartet structure, it was not until recently[3,4,5] that ^{8}Be detection appeared likely to become a standard laboratory technique. This is partly due to the greater ease with which outgoing ^{8}Be products can be detected when formed in heavy ion reactions as compared with light ion reactions which give a much smaller momentum to the outgoing ^{8}Be for the same incident kinetic energy.

We have just finished construction of an array of 16 rectangular detectors that will be used to measure the kinetic energy of ^{8}Be from the sum energy of adjacent detector pairs that are taken in fast coincidence and subjected to the side-condition that the energy deposition in each be nearly equal.

Figure 1 is a photograph of the 16-detector array, where each detector is mounted on a copper holder which has been bent into an arc so that each detector is separated from its nearest neighbors by 5^{o}. This configuration results in a detector array spanning 75^{o}, with a sampling taken in the differential cross section every 5^{o}. At present we are using this detector to study only those reactions leading to the ^{8}Be ground state. Thus, only adjacent detector pairs are taken in coincidence and some of the circuit complication described by Cramer _et al_[4] has been done away with.

A program for calculating the efficiency for ^{8}Be detection from a coincident measurement of each alpha-pair is described in the PROGRAM

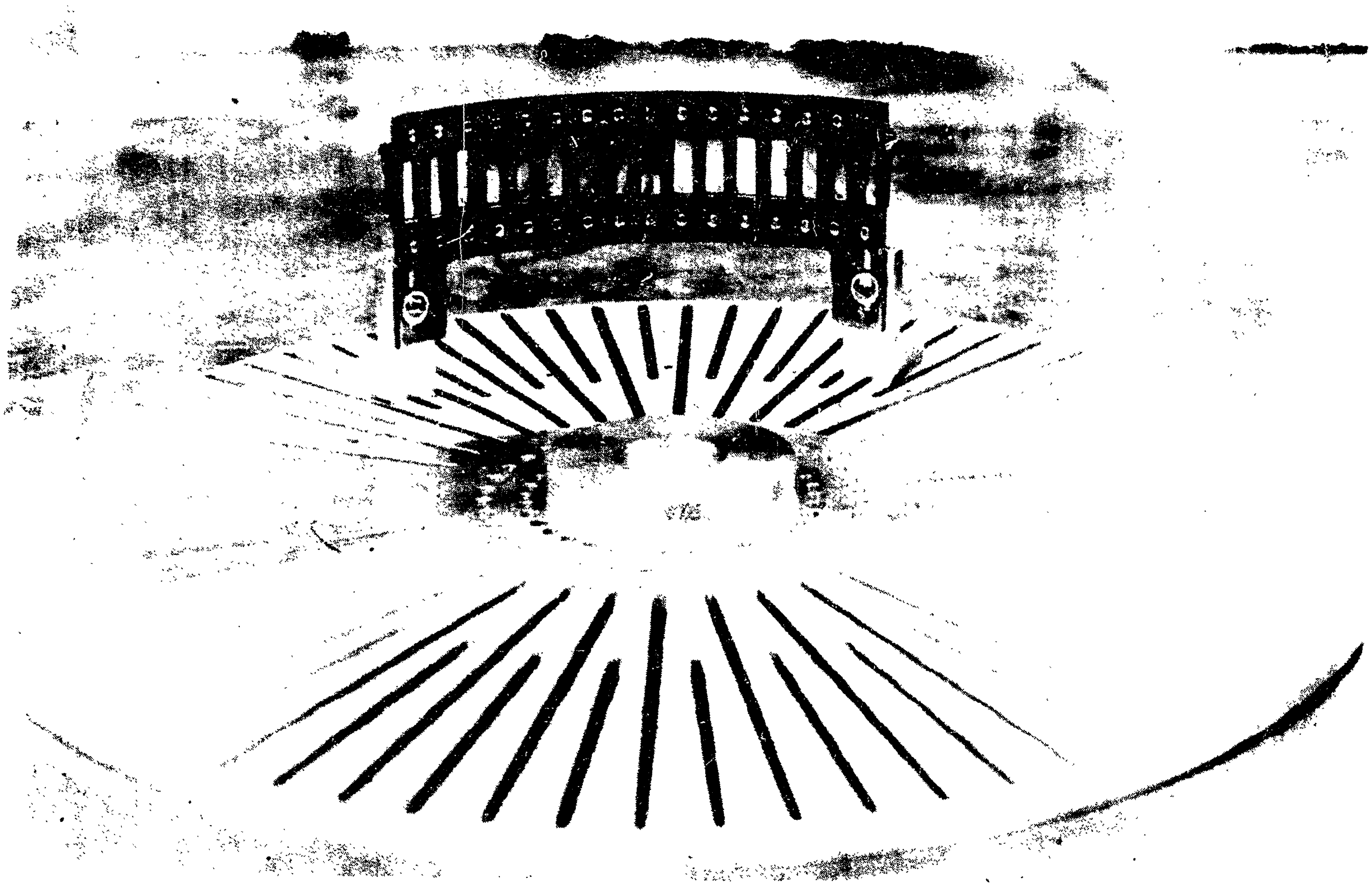

Figure 1 Photograph of the 16-detector array for identifying and measuring the kinetic energies of ground-state ^8Be's outgoing in nuclear reactions.

DIRECTORY section of this year's Annual Report.

In addition to constructing a 16-detector array following the ideas of Cramer, et al (for their 8-detector array), we have constructed a ΔE-E detector telescope that combines ideas due to Cramer et al and Wozniak et al. This telescope uses a commercial 25 μ ΔE-detector with an E' detector that is split into two independent adjacent semicircular active areas. Although this system will provide the extra condition of particle identification (and automatic rejection of all single-particle events such as ^7Li) it is at considerable cost in counting rate, since an array of 16 telescopes is not possible without roughly tripling the number of independent silicon detectors, with a corresponding increase in the electronic complication.

This device is being built to see experimentally just what problems arise from ignoring the extra condition of "particle identification". Perhaps the coincident requirement invoked between adjacent detector pairs and the stringent kinematic requirement that E'_{left} be roughly equal to E'_{right} (see Figure 2) are sufficiently restrictive to "identify" ^8Be without the additional complications implicit in using detector telescopes. Not only is there a strong "kinematic focussing"[7] (due to the low breakup energy of ^8Be into two alphas) to favor the sweeping of the two ^8Be alphas into adjacent detectors but none of the likely candidates[7] for sequential decays will satisfy the stringent kinematic conditions that both the kinetic energy and the time of flight be roughly the same for each detector. In any event, this device is an improvement over the telescope described by Wozniak et al (even if the improvements outlined by Scott[6] are taken into account) since their device (unlike ours) admits a $^8Be^*$ contaminant with kinematic-geometric efficiency of abut 4% that of $^8Be_{gs}$. However, kinematics and geometry don't tell the whole story. A reaction rate that strongly favors the $^8Be^*$ would result in a much larger contamination of the excited beryllium than is expected by efficiency considerations alone.

Two improved detection systems are being considered for possible future use. Of these two systems, the most radical one involves the construction of a pair of long rectangular positron sensitive detectors. These two detectors are stacked, one above the other, so that each one of the alphas from $^{8}Be_{gs} \rightarrow 2\alpha$ enters a separate detector. Since both in-plane POSITION as well as energy is measured for EACH alpha, the in-plane emission angle for ^{8}Be can be determined. As a result, an angular distribution can be taken over a large angular range. In addition, there are no kinematic broadening problems and the electronic system is less complicated than that for the 16-detector array. Further, the $^{8}Be^{*} \rightarrow 2\alpha$ is much easier to unravel for this pair of vertically-stacked position-sensitive detectors than it is for the array.

The large area detectors being considered for this application are described in another section of this report entitled: "A New Type of Position Sensitive Detector".

The other improved detection system under consideration is only good for $^{8}Be_{gs} \rightarrow 2\alpha$. It involves a modification of the existing 16-detector array. At present, the ^{8}Be resolution is poor due to kinematic broadening. A first-order correction to the kinematic broadening is possible with only a slight complication of the present system. This can be done by making EACH detector in the array POSITION SENSITIVE by replacing the conducting layer on the reverse side of each detector by a surface layer with sufficient resistivity to provide good charge division. Thus, both an E and an Ex signal are taken from each detector. A first order correction to to the kinematics may be provided ELECTRONICALLY by adding a slightly <u>different</u> fraction of the Ex signal to the E signal for <u>each</u> detector, since $\Delta E = \frac{\partial E}{\partial \theta} \Delta\theta \approx Ex\ f(\theta)$ and each detector is at a different angle. [N.B. Although the detectors in the array are higher than they are wide, charge-

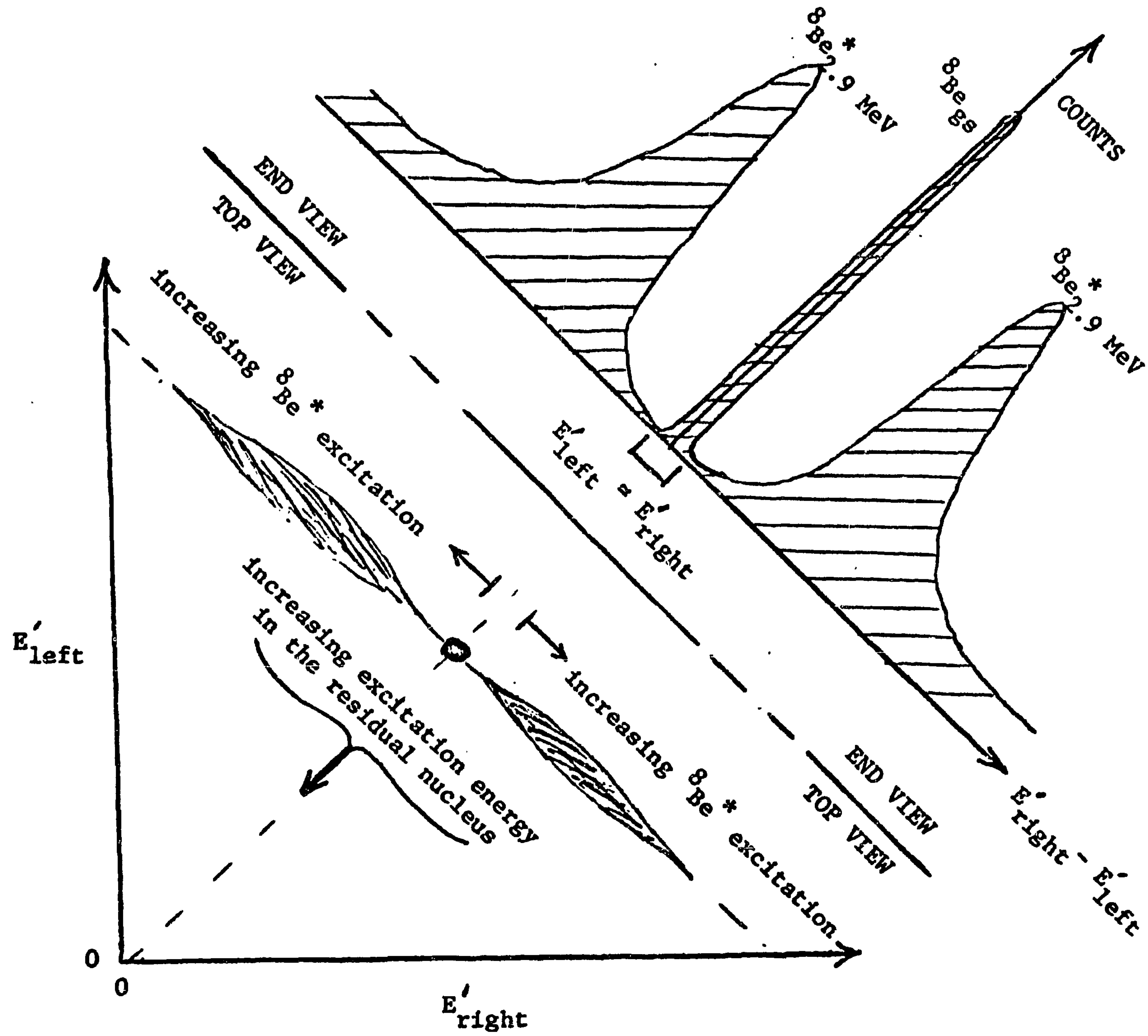

Figure 2 A schematic of the two-dimensional spectrum (of COUNTS vs) E_{left} E_{right}. Note that a tight condition of $E_{left} \approx E_{right}$ can make negligible the contribution of $^{8}Be^{*}$ to the ground state group. Only the contribution of one excited state in the residual nucleus is shown.

division will still give a good Ex pulse since one finds that charge division is INDEPENDENT of the vertical coordinate.[8]]

Very little complication arises from this change since the weighted addition between E and Ex can be done with PREAMP pulses. Apart from this the electronic system is unchanged.

This array has at least three advantages over the single pair of large-area vertically-stacked position-sensitive detectors. First, the 16-detector array will be able to stand much higher counting rates than pair. Second, the α-α coincidence resolving time will be better for the array. Third, the sorting of the data into various angle-groups will be easier for the experimenter and will require less on-line computation difficulty.

There are two serious disadvantages in using the 16-detector array. They are: (1) its associated electronic complication, and (2) the difficulty in handling $^{8}Be^{*} \rightarrow 2\alpha$. In this latter case the correction for kinematic broadening <u>must</u> be done in the computer in contrast to the weighted addition of E and Ex that is only valid for $^{8}B_{gs}$.

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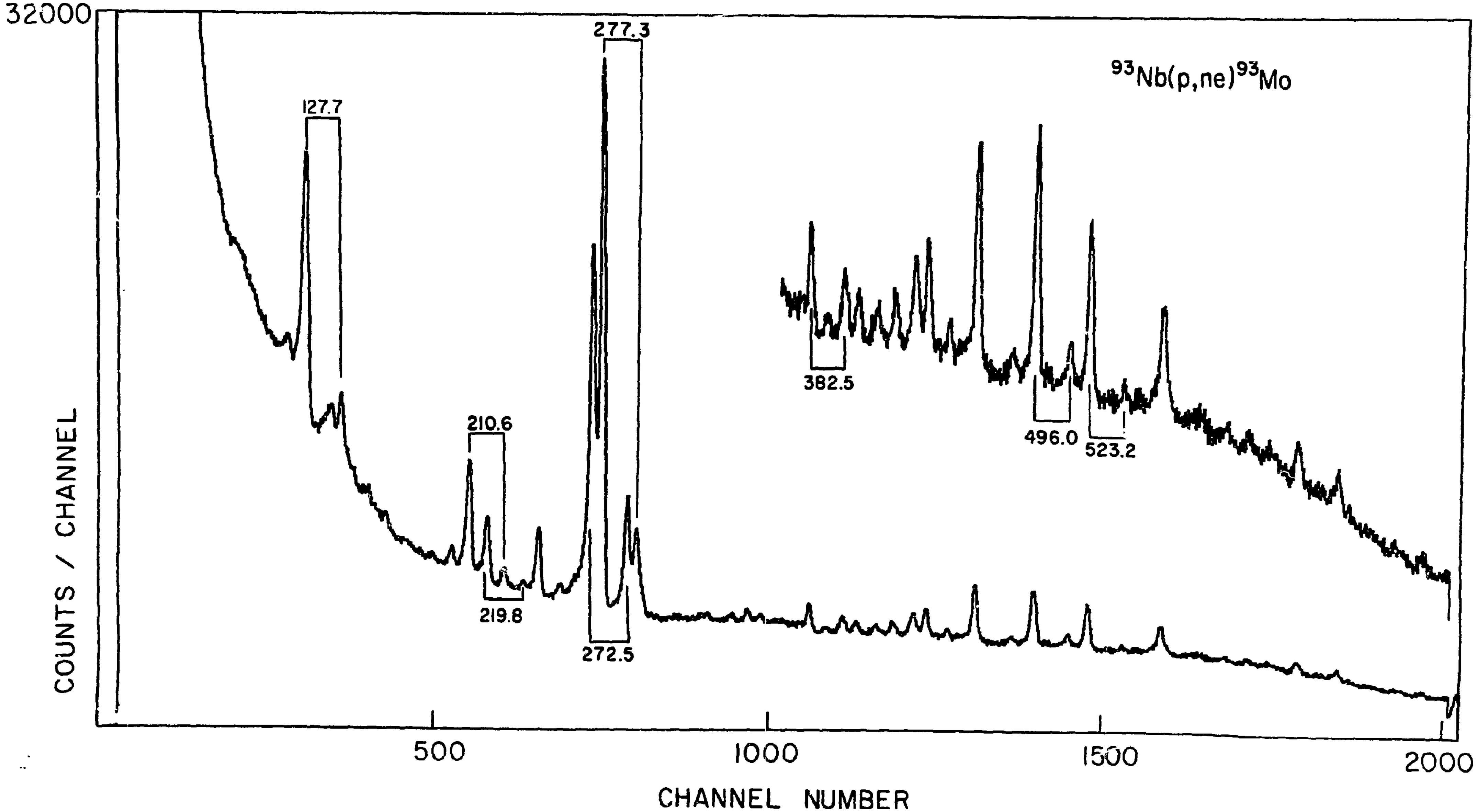
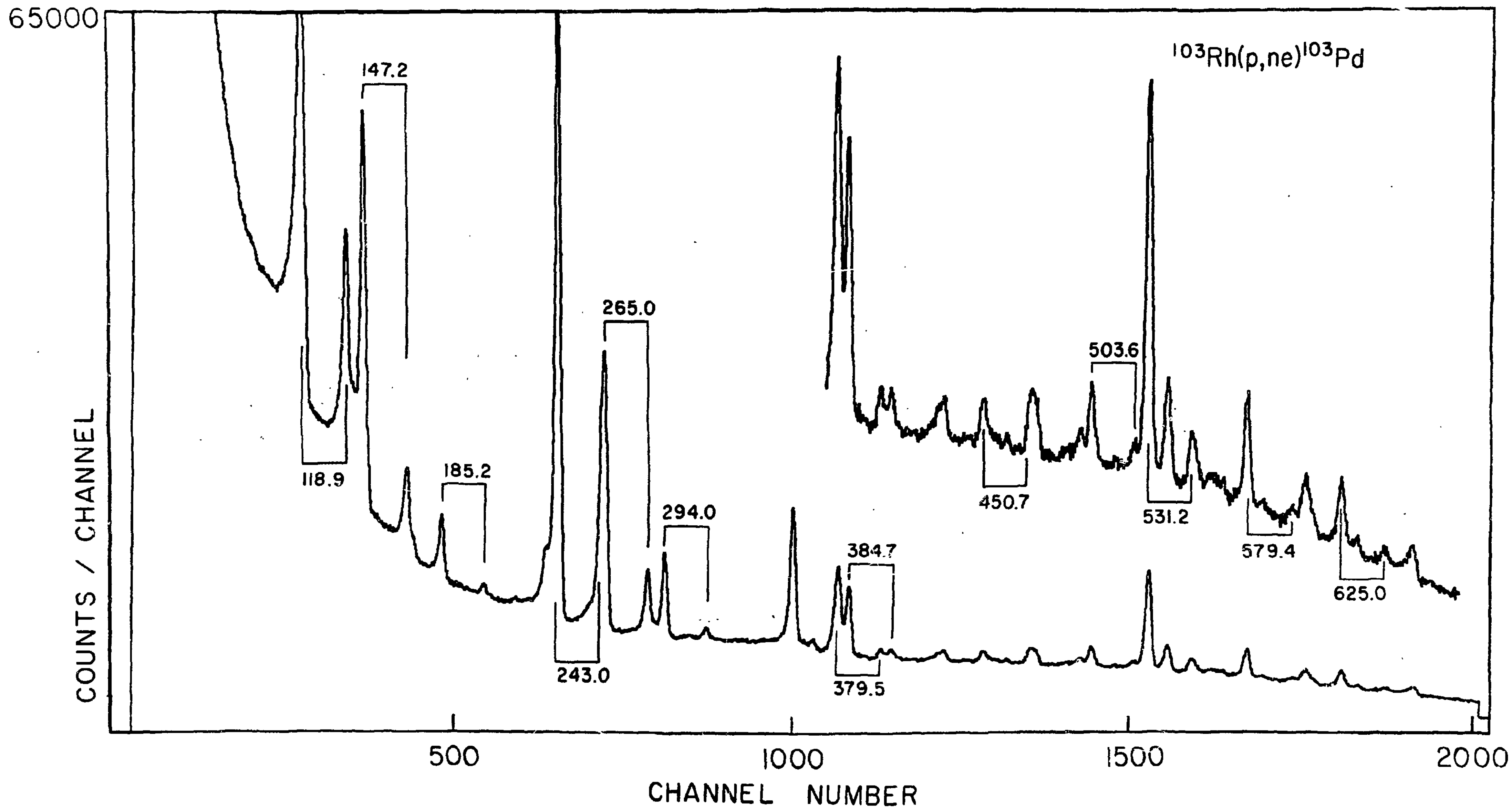
[1] D. Robson, Comments Nucl. Particle Phys. 5, 255 (1970).
[2] R. E. Brown, J. S. Blair, D. Bodansky, N. Cue, and C. D. Kavaloski, Phys. Rev. 138, B1394 (1965); G. Goldring, I. Plesser, and M. M. Sachs, Phys. Rev. 160, 827 (1967).
[3] M. B. Greenfield, J. L. Artz, and N. R. Fletcher, Bull. Am. Phys. Soc. 17, 489 (1972).
[4] J. G. Cramer, K. A. Eberhard, N. R. Fletcher, E. Mathiak, H. H. Rossner, and Weidinger, to be published.
[5] G. J. Wozniak, H. L. Harney, K. H. Wilcox, and J. Cerny, Phys. Rev. Letters 28, 1278 (1972).
[6] D. K. Scott, to be published in Vol. I of the Proc. of the Int'l. Conf. on Nucl. Phys., Edited by J. de Boer and H. J. Mang, Munich, 1973.
[7] D. Robson, Nucl. Phys. A204, 523 (1973).
[8] S. Kalbitzer and W. Stumpfi, Nucl. Inst. Meth. 77, 300 (1970).

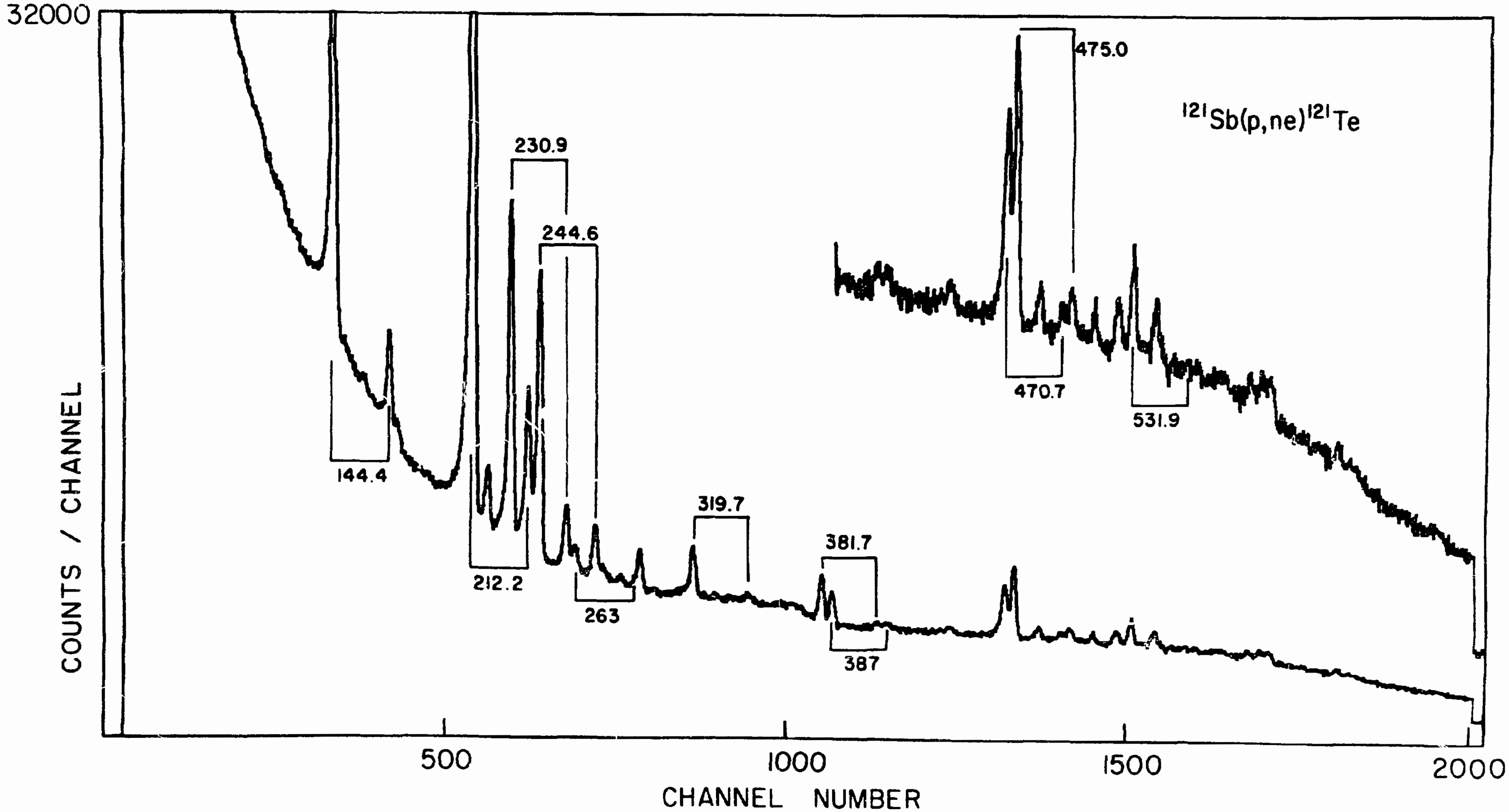
h. In-Beam Internal Conversion Electron Measurements

(J. R. White, G. W. Hoffmann, C. F. Moore)


32000
COUNTS / CHANNEL
CHANNEL NUMBER
500
1000
1500
2000
$^{93}Nb(p,ne)^{93}Mo$
127.7
210.6
219.8
277.3
272.5
382.5
496.0
523.2



65000
$^{103}Rh(p,ne)^{103}Pd$
147.2
118.9
185.2
265.0
243.0
294.0
384.7
379.5
503.6
450.7
531.2
579.4
625.0
COUNTS / CHANNEL
500
1000
1500
2000
CHANNEL NUMBER


32000
COUNTS / CHANNEL
CHANNEL NUMBER
500
1000
1500
2000
$^{121}Sb(p,ne)^{121}Te$
144.4
212.2
230.9
244.6
263
319.7
381.7
387
470.7
475.0
531.9

During the past year studies have been carried out on several nuclei using the recently designed and constructed axial beta-ray spectrometer for in-beam detection of internal conversion electrons.(1) These nuclei, ^{93}Nb, ^{95}Mo, ^{103}Rh, ^{107,109}Ag, ^{121,123}Sb, ^{124}Sn, ^{141}Pr, ^{167}Er, ^{177}Hf, ^{197}Ag, ^{206,208}Pb, ^{238}U, were bombarded with 9 MeV protons. Protons of this energy were, in all cases, above the (p,n) threshold. Figures showing the conversion electron spectra of ^{93}Nd, ^{103}Rh, and ^{121}Sb are in the preceding pages. The electron spectra were scanned and the data interpreted, and in most cases conversive transitions from both new and previously known lines were identified. Energies from the internal conversions electrons spectra are in good agreement with energies as obtained in γ-ray work.

At the present time our efforts are being directed toward accurately calibrating the beta-ray spectrometer. The detection efficiency of the high resolution Ge(Li) gamma detector has been determined, and upon receipt of electron sources of known activity, both the detection efficiency of the Si(Li) electron detector and the transmission efficiency of the beta-ray spectrometer will be determined. Intensities obtained from the internal conversion electron spectra are not at present realiable, due in part to the absence of shielding of the earth's magnetic field and the presence of magnetic materials in the environment of the spectrometer. Intensity calibration is being done at present in hopes to obtain some consistency. Upon completion of these tasks it will be possible to accurately directly measure internal conversion coefficients.

i. The Spin of the 14.08 MeV State in C^{12}

(W. J. Braithwaite, A. W. Obst, and C. H. King)

In the course of the last decade several different spins have been proposed for this state. Three of these spin assignments will be discussed below, where the proposed values for J^{π} are 4^{+}, 3^{-}, and 2^{+}, respectively. Following this discussion, we will briefly outline the status of the present work.

Garvey *et al*[1] performed $C^{12'} - \alpha_o$ in-plane angular correlation using the reaction C^{12} $(C^{12}, C^{12'})$ $C^{12*}_{14.08}$ $(\alpha_o)Be^{8}_{gs}$ where the outgoing $C^{12'}$ was fixed at 12^{o} in the laboratory. They used a Born approximation to calculate the α_o angular correlation which showed the shape for L = 4 to be slightly favored over L = 2. They concluded that "as no evidence to the contrary can be found, it is felt that the level observed as a 4^{+} corresponds to a level observed in C^{12} at 14.05 MeV". Several supporting arguments were given for a 4^{+} to be found in this region of excitation. Among these, it was pointed out that the measured excitation energy of this state is in substantial agreement with the L(L+1) predicted excitation energy [(10/3) 4.43 MeV = 14.8 MeV] for the 4^{+} member of the ground-state rotational band.

Fawzi[2] assigned to the 14.08 MeV state a J^{π} of 3^{-} on the basis of α-particle angular distributions. On the same basis he assigned to a broad state seen at 15.62 MeV the J^{π} of 4^{+}, suggesting that this state and not the state at 14.08 is the 4^{+} member of the ground state rotational band. The previously undetected level at 15.62 MeV has a large alpha width (Γ = 1.2 MeV) which would keep it from standing out in a "singles" measurement. A recent measurement[3] of deuterons inelastically scattered from C^{12} is shown in Figure 1. This spectrum shows a broad peak near 15.62 MeV in fair agreement with the excitation energy and width of the new state proposed by Fawzi.

The most recent spin assignment comes from a French group.[4] They used nuclear emulsions to pick out the $^{12}C(\alpha,\alpha')^{12}C^{*}(3\alpha)$ reactions where for each event, the four alphas (α' and 3α) form a vertex where range-energy considerations and charge, mass, energy and momentum conservation allow com-

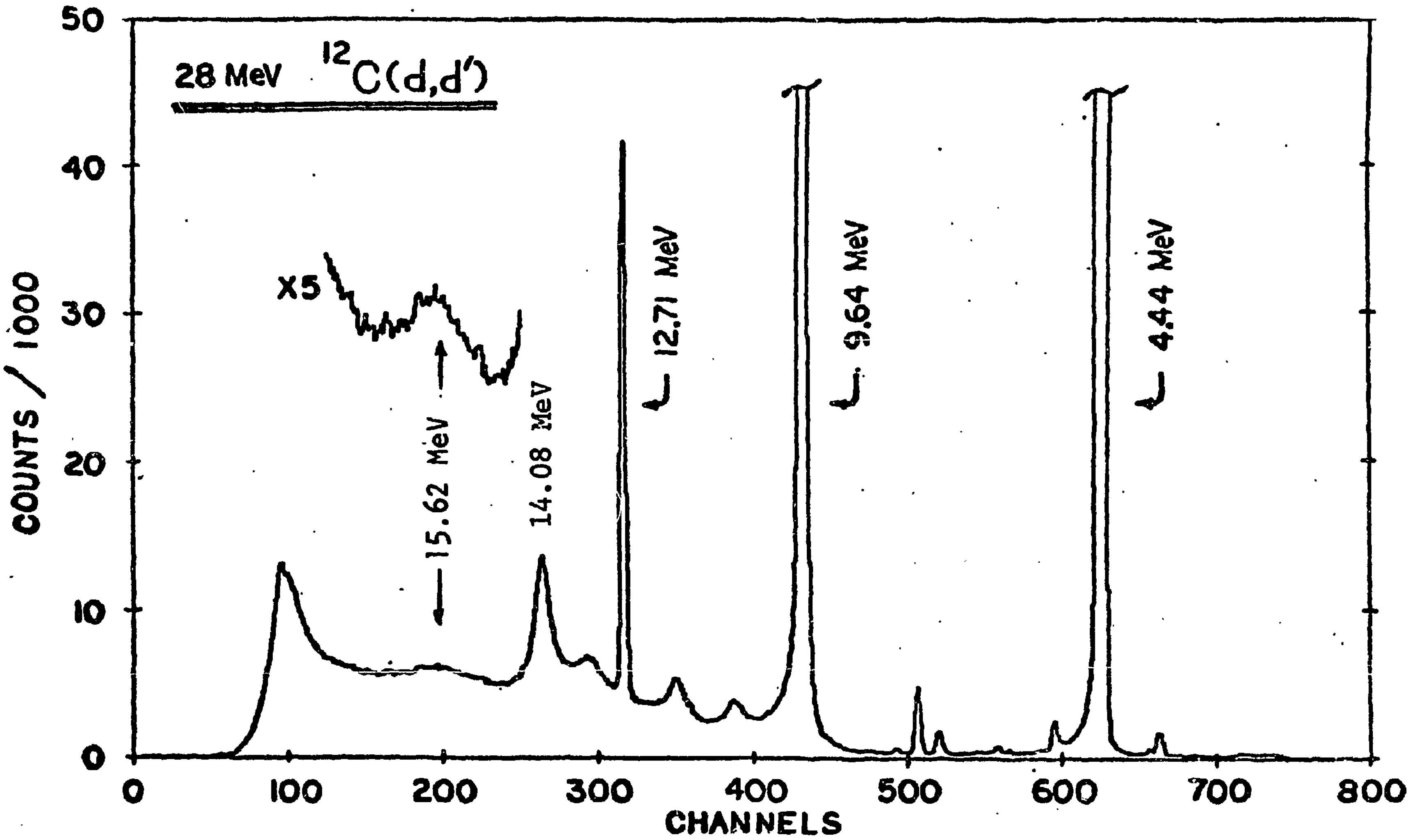


Figure 1 Spectrum of 28-MeV deuterons inelastically scattered from C^{12} at 55^o in the lab. A broad state is seen near 15.67 MeV in agreement with the observation of such a state by Fawzi. Fawzi proposes that this state is the 4^+ member of the ground state rotational band, instead of the 14.08 MeV state.

plete identification of the event, including the excitation energy in C^{12}. Their model calculations of the density distributions of the emerging alphas are plotted as Dalitz diagrams.

Good agreement is obtained with states in C^{12} of known J^{π} for the following: 9.6 MeV, 3^-; 10.3 MeV, 2^+; 11.8 MeV, 2^-; 15.2 MeV, 1^+; 16.6 MeV, 2^-; 17.3 MeV, 1^-; 17.8 MeV, 0^+; and 19.3 MeV, 2^+. Using this technique they propose a number of spin assignments for other excited states in C^{12}, including a 2^+ assignment for the 14.1 MeV state.

The Dalitz plots for 2^+ and 4^+ predictions are not too different from each other and both appear to be in fair agreement with the data presented, with the 2^+ slightly preferred. However, the predicted 3^- distribution is in considerably poorer agreement with the data.

It is worth noting that this group makes no 4^+ assignments even though they study states with excitation energies up to 32.5 MeV in C^{12}.

In the present work we are using the $C^{12}(C^{12},C^{12\prime})C^{12*}_{14.08}(\alpha_o)$ reaction at an incident energy of 36 MeV to measure the spin of the 14.08 MeV state of C^{12}. This assignment is being made using "A New Method for Spin Determinations Using Heavy-Ion-Alpha Angular Correlations", which is described elsewhere in this report (II. E. f.).

We have constructed "An Array of Alpha Detectors for Use in Spin Assignments" which is discussed elsewhere in this report (II. F. 5).

This measurement has been hindered by the lack of a sufficiently intense carbon beam, but a new ion source has been constructed following the Middleton design. Beam has been extracted from this source on the testing bench, but some minor improvements are needed before it is installed on the Tandem. This ion source is discussed elsewhere in this report (II. G. 2 b.).

[1]G. T. Garvey, A. M. Smith, and J. C. Hiebert, Phys. Rev. 130, 2397 (1963).
[2]M. A. Fawzi, Z. Physik 250, 120 (1972).
[3]W. J. Braithwaite, J. E. Bussoletti, F. E. Cecil, and G. T. Garvey, Phys. Rev. Letters 29, 376 (1972).
[4]C. Jacquot, Y. Sakamoto, M. Jung and L. Girardin, Nucl. Phys. A201, 247 (1973).

j. Studies of Level Structure of ^{66}Ge

(R. Pardo, C. N. Davids)

In the heavier mass region it is felt the majority of nuclei are synthesized by either slow or fast neutron capture on seed nuclei in the region of iron. But some nuclei are isolated from this type of event and cannot be produced by neutron capture. A possible alternative is to synthesize heavier nuclei in oxygen and silicon burning stages by quasi-equilibrium processes.* In order to calculate nucleosynthesis for this type of process it is necessary to accurately know the masses and level structure of the nuclei. Presently, work is being conducted on understanding the level sturcture of ^{66}Ge by the reaction $^{54}Fe(^{14}N,pn)^{66}Ge$. Preliminary results have been obtained from γ-n coincidences, and γ-γ coincidences as well as γ-ray singles studies. Additional γ-γ coincidence data and angular correlation work must be done to recheck this scheme and assign spins to the states observed.

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*The quasi-equilibuium assuption must be modified as the temperature of the material falls to that corresponding to the threshold region of the reactions involved which is known as "freeze-out".

k. Electromagnetic Decay of the 7.65-MeV State of ^{12}C

(C. N. Davids, R. Pardo, A. Obst)

The synthesis of ^{12}C during the helium burning stage of a star is quite sensitive to the branching ratio, Γ_{rad}/Γ, for the 7.65-MeV state in ^{12}C. This state is fortuitously located just 278 KeV above the combined mass of $^{8}Be + ^{4}He$. Thus the 3α reaction proceeds a most entirely through the 7.65-MeV state and the production of ^{12}C is proportional to Γ_{rad} for this state. The final abundance of ^{12}C and ^{16}O at the end of helium burning will be determined by considering the competition between the 3α reaction and the $^{12}C(\alpha,\gamma)^{16}O$ reaction.

A recent measurement by Chamberlin, Bodansky, et al.[1] has produced a value of $(4.2 \pm 0.2) \times 10^{-4}$ for Γ_{rad}/Γ. This compares to the accepted average of $(2.9 \pm 0.3) \times 10^{-4}$[2] due mainly to the work of Seeger and Kavanagh.[3] The discrepancy between the two values is significantly outside their respective error bars and the uncertainty introduced produces significant changes in the calculated abundances in helium burning. As an example, for a 4 solar mass case the helium burning code SPRO of Couch yields an increase of 17% in the final carbon abundances and a corresponding decrease in the final ^{16}O abundance.

We are in the process of remeasuring the branching ratio, Γ_{rad}/Γ of the 7.65-MeV state of ^{12}C in an effort to reconcile the discrepancy presently existing. The state is formed by inelastically scattering protons from ^{12}C and observing coincidences between the scattered protons and the recoil ^{12}C. We intend to make use of the differing pulse shapes produced by protons and heavier ions in silicon detectors to significantly improve the background levels, in addition to using the time of flight technique. A resonance in $^{12}C(p,p')^{12}C^{*}(7.65)$ conveniently exists at a lab proton energy of about 10.8 MeV[4].

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[1] D. Chamberlin, D. Bodansky, W. W. Jacobs, D. L. Oberg, (1973), preprint.
[2] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys., A114, 1 (1968).
[3] P. A. Seeger and R. W. Kavanagh, Nucl. Phys., 46, 577 (1963).
[4] C. N. Davids and T. L Bonner, Ap. J., 166, 405 (1971).

ℓ. Double Gamma Decay in Nuclei with 0^+ First Excited States

(W. J. Braithwaite, A. W. Obst, C. H. King, and C. Fred Moore)

A positive indication of double gamma decay in Ca^{40} has been reported[1] recently by a Rutgers-Bell (RB) collaboration. This work has encouraged us to attempt a similar measurement in ^{90}Zr. This report discusses the present state of the ^{90}Zr experiment along with some comments about similar measurements that may be made once the ^{90}Zr work is completed. Since the RB experimental design was quite good, we have used it as a guide in the present work. We will outline below the major differences between our systems.

The RB design features used two 5" x 5" NaI detectors (γ_1,γ_2) in coincidence with an annular proton detector. In contrast, the present system uses four 5" x 5" NaI where any pair can detect γ_1 and γ_2. This increases the effective pair-coincidence counting rate by a factor of 6. The protons are detected by an array of 4 detectors symmetrically placed around the beam so that they are as close to 180^o as possible. Despite this backward angle, the counting rate is limited by the elastic scattering so the use of 4 separate detectors makes it possible to increase this rate. Since a 0_2^+ state must decay isotropically, the γ_1-γ_2 correlation is not affected by the position of the particle detectors, so there is no loss in design simplicity by the replacement of the annular detector by a detector array.

Each of the fast logic signals from the γ-detectors are delayed by a fixed amount (0, 70, 210, 490 nsec) in order to determine which detector was struck. After being delayed, the logic signals are sent to a fast summing amplifier. This summed logic is used both to start and to stop the γ_1-γ_2 TAC, thus assuring that each of the six possible γ_1-γ_2 coincidences is separately resolved in the TAC spectrum with a minimum time spacing of 70 nsec.

The PACE-8 data acquisition system of our PDP-15 will digitize up to eight independent signals. Thus, we were able to connect to separate analog to digital converters the signals from each gamma detector, the γ_1-γ_2 TAC, the p-γ TAC, and the mixed output of the gain-matched proton detectors (summed after each passes through a linear gate).

Figure 1 shows data that has been reported[2] by Courtney and Moore. Fig. 1a shows a proton spectrum taken at an incident proton energy of 7.34 MeV. As seen in Fig. 1b, the 0_2^+ is strongly resonant at this bombarding energy. Unfortunately, this energy is above the (p,n) threshold by about 450 keV. As a result, we decided to investigate the resonance at 6.231 MeV. Fig. 2 is a proton spectrum taken at this energy. Note that the (p,p') yield to the 0_2^+ state at 155^o is much greater than the 0_2^+ yield of internal conversion electrons from its ISOTROPIC decay. Despite the branch ($\Gamma_e/\Gamma_{TOT} \approx$ 1/2), this indicates that the (p,p') angular distribution at the back angles is STRONGLY ENHANCED over its angle-averaged value. Further, this enhancement is much more striking at an incident energy of 6.23 MeV (Fig. 2) than it is at 7.34 MeV (Fig. 1a). This should help to compensate for the small resonant formation cross section which is only about 1/5 of the total resonant yield at 7.34 MeV.

Using 5% Ge(Li) detectors, we have studied the singles γ spectrum as well as the γ_1-γ_2 coincident spectrum. We find that the 2.32 MeV gamma and the 2.18 MeV gamma both have RESONANT enhancements at Ep = 6.23 MeV. Gammas are seen at appropriate energies for the decay of those excited states of Zr^{90} shown in Fig. 2. Several lines are seen in the coincident $E_{\gamma 1} + E_{\gamma 2}$ sum spectrum. Most of these lines have been attributed to cascades from proton induced reaction on Al. With proper shielding, these cascades will not be present in the double-gamma measurements.

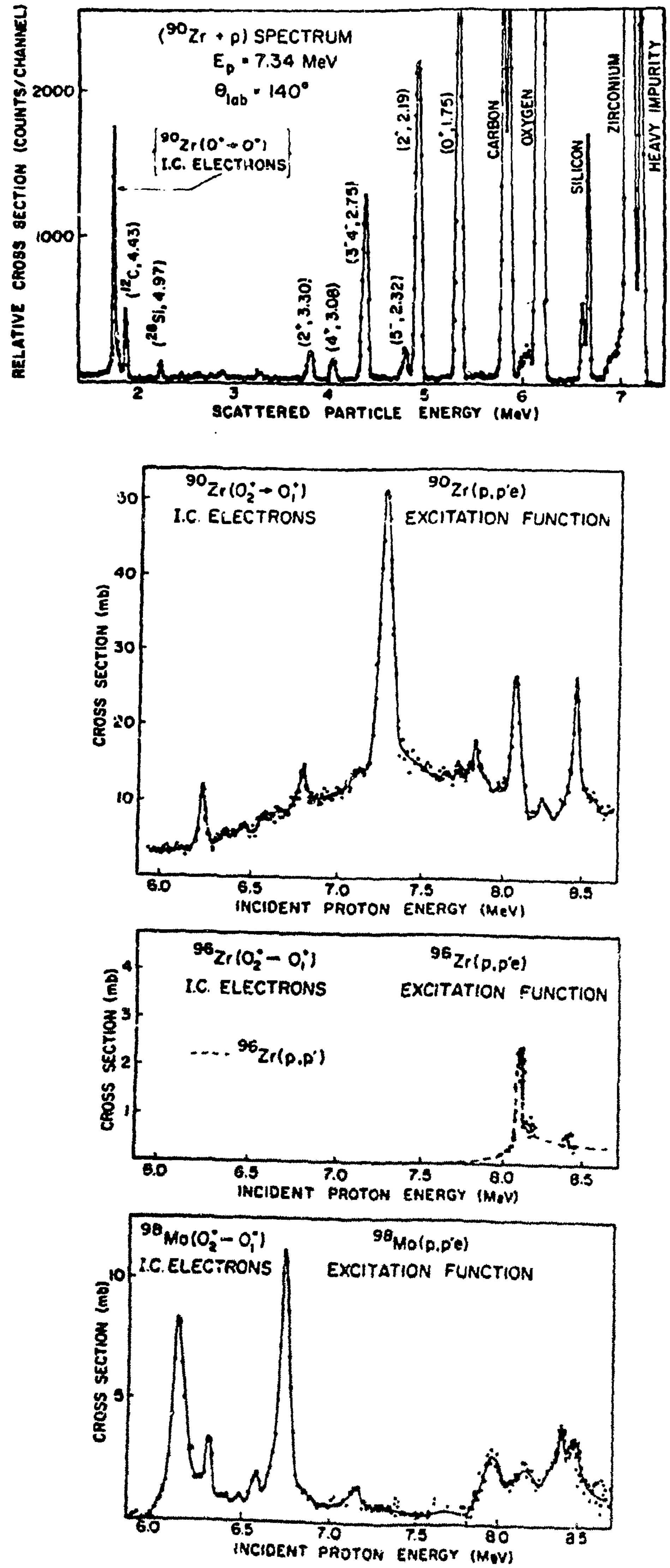
We intend to repeat the ^{40}Ca measurement once we make suitable

(a)

(b)

(c)

(d)



(^{90}Zr + p) SPECTRUM
E_p = 7.34 MeV
θ_{lab} = 140°
^{90}Zr(0⁺→0⁺) I.C. ELECTRONS
(^{12}C, 4.43)
(^{28}Si, 4.97)
(2⁺, 3.30)
(4⁺, 3.08)
(3⁻4⁺, 2.75)
(5⁻, 2.32)
(2⁺, 2.19)
(0⁺, 1.75)
CARBON
OXYGEN
SILICON
ZIRCONIUM
HEAVY IMPURITY
RELATIVE CROSS SECTION (COUNTS/CHANNEL)
SCATTERED PARTICLE ENERGY (MeV)
^{90}Zr(0_2^+→0_1^+) I.C. ELECTRONS
^{90}Zr(p,p'e) EXCITATION FUNCTION
CROSS SECTION (mb)
INCIDENT PROTON ENERGY (MeV)
^{96}Zr(0_2^+→0_1^+) I.C. ELECTRONS
^{96}Zr(p,p'e) EXCITATION FUNCTION
^{96}Zr(p,p')
CROSS SECTION (mb)
INCIDENT PROTON ENERGY (MeV)
^{98}Mo(0_2^+→0_1^+) I.C. ELECTRONS
^{98}Mo(p,p'e) EXCITATION FUNCTION
CROSS SECTION (mb)
INCIDENT PROTON ENERGY (MeV)

Fig.1

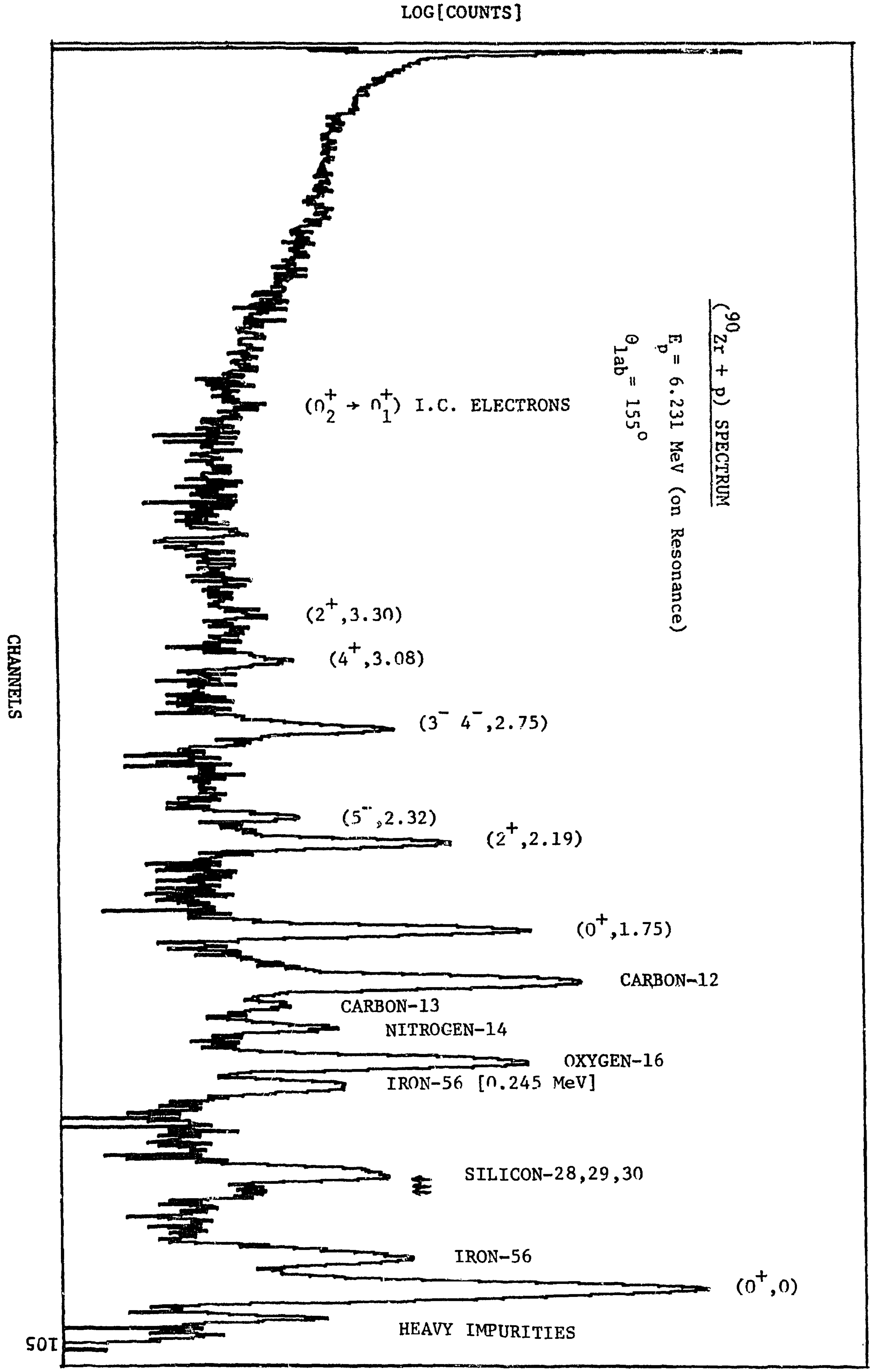

LOG[COUNTS]
CHANNELS
105
(^{90}Zr + p) SPECTRUM
E_p = 6.231 MeV (on Resonance)
θ_{lab} = 155°
($0_2^+ \rightarrow 0_1^+$) I.C. ELECTRONS
(2^+,3.30)
(4^+,3.08)
(3^- 4^-,2.75)
(5^-,2.32)
(2^+,2.19)
(0^+,1.75)
CARBON-12
CARBON-13
NITROGEN-14
OXYGEN-16
IRON-56 [0.245 MeV]
SILICON-28,29,30
IRON-56
(0^+,0)
HEAVY IMPURITIES

Fig.2

target handling arrangements. Then, assuming both the $^{90}Zr(0^+\rightarrow 0^+)$ and the $^{40}Ca(0^+\rightarrow 0^+)$ measurements are successful, we will attempt to measure similar $(0^+\rightarrow 0^+)$ double gamma decays in ^{96}Zr, ^{98}Mo, ^{72}Ge, and possibly ^{16}O. Figure 1c shows that the $^{96}Zr(0^+$, 1.59 MeV) production resonates at E_p = 8.1 MeV and the $^{98}Mo(0^+$, 0.736 MeV) production resonates at several incident proton energies above 6 MeV. Unfortunately, the resonant proton energies for both these reactions are well above each (p,n) threshold. This makes the $(p,p'2\gamma)$ measurements difficult. The $^{72}Ge(0^+$,0.690 MeV) state has a lifetime of 0.29 microseconds. This is an additional experimental condition that double gamma decay from this state must follow.

In closing we are quite hopeful that $(0_2^+ \rightarrow 0_1^+)$ double gamma decays will be successfully studied in several nuclei using the technique of tagging the gamma pairs with the formation particle.

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[1] E. Beardsworth, R. Hensler, J. W. Tape, N. Benczer-Koller, W. Darcey and J. R. MacDonald, Phys. Rev. C8, 216 (1973).
[2] W. J. Courtney and C. F. Moore, Phys. Letters 31B, 131 (1970).

m. Nucleon-Nucleon Measurements at LAMPF

(C. W. Bjork and P. J. Riley)

This work is a large collaborative effort between the Physics Division of Research, Los Alamos Scientific Laboratory, The University of New Mexico, Texas A&M University, and The University of Texas. The first experiment to be carried out in the nucleon physics laboratory at LAMPF is the measurement of the neutron spectrum in the p(d,n)2p reaction. (Experiment 56) The system layout however, as shown in the figure, has been chosen so that the different goals of several nucleon-nucleon experiments can be attained without major changes. During the past year the bulk of the experimental equipment has been fabricated, tested, and installed in the NPL.

Measurement of the energy distribution of the neutron beam is proposed in Experiment 56 by momentum analysis of the proton produced in the forward direction by the n-p charge exchange. Neutrons are produced in a 10-cm long liquid Deuterium target at a chosen angle θ_1 to the proton beam. The neutron beam emerges from the end of the collimator at a distance of $\simeq$ 8 meters from the LD_2 target and passes through a monitor system comprised of a charged particle veto counter, a polyethylene radiator, and two range telescopes. Charged particles in the beam or originating from the radiator will be removed by the sweep magnet M1. We plan to use a sweep magnet inside the beam channel to remove charged particles originating directly from the neutron source.

In the liquid hydrogen target (LH_2), a small fraction of the beam is converted to protons by charge exchange scattering. The nominal length of the LH_2 target cell is 10 cm, with a comparable diameter. Momentum analysis of the protons by means of the magnet M2 then gives information on the momentum distribution in the incident neutron beam. In Experiment 56 the spectrometer system is set at the nominal angle $\theta_2 = 0^G$ with respect to the neutron beam.

The same setup, since it has sufficient solid angle ($\simeq$ 5 msr) can be used to measure the angular distribution of backward angle n-p scattering (LAMPF Proposal #125). Tha analyzing magnet (M2 in Fig. 1) and the MWPC's form a rigid entity, the spectrometer, which is mounted on a movable stand and rotates about a pivot under the LH_2 target.

The design also includes provision for optical alignment and accurate replacement of chamber housings after repair or maintenance. The system can be used without major changes in the pion production experiment No. 129, or in experiment No. 65 where a polarized target is intended to replace the LH_2 target.

The magnetic analysis is to be done with a 18D36H frame magnet with "pancake" coils. The nominal field is B = 18kG in a 6-in. gap and allows a bend angle $\alpha = 22^{o}$ for 800 MeV protons. We hope to obtain a precision of < 5 mrad for the angular measurement and so obtaining $\Delta p/p = \Delta\alpha/\alpha = 5/384 =$ < 1.3%. The bend angle is obtained by reconstruction of the proton trajectory using the information obtained from the MWPC's (W1....to W4). The sensitive area of the chambers is $\simeq 20 \times 40\ cm^2$ for W1 to W3 and $\simeq 40 \times 60\ cm^2$ for W4. The geometrical resolution for four x or four y chambers can be estimated by means of the root mean square deviation for detectors of uniform response and of extent X/2 in x, for example. For a single such detector $(\Delta x)^1_{RMS} = \pm S/\ 12$, and for four detectors (adding in quadrature) $(\Delta x)^4_{RMS} = \pm S/\ 3$, or $\pm$ 1.15 mm, considered as a standard deviation. Using an inter-chamber spacing of 1 m, the standard deviation in angle for four detectors is then $\pm$ 1.15 m rad. Multiple scattering will bring the uncertainty in angle up to values ranging from 4.6 to 1.7 m rad for proton energies in the range 200 to 800 MeV, respectively.

Since we don't use the MWPC in autotriggering mode, a set of three scintillators (S0, S1, S2) is used to give a trigger signal. S0 eliminates residual charged particles from the neutron beam. The time-of-flight of the analyzed particles. This information will allow us to distinguish protons and deuterons of the same momentum. For 1460 MeV/c protons and deuterons, the difference of the time-of-flight is $\simeq$ 6 nsec.

During the period from July to November, 1973, we have had a total of 7 experimental runs in Area B at LAMPF, the first few of which were preliminary monitory diagnostic runs yielding rather little experimental time. The following objectives have been carried out:

1. The performances of the neutron monitor telescopes have been

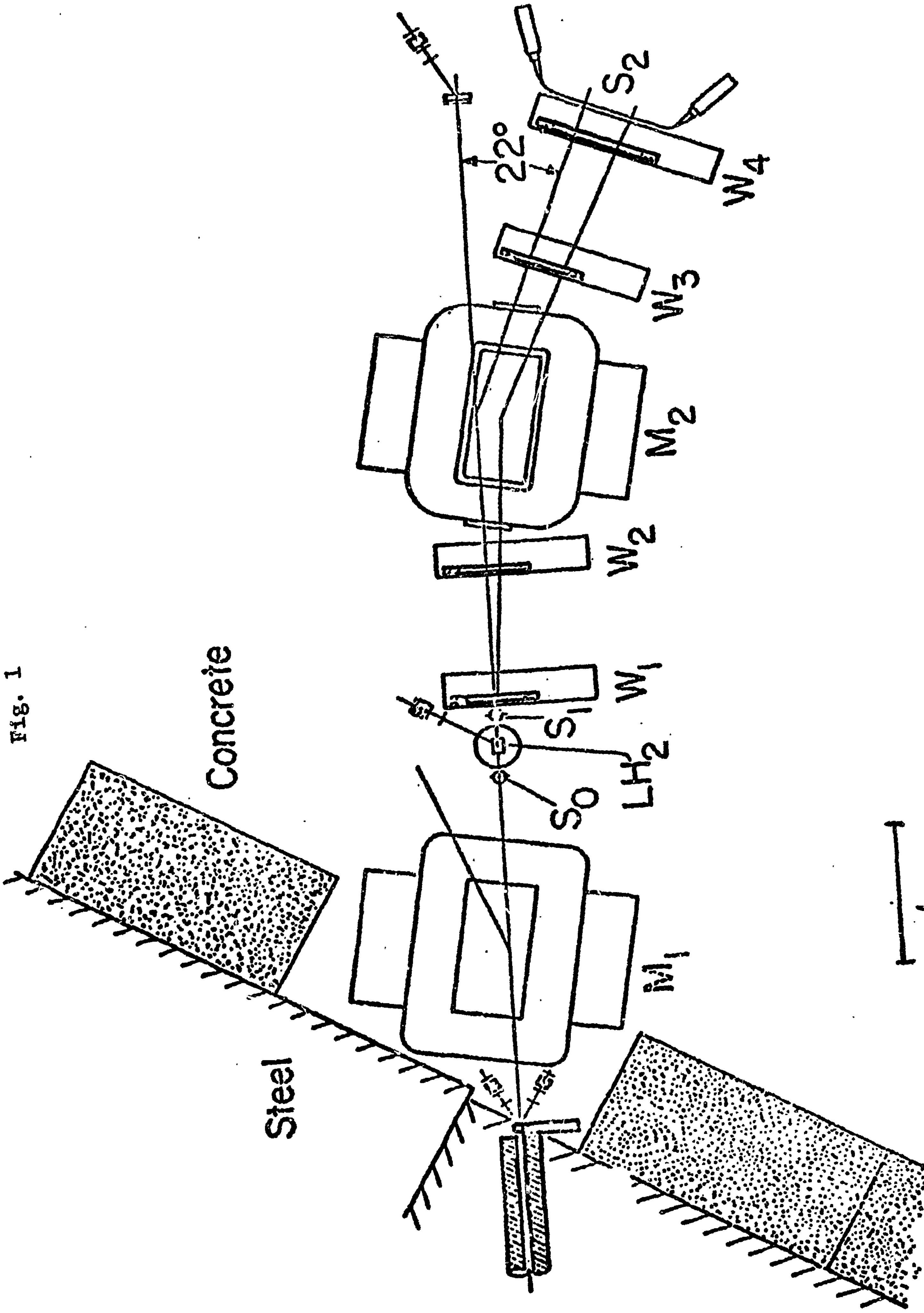

Fig. 1

thoroughly tested.

2. The neutron and gamma background dose rates in m rem/hr in and around area B and the experimental trailers have been carefully measured.

3. The charged particle contamination of the neutron beam has been investigated by using the beam sweep magnet upstream of the proton telescope.

4. Preliminary tune-up measurements on the 18D36 spectrometer system including the 3 scintillation counters and the 4 MWPC's has been accomplished.

5. During the last run the liquid hydrogen target was installed and shown to be working satisfactorily. Satisfactory "target in"/"target out" counting ratios were obtained.

Most of the runs have taken place near 500 MeV proton energy with duty factor in the range 0.01 to 0.038 and at average beams in the range 0.15 to 0.95 μamp. The experience indicates that it is a time consuming process to bring a well focussed beam onto a neutron production target in area B, although during the last run, using a beryllium neutron production target, satisfactory true/background neutron counting ratios (~30/1) with the Be target in the "in" and "out" positions respectively were obtained. Ten to 15 per cent beam loss in the target vault gives rise to background radiation at the experimental equipment and in the electronic trailer.

The following table gives some typical operating conditions for the run that occurred during the day of Sept. 20, 1973.

Beam energy: 497 MeV

Rep. rate: 120 Hz

Macro pulse length: 320 μsec

D. F.: 0.038

Average beam intensity: 0.95 μA

Transmission (Target to beam stop): 83%

Av. singles reate of L1 monitor counter (3x3x.062 in.^{3}): 900 Hz

Av. singles rate of S0 counter (4x8x.062 in.^{3}): 4800 Hz (in beam)

Av. singles rate of S2 counter (16x30x.125 in.^{3}): 6710 Hz (in beam)

Av. singles rate per wire in MWPC - W1V: 27 Hz

Neutron dose rate near shield wall in Area B: 50 m rem/hr.

Neutron dose rate in the experimental trailer: 2.5 m rem/hr.

Gamma dose rate in the experimental trailer: 2.0 m rem/hr.

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*Research at LAMPF sponsored by Associated Western Universities, Inc.

2. Atomic Research in Progress

a. Experimental Energy Dependence of Double K-Shell Ionization of Calcium by Oxygen Bombardment

(D. K. Olsen, J. McWherter, and C. F. Moore)

Recently it has been shown that the thick-target X-ray yield for producing calcium double K-shell vacancies from 30.0-MeV oxygen bombardment is of the order of 1% of that for single K-shell vacancy production.[1] Furthermore, it has been shown that the thick-target yield for double K-shell vacancy production exhibits a maximum when $Z_1 \approx Z_2$ where the target atomic number Z_2 is varied and the projectile atomic number Z_1 is held fixed.[2] This target dependence indicates an electron-promotion reaction mechanism. Perhaps when $Z_1 << Z_2$, the double K-shell vacancy production can be explained by a simple, simultaneous, multiple-Coulomb ionization formalism. In any case, double and single K-shell ionization provides an excellent test for multiple ionization formalisms because only one atomic orbital is involved in both cross sections.

In order to obtain further experimental information on this process, the thick-target yields of calcium single and double K-shell ionization from 24.0 to 48.0-MeV oxygen bombardment have been measured in 3.0-MeV steps. The data were taken with a high-resolution curved-crystal spectrometer employing an LiF crystal. The unreduced data shows the single-K-vacancy yield to increase by a factor of 20 over this energy range, whereas the double-K-vacancy yield increases by a factor of 200. That is, at 24.0 MeV the ratio of double-K to single-K vacancies is 0.2%. Such an energy dependence is expected from multiple-Coulomb ionization. At present, the total X-ray cross sections at each energy are being extracted from the thick target yields using standard techniques.

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[1] P. Richard, W. Hodge, and C. F. Moore, Phys. Rev. Lett. 29, 393 (1972).
[2] C. W. Woods, F. Hopkins, R. L. Kauffman, D. O. Elliott, K. A. Jamison, and P. Richard, Phys. Rev. Lett. 31, 1 (1973).

b. Lifetimes, Cascades and the Beam-Foil Collision Mechanism

(W. J. Braithwaite, D. L. Matthews, and C. F. Moore)

Delayed X-ray emission has been observed from highly-ionized oxygen in the wavelength region between 14 and 24 Å. This region includes the Lyman and Lyman-like series of transitions for both H-like and He-like oxygen.

A curved crystal spectrometer was used for energy and intensity measurements under a system vacuum of about 10^{-6} torr. The spectrometer energy resolution was $E/\Delta E \simeq 300$ using a RbAP crystal. The spectrometer was set at 90° to the incident ion beam at a variable downstream distance from the exciter foil. 2 mm vertical entrance slits were used to restrict the observed path length of the excited oxygen ion beam.

Using this apparatus, we have measured the lifetimes of two metastable states. The lifetime for the Li-like oxygen state $^4P_{1/2}(1s^2 2s - 1s2s2p)$ was found to be 3.48 ± 0.08 nsec, in excellent agreement with a delayed Auger measurement by Sellin, et al.[2], and the lifetime for the He-like oxygen state $^3P_1(1s^2 - 1s2p)$ was found to be 1.47 ± 0.08 nsec.[1]

While making the above measurements we were surprised by the persistence of the Lyman (and the Lyman-like series) in oxygen since scaling their lifetimes in hydrogen by Z^{-4} predicts lifetimes in the picosecond region. In addition, both series limit regions were seen to grow in relation to the other transitions during the first 0.4 nsec[2] after which each transition drops off at the same rate. This suggests that the lower-lying Lyman (and Lyman-like) transition strengths are dominated by the cascade decays from the states near the (appropriate) ionization limit.

Our initial work shows that the decay curves for several of the lower-lying states are very similar, with each dropping away less rapidly with decay length than an exponential decay would predict. Figure 1 shows this for the first two Lyman transitions in hydrogen-like oxygen, where each decay curve has an arbitrary normalization.

We have attempted some very simple calculations to see under what conditions non-exponential delay curves would be predicted for the low-lying Lyman (and Lyman-like) transitions. Several calculations gave a power law prediction for these delay curves. Each such calculation provided a different exponent-value for the power law depending on the particular model used to describe the formation of the states near the ionization limit.

A power law would graph as a straight line on log-log paper. We have tried plotting our preliminary data in this way and have found that

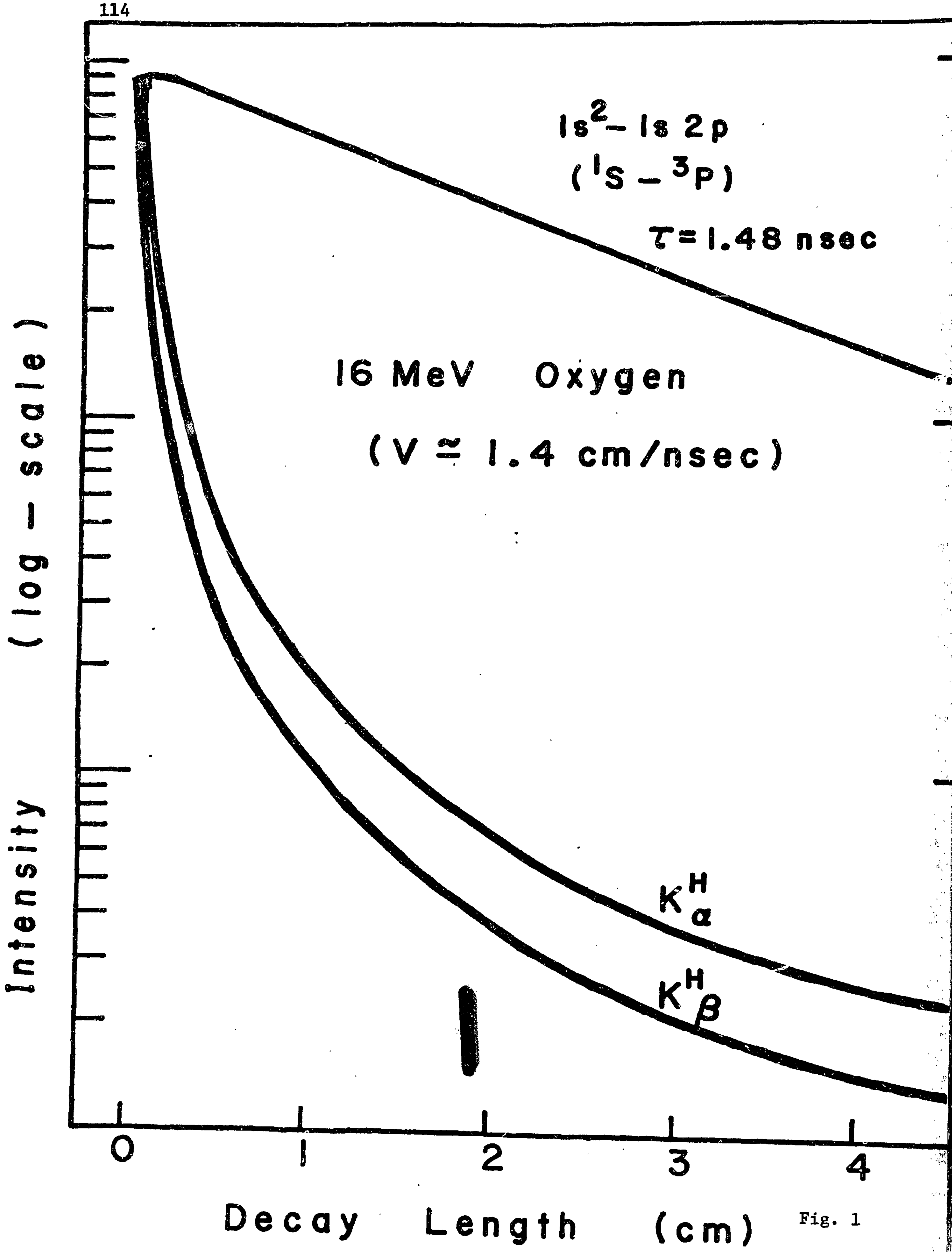
1s^2 – 1s 2p
(^{1}S – ^{3}P)
τ = 1.48 nsec
16 MeV Oxygen
(V ≃ 1.4 cm/nsec)
Intensity (log - scale)
K_α^H
K_β^H
0
1
2
3
4
Decay Length (cm)

Fig. 1

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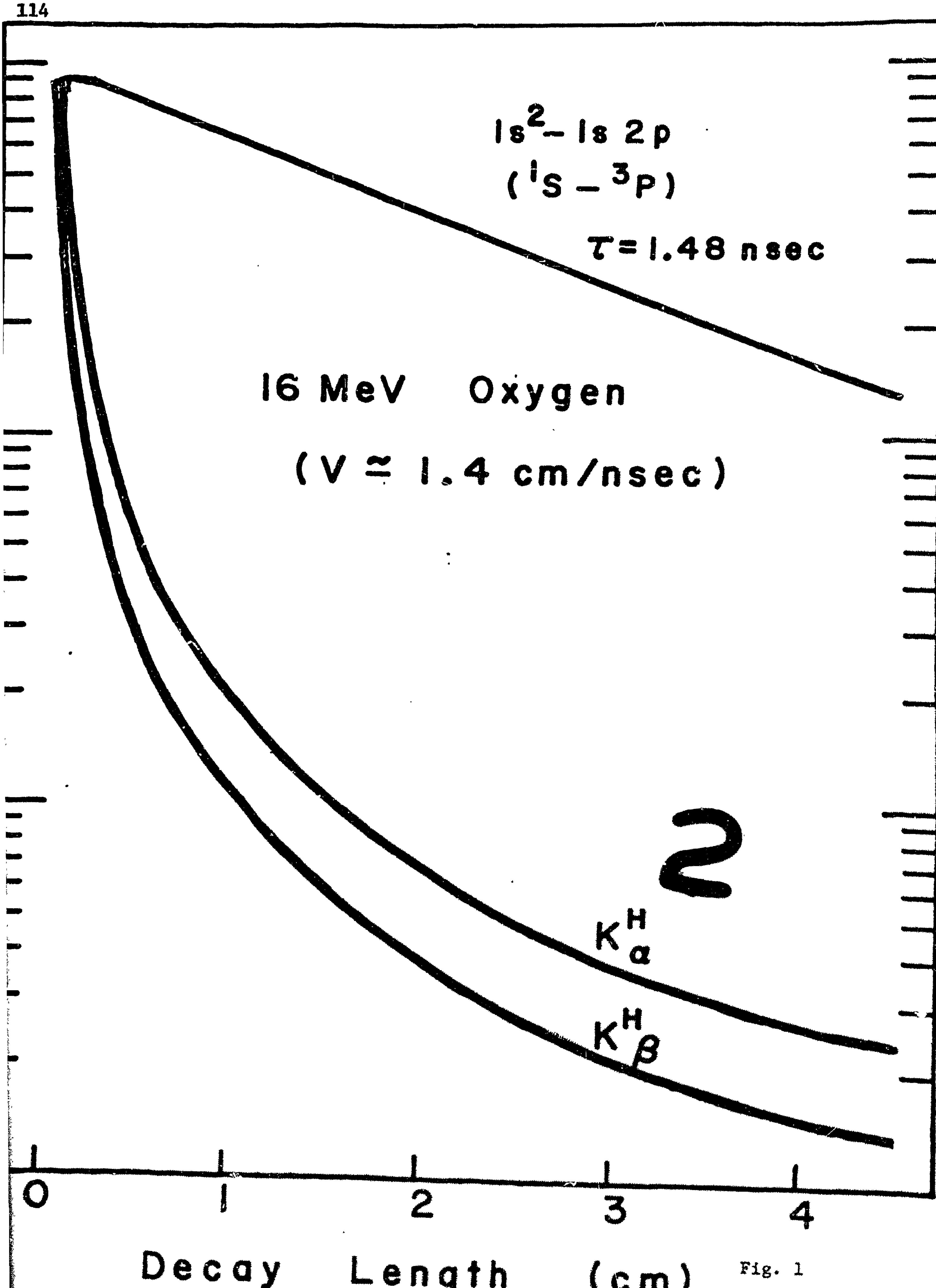
1s² – 1s 2p
(¹S – ³P)
τ = 1.48 nsec
16 MeV Oxygen
(V ≃ 1.4 cm/nsec)
2
K^H_α
K^H_β
0
1
2
3
4
Decay Length (cm)

Fig. 1

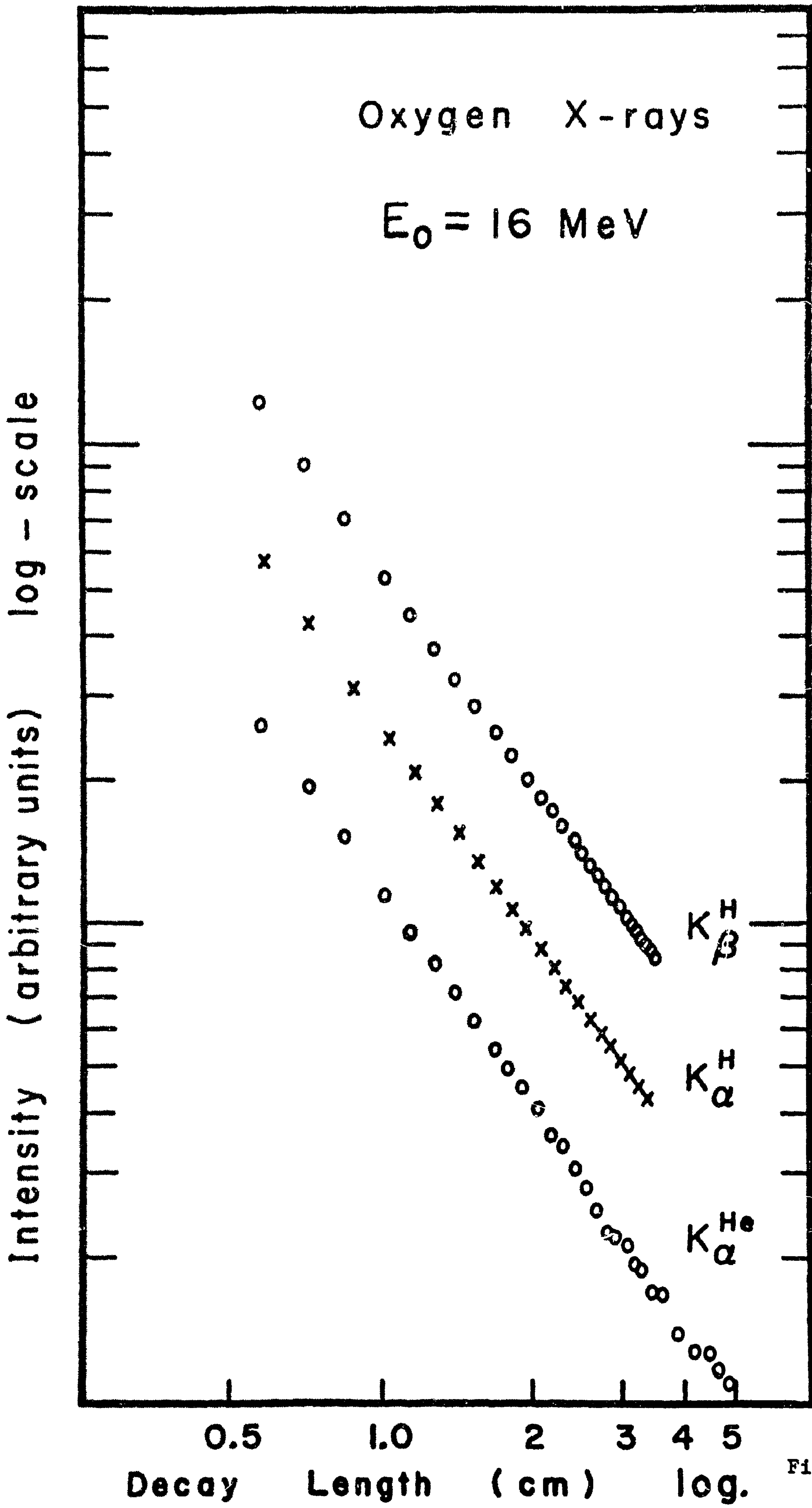
Oxygen X-rays
E_0 = 16 MeV
Intensity (arbitrary units) log - scale
K_β^H
K_α^H
K_α^{He}
0.5
1.0
2
3
4
5
Decay Length (cm) log.

Fig. 2

the three strongest lines in the spectrum follow a power law shape fairly well. The value for the exponent is the slope of the straight line on log-log paper. We find a value close to -1.5 for the data at 16 MeV. (see Fig. 2) Preliminary work at other bombarding energies indicates that this exponent value may be energy dependent.

None of our proposed formation models led to this particular exponent-value, but since different models give different exponent values, we are hopeful that the experimentally-determined exponent-values for the power law may aid in the determination of the particular beam foil collison mechanism that is appropriate to the particular bombardment conditions.

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[1] C. Fred Moore, W. J. Braithwaite, and D. L. Matthews, Physics Letters 44A, 199 (1973).
[2] I. A. Sellin, B. Donnally, and C. Y. Fan, Physical Review Letters 21, 717 (1968).
[3] W. J. Braithwaite, D. L. Matthews, and C. Fred Moore, Proceedings of the Eighth Int.'l Conf. on the Physics of Electronic and Atomic Collisions edited by B. C. Cobić and M. V. Kurepa (Printed in Yugoslavia by Grafico Preduzece "Budúcnost", Zrenjanin, 1973), post-deadline insert.

c. Stark Enhancement Near the Series Limits in Hydrogenic and He-Like Oxygen

(J. E. Bolger, W. J. Braithwaite, W. J. Courtney, and C. F. Moore)

In order to perturb the barely-bound electrons in highly-ionized oxygen using the Stark effect, high-velocity oxygen ions ($v = 0.5\ c$) were passed through an exciter foil which was suspended in a magnetic field of 8 kilogauss or less.

The Lyman and Lyman-like transitions near the series limits in hydrogenic and He-like oxygen both showed an enhancement when a B-field was imposed on the exciter foil, with the He-like oxygen transitions showing the greatest enhancement.

A static electric field of about 10^5 Volts/cm is generated in the rest-frame of the excited oxygen as a consequence of its motion through the magnetic field. This perturbation leads to some dynamic feeding of some S and D strength into $^1P(1s\otimes np)$ states, thus permitting this strength to appear in the radiative channels of the very fast Lyman-like transitions ($1s^2 \leftarrow 1snp$). Sizeable contributions of this type might lead to an observable enhancement in the series limit region of He-like oxygen. The same mechanism would predict a similar enhancement in the hydrogenic oxygen system.

A beam foil technique is used to produce excited states in highly-stripped oxygen in the uniform-field region between the poles of a dipole magnet. Energy and intensity measurements are performed using a vacuum curved-crystal spectrometer ($E/\Delta E \approx 300$) positioned at 90° to the incident ion beam. Both the ion beam and the spectrometer are perpendicular to the magnetic field lines. The (≈ 10 $\mu gm/cm^2$) exciter foil is oriented at 45° to the ion beam and with its downstream surface facing the spectrometer. The point at which the ion beam intersects the exciter foil changes slightly when the magnetic field is applied. This change does not affect the detection efficiency appreciably, but is is large enough to produce an observable doppler shift in the experimental spectrum. The sign of the doppler shift provides a redundant identification of the deflection direction of the ion beam within the magnetic field (i.e., increasing wavelength corresponds to the beam intersecting the target downstream, and vice versa).

Prompt X-ray emission was measured under strong-field conditions in the wavelength region from 14.0 to 24.0 Å. This region contains the entire Lyman series in H-like oxygen and the entire Lyman-like series in He-like oxygen, including both series limits. Comparison of this spectrum with one taken under field-free conditions shows that the most outstanding difference between these spectra occurs in the He-like oxygen series-limit region. In view of this, the region from and including the He-like K_{γ}^{He} transition to and including the series limit was measured with good statistical accuracy for magnetic fields of +4.3 kG, 0, and -6.6 kG. These three spectra are presented in the figure on the following page. This series limit region is enhanced under the strong field conditions, independent of the sign of the deflection (i.e., independent of the sign of the small deflection of the ion beam). This fact is important to note, since a strong enhancement of the series limit region has been reported previously in the delayed spectrum of He-like oxygen (see section 2-E). However, we may be assured that the observed enhancement is not due to delayed effects since the enhancement was found to persist under strong field conditions for both a slight downstream and a slight upstream deflection, when compared to the zero-field (no-deflection) spectrum.

The enhancement of the Lyman and Lyman-like transitions in the series-limit region may provide a new technique by which the ionization thresholds of these bound electronic systems can be measured.

d. Scattering of Electrons from Highly-Ionized Atoms

(W.J. Braithwaite, D.L. Matthews, and C.F. Moore)

A substantial population of excited states near the (appropriate) ionization limit of hydrogenic (and He-like) oxygen may be inferred from the delayed X-ray decay measurements. Since these states are quite long-lived and since the electrons in these states are very loosely bound, experiments were started to examine the vulnerability of these electrons to external perturbations.

Initially, electrons were scattered from these highly-ionized atoms since it was hoped that even a very weak collisional perturbation would be sufficient to excite these barely-bound electrons

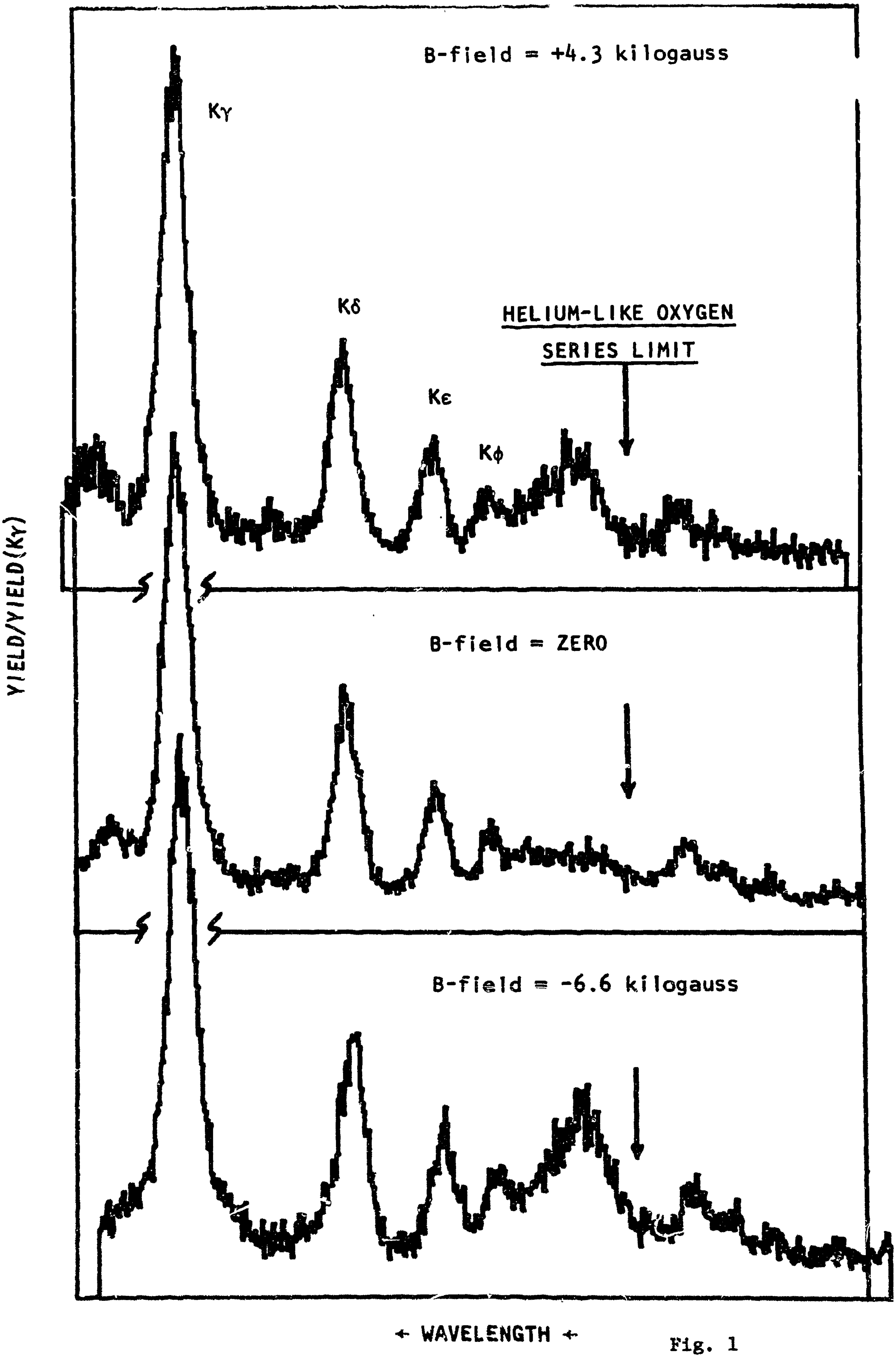
B-field = +4.3 kilogauss
Kγ
Kδ
HELIUM-LIKE OXYGEN
SERIES LIMIT
Kε
Kϕ
B-field = ZERO
B-field = -6.6 kilogauss
YIELD/YIELD(Kγ)
← WAVELENGTH ←

Fig. 1

into the continuum. A 90%-transmission conducting grid was mounted about 1 mm downstream from the exciter foil from which it was insulated. Tests with the grid alone show X-ray production in a delayed spectrum, whereas the X-ray transition strengths near the series limit, following excitation by the foil shows an enhanced relative yield in the delayed spectrum. Thus, the enhanced yield of the Lyman X-ray transitions near the series limit in hydrogenic oxygen was used to measure the number of electrons <u>not</u> scattered into unbound states. Since all of the knockout electrons, associated with a particular oxygen projectile, must emerge from the beam-foil very near the direct path of the oxygen ion, their current density near this ion should be quite large.

Surprisingly enough, accelerating these electrons toward the oxygen ion INCREASED the number of observed X-rays. In order to probe further, a decelerating field was imposed which resulted in a decrease in the number of observed X-rays. These results might be explained by suggesting that an energetic flux of electrons of varying velocities emerge from the exciter foil as a result of collisions between each ion and many electrons in the foil and the grid-foil apparatus only served to accelerate or decelerate this energetic electron stream.

Further experimentation showed a correlation between the X-ray yields and the grid-foil current. As a result, other macroscopic effects were sought using the grid-foil apparatus, but none were observed. The most interesting effect sought was a macroscopic change in the charge state of the heavy-ion beam as it passed through the foil-grid apparatus. The 0° magnetic spectrometer (described in section II.E.) had an insulated, shielded and electron-suppressed Faraday cup installed

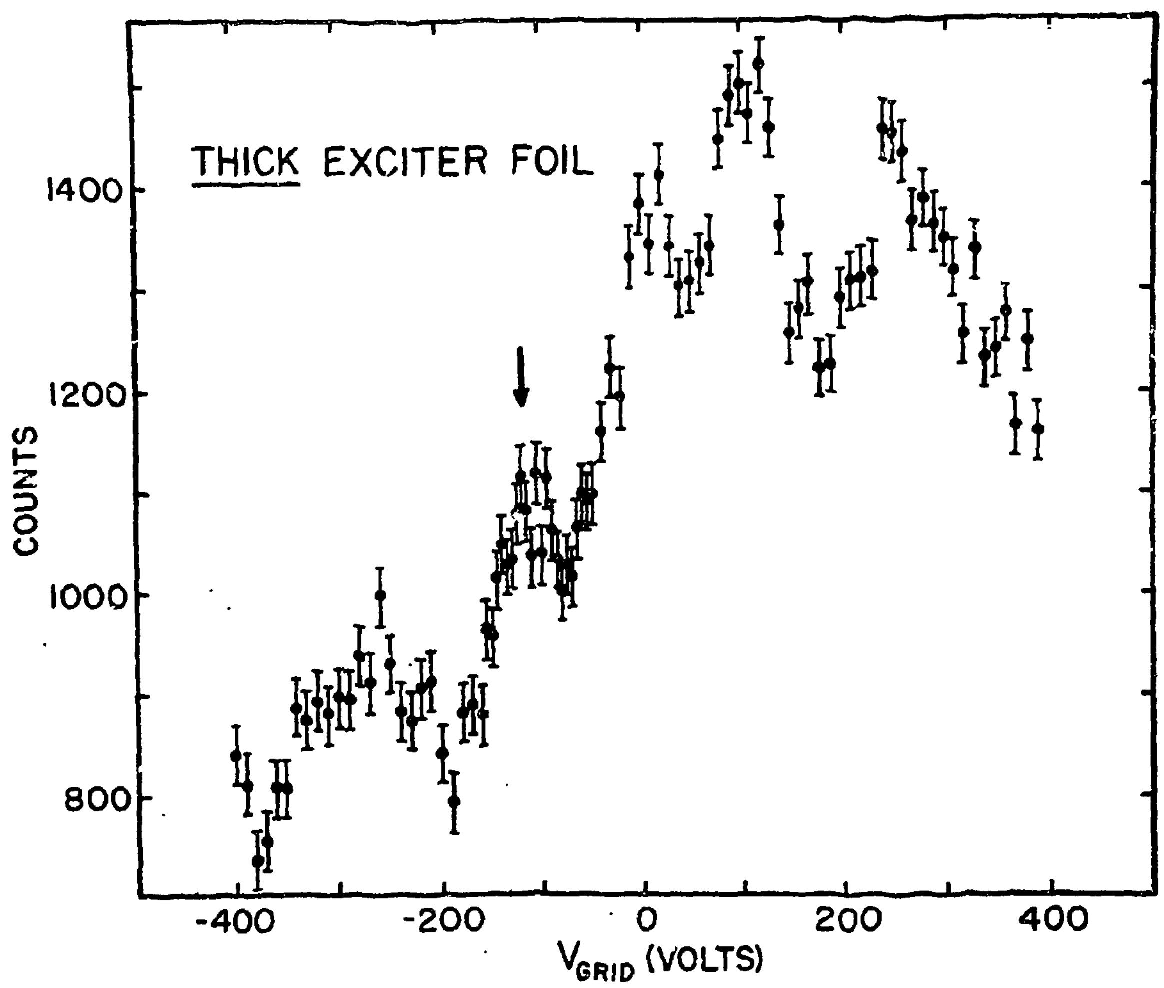

Figure 1

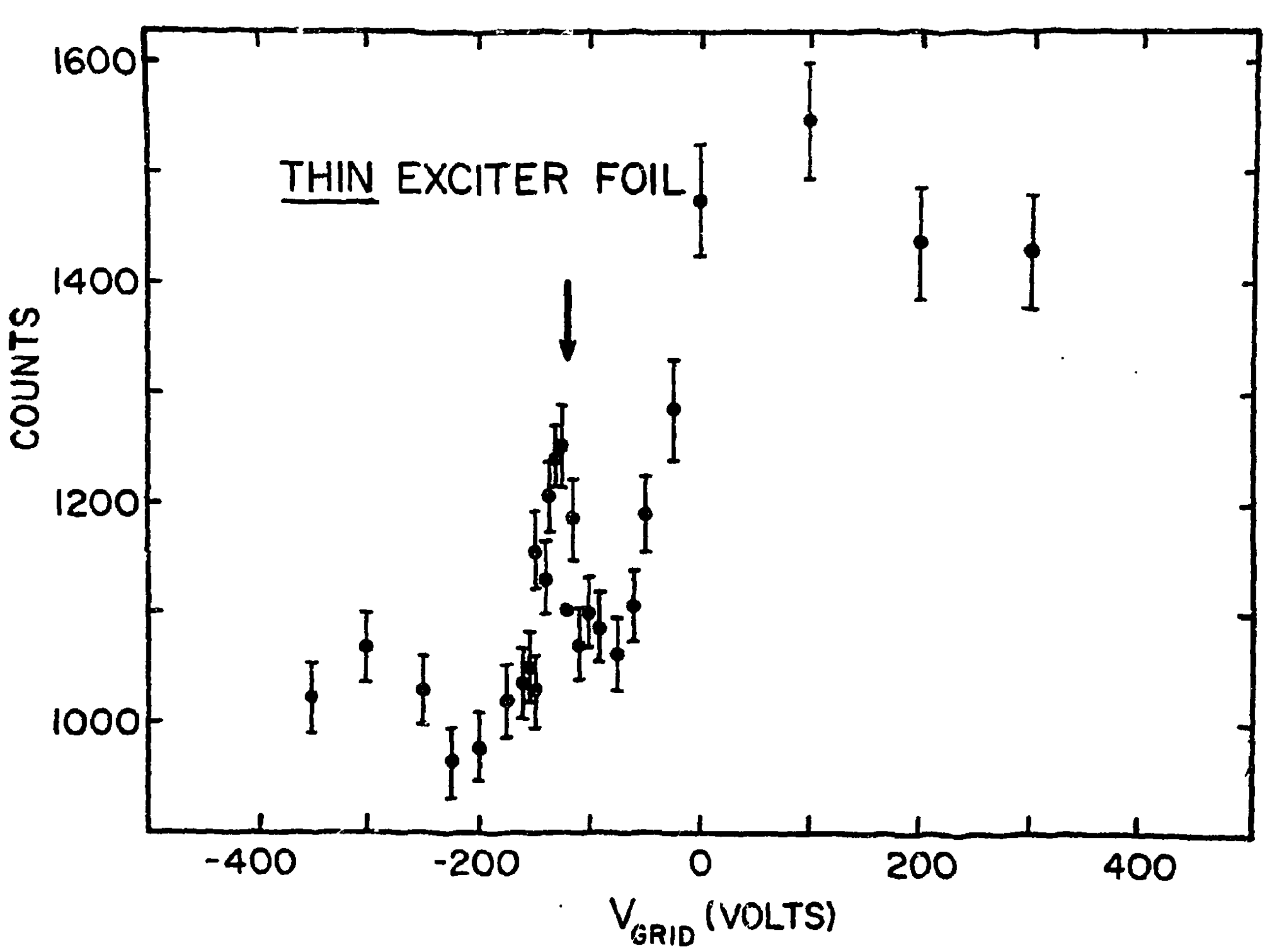

Figure 2

at the double-focussing point. All the oxygen charge states from 3 to 8 were inspected individually by the Faraday cup, but none showed any current change for a systematic stepping of grid voltages at both polarities.

The original grid-foil experiment was repeated using much smaller steps in changing the grid-foil voltage. Preliminary work on a thick exciter foil showed an X-ray yield that fluctuated with applied voltage. This may be seen in Figure 1. The thick exciter foil was replaced by a thin one and the experiment was partially repeated. Figure 2 shows that the yield using the thin-exciter foil shows sharper structure. These peaks may be due to some sort of resonant atomic excitation, leading to a final state where only one electron is bound to the bare oxygen nucleus.

e. The Neon K-Auger Electron Spectrum Following Ionization by 0.15 - 6.0 MeV Protons

(D.L. Matthews, B.M. Johnson, J.J. Mackey, L.E. Smith and C. Fred Moore)

This research presents part of a more detailed experiment to measure the variation in the fluorescence yield for multiply-ionized neon as a function of proton bombarding energy. The remaining experiment (in progress) will be to make the analogous measurement of x-ray yields versus proton energy. Evidence that the fluorescence is not constant with proton bombarding energy has already been noted in low resolution measurements by Schneider et al[1]. Several colleagues have suggested we check the validity of this work with high resolution measurements. The results, although lacking the x-ray measurements, are interesting enough to present herein.

Electron[2-5] and proton[4,5] induced Ne K-Auger spectra have been studied in great detail. These spectra have shown that in addition to the normal Auger lines (associated with single K-shell ionization) satellite lines resulting from simultaneous K and L-shell ionization are also observable. Electron and photon bombardment[4] of neon produced satellite lines of nearly the same intensities. In addition, no variation in the amount of L-shell excitation produced by bombardment with electrons of different energies has been observed[6]. This implies that L shell excitation is mainly caused by electron shakeoff[4]. In contrast, 300 keV proton induced Ne spectra[7] show much more intense satellite lines than observed in the electron or photon impact. Measurements with 4.2 MeV proton[8], however, yield approximately the same satellite intensities as with electron or photon bombardment. Further, measurements with low resolution[1] in the energy range from 0.10 to 2.0 MeV have shown the satellite production probability, Q_s

$$Q_s = \frac{\text{satellite yield}}{\text{satellite + normal yield}}$$

to be a smoothly decreasing function of proton bombarding energy.

Hansteen and Mosebekk[9] have discussed the strong satellite production for light ion-atom collisions in terms of consecutive Coulomb ionization of the K and L shells by the bombarding projectile. With Coulomb excitation, the amount of energy transferred to the inner and outer shells is strongly dependent on the velocity of the projectile, (i.e., interaction time) and the relevant impact parameters. For proton bombardment, Hansteen and Mosebekk also noted strong variation in the peaks of K and L shell ionization cross sections as functions of both bombarding energy and impact parameters. Experimental results appear to support their Coulomb ionization description as the dominant excitation mechanism in light ion-atom collisions.

The experiment presented in this section was performed with the same double focussing electron analyzer discussed earlier in this report. The experiment consisted of measuring the single 2p vancancy Auger satellite yield to total Auger yield at proton energies of 150, 200, 250, 400, 500, 700, and 6000 keV. The energy resolution of our spectrometer was 0.02% FWHM for all measurements. A variation in the observed peak width of the $KL_{2,3}L_{2,3}$ ($^1D_2$) line as a function of the bombarding energy was also measured. Table 1 shows that linewidths vary in a smoothly decreasing fashion with ion velocity. The more than 100% decrease in linewidths going from 150 keV to 6.0 MeV proton bombardment reflects the variation in the amount of Coulomb excitation (target recoil broadening effects are smaller for small energy transfers).

Figure 1 shows the Auger spectra taken at some of the more interesting bombarding energies. The lines marked D are normal Auger lines arising from single K shell ionization. The remainder are from simultaneous K shell and L shell ionization resulting in the doubly ionized configuration $1s^2 2s^2 2p^5$ for neon. Some lines associated with initial 2s instead of 2p L shell vacancies are possibly observed. However, unique identification of these lines is not certain (see Schmidt[10]), and therefore no tabulation of KL_1 vacancy production is given. The spectra show the dominance of satellite transitions due to the enhanced KL/k shell relative ionization cross section for low ion velocities and large impact parameters. These qualitative features are in good agreement with the Coulomb excitation theory discussed earlier[2].

Figure 2 shows a graph of Q_s versus proton bombarding energy both for this measurement and the previous data by Schneider _et al_. In the energy range from 150 - 600 keV, our Q_s is consistently 40 - 50% smaller. However, the two sets of data are in closer agreement for higher incident proton energies. The only explanation for this discrepancy must be in the inability to accurately extract satellite to normal yields when performing an experiment with low resolution. In our measurements, the maximum error came in extracting the intensity of the $^3P_{012}$ normal line which is overlapped in strength by a nearby satellite for some bombarding energies. The error which could be contributed to Q_s by completely omitting either of these lines is 10%. Qualitatively, we agree with their observations, although the fluorescense yield variation they report should now be reconsidered.

The value of Q_s at the proton energy of 6.0 MeV merits attention. It is 20% lower than that obtained with electron bombardment. This could imply that electron shakeoff is not the dominant L shell ionization mechanism for high energy proton bombardment. However, further verification of these preliminary results will be necessary before further conclusions can be made.

Extension of the measurements to the satellite productions using various energies of He^+ projectiles is also planned. A detailed comparison of satellite spectra produced by bare He^{++} to that of He^+ bombardment will also be measured to investigate the L-shell ionization effects of compound e^- + nucleus projectiles

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[1] D. Schneider, et al., Proc. of VIIIth Internatl. Conf. on Electronic and Atomic Collisions, Beograd, 1973, Abstract of Papers, p. 729.
[2] H. Körber and W. Mehlhorn, Z. Physik 191, 217 (1966); W. Mehlhorn, et al., Z. Naturf. 23A, 287 (1968).
[3] K. Siegbahn, et al., ESCA Applied to Free Molecules, North-Holland Publishing Company, Amsterdam-London (1969).
[4] M. O. Krause, et al., Phys. Lett. 31A, 81 (1970).
[5] M. O. Krause, et al., J. Phys. 32, C4 - 139 (1971).
[6] T. A. Carlson, et al., Phys. Rev. A1, 1327 (1970).
[7] A. K. Edwards and M. E. Rudd, Phys. Rev. 170, 140 (1968).
[8] N. Stolterfoht, et al., to be published in Phys. Lett. A.
[9] J. M. Hansteen, et al., Phys. Rev. Lett. 29, 1361 (1972).
[10] V. Schmidt, Proc. of Internatl. Conf. on Inner Shell Ionization Phenomena and Future Applications, p. 548.

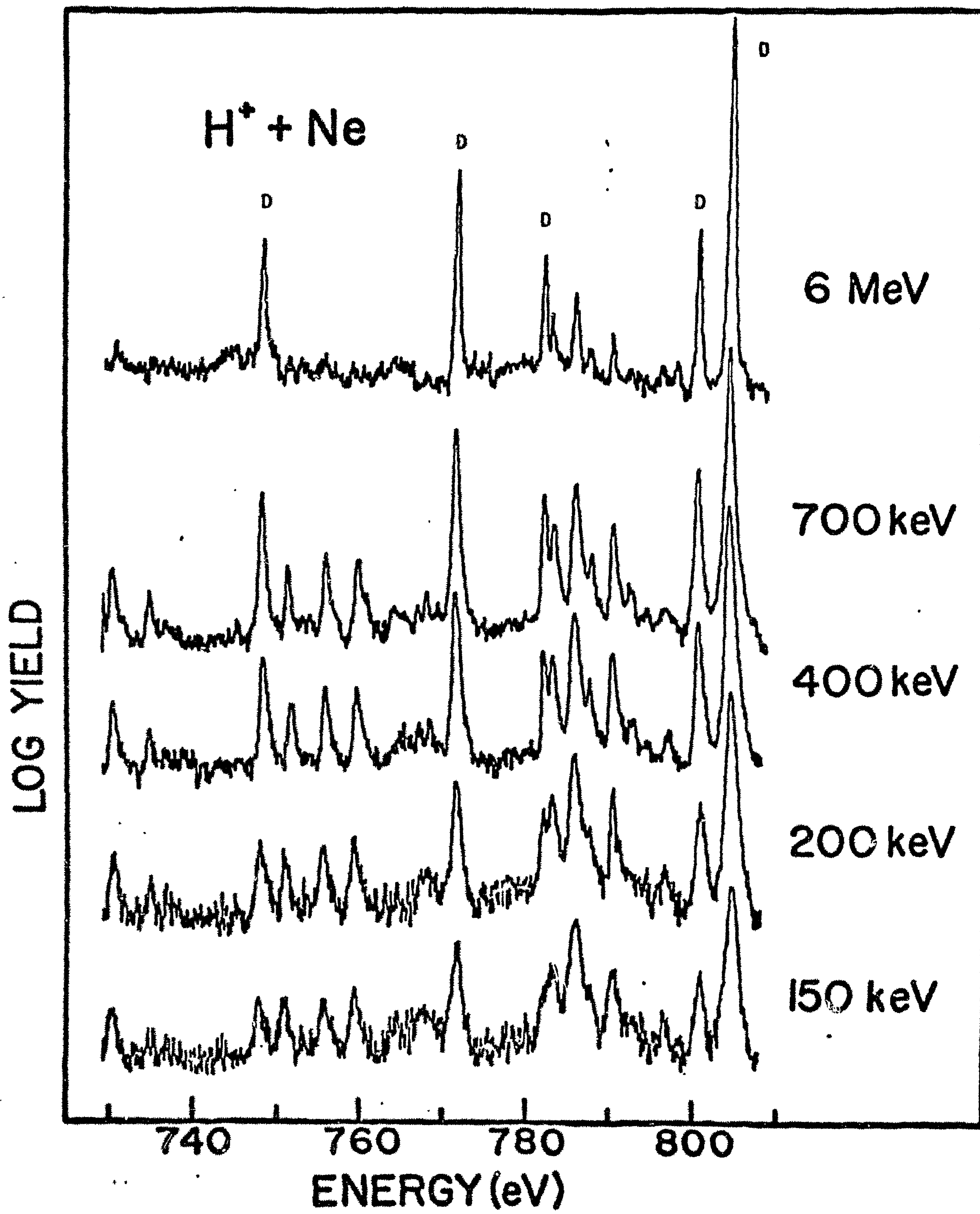
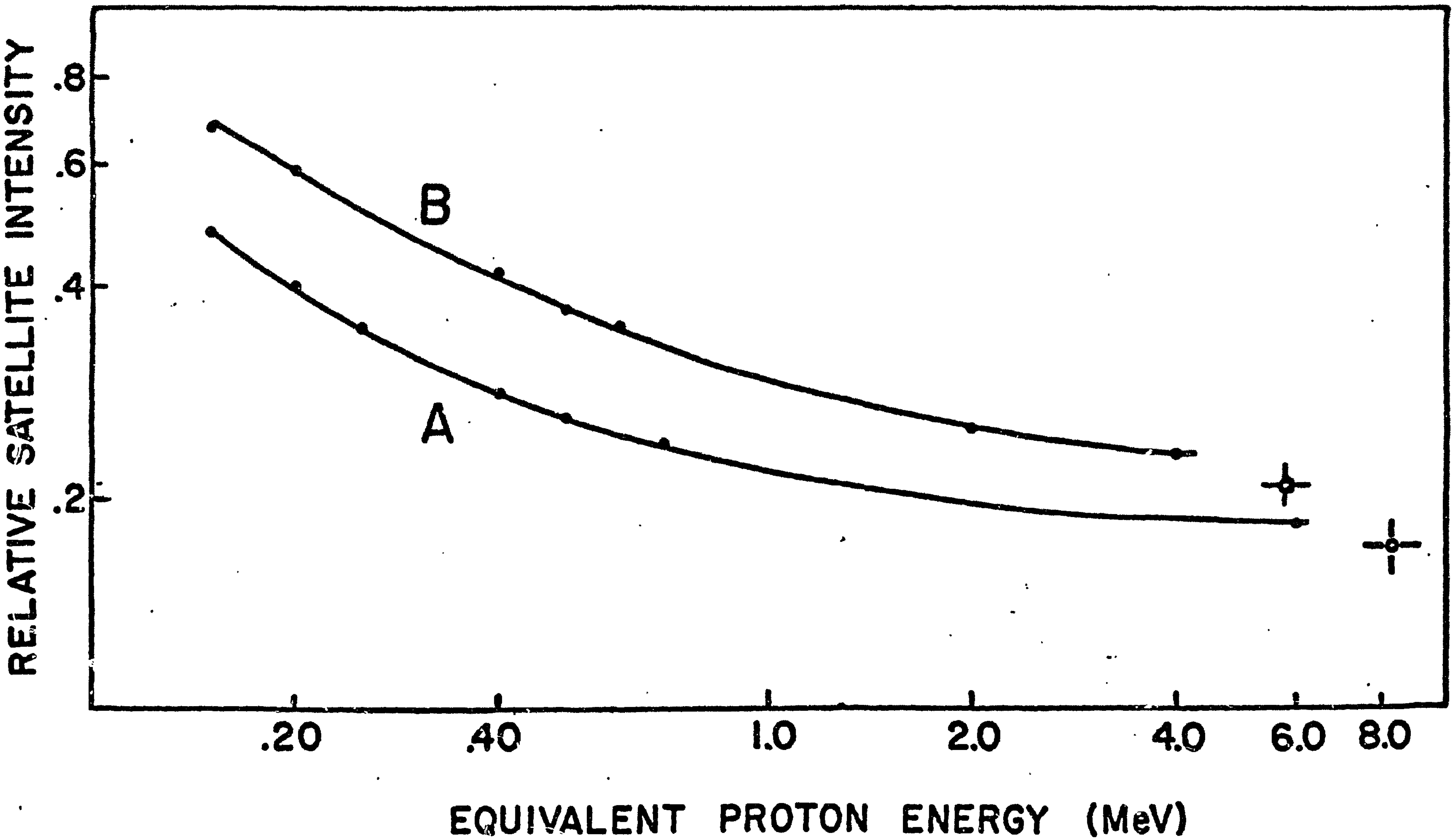

H⁺ + Ne
D
D
D
D
D
6 MeV
700 keV
400 keV
200 keV
150 keV
LOG YIELD
740
760
780
800
ENERGY (eV)

FIGURE 1



RELATIVE SATELLITE INTENSITY
.8
.6
.4
.2
B
A
.20
.40
1.0
2.0
4.0
6.0
8.0
EQUIVALENT PROTON ENERGY (MeV)

Fig. 2

TABLE 1

Peakwidths Versus Proton Bombardment Energy in H^+ + Ne K-Auger Measurements

Proton Energy (MeV)	ΔE FWHM, $KL_{2,3}L_{2,3}(^1D_2)$ Line(eV)
0.15	1.06
0.20	0.81
0.40	0.73
0.50	0.67
0.60	0.64
6.0	0.51

f. A Momentum Representation Treatment of the Hydrogen Atom Problem

(E. V. Ivash)

Energy levels and wave functions are obtained for the quantum mechnical, nonrelativistic, hydrogen atom problem for the $\ell = 0$ case, using the momentum representation. The result for the energy levels is extended to the general case of arbitrary ℓ, using the factorization method.

A paper describing this work is published in Amer. J. Phys. 40, 1095 (1972).

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II. F. RESEARCH INSTRUMENTATION

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1. High Resolution QDDQ Magnetic Spectrometer

(G.W. Hoffmann, C.F. Moore, Gary Hogan)

A high resolution quadrupole-dipole-dipole-quadrupole (QDDQ) magnetic spectrometer for use with the tandem accelerator is now in its final stages of design. The design, which incorporates special mirror symmetries about the geometrical center of the system allows a realistic resolution of a few kilovolts (at tandem energies) with an enormous 20 msr solid angle. The system is strictly a spectrometer as opposed to a spectrograph and the dipole and quadrupole fields will be computer controlled from the PDP-7 with the data being accumulated using the multiscaler facility of the PDP-7. The QDDQ system was designed with the computer codes TRANSPORT[1)] and RAYTRACE[2)] in the spirit of the matrix approach[3)] to the design of magnetic analyzing systems. In particular, we choose the matrix elements (θ/θ) and (y/ϕ) to be identically zero at the mirror symmetric point of the geometrical system, i.e. along the plane midway between the dipoles and perpendicular to the central trajectory. The second order pole face curvatures are then chosen to make this point to parallel (in the analyzing plane) and point to point (in the non-analyzing plane) condition exact to all orders at the mirror symmetric plane of the system. When this condition is met, rays from a point source follow mirror trajectories in the second half of the QDDQ system, double focussing occurs along the focal plane of the spectrometer and aberrations in θ and ϕ are zero. The figure shows a schematic layout of the system with the pertinent data. An important feature of the design is that the

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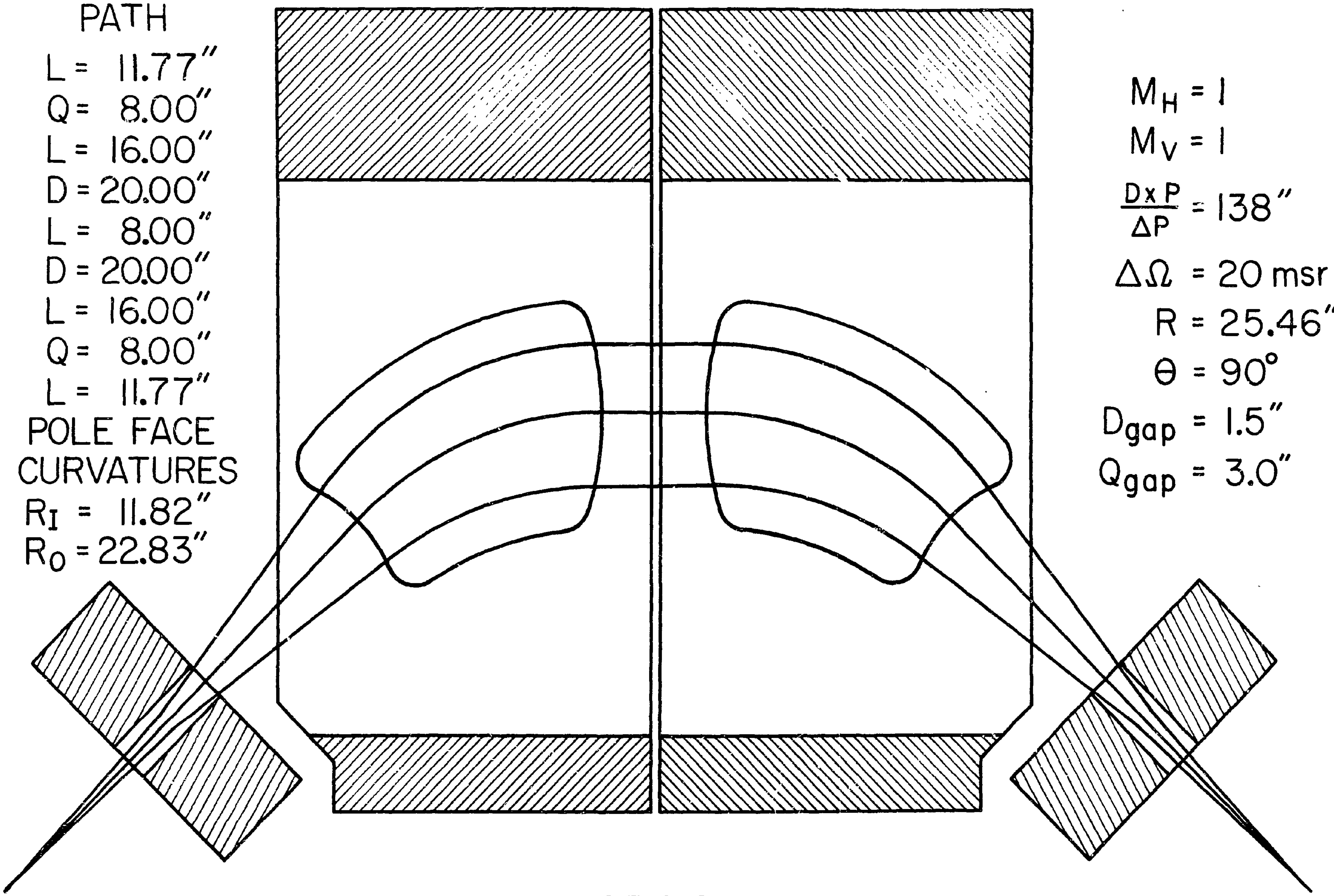

QDDQ
SPECTROMETER

quadrupole fields and positions may be slightly varied to correct the rather large $\frac{dE}{d\theta}$ kinematical broadening associated with heavy ion induced reactions.

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1)Karl Brown, Stanford Linear Accelerator Project, Stanford University, Stanford, California.

2)Stan Kowalski, Massachussets Institute of Technology

3)Karl Brown, SLAC Report #75, Stanford Linear Accelerator Center, Stanford University, Stanford, California

2. Low Dispersion Magnetic Analyzer for Reaction Products Involving Heavy Ions

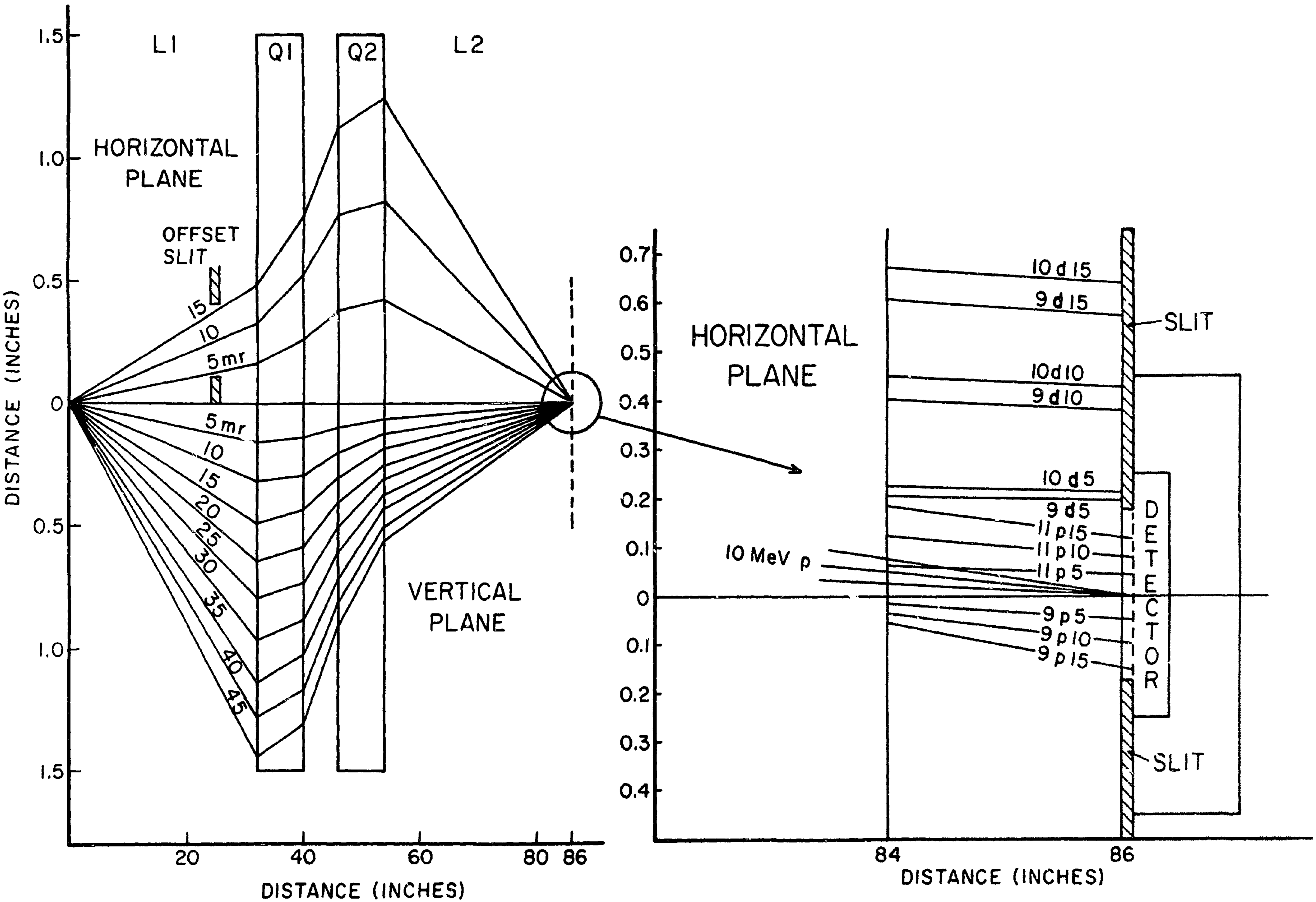
(S.A.A. Zaidi and Gary Westfall)

The study of heavy-ion induced reactions requires the knowledge of momentum as well as the energy of the reaction products so that the corresponding masses may be determined. We have constructed a sector focussing magnet that employs a high field gradient and strong edge focussing properties to produce approximate double focussing of up to 30 MeV protons. The total deflection is about 13° and the radius of curvature is about 70 cm. The magnet and detector fit in the 40" scattering chamber in which they can be used in conjunction with other detectors. We hope to use this analyzer for study of heavy-ion induced reactions.

3. Biased Quadrupole Doublet Magnetic Spectrometer

(G.W. Hoffmann, W.R. Coker, J. McIntyre, and M. Mahlab)

Another system utilizing magnetic deflection, known as a biased magnetic quadrupole spectrometer, has also recently become operational for experiments requiring particle identification with the best energy resolution from a single charged particle detector. Basically, this spectrometer consists of a magnetic quadrupole doublet on a moveable arm (from 0° to 70° laboratory angle) radial from the target. The image and object distances are each 33 inches and the magnetic fields in the quadrupoles are chosen to double focus a particle of a given energy. However, by moving the magnetic center of this quadrupole off axis, an effective dipole field is superimposed upon the quadrupole field, and the system is dispersive as well as double focussing. This dispersive nature makes particle identification routine. The system's focussing and dispersing properties have been studied extensively with TRANSPORT[1]. For example, with the geometry shown in the figure, a schematic of the system, protons admitted through the slits (solid angle $\simeq$ 1 msr) of energies between 9-11 MeV (if the quadrupoles were adjusted to focus 10 MeV protons exactly) would all be focussed through a 0.25 in.slit in front of a solid state detector, while deuterons of this energy range would not be admitted by the slit. Hence, the system is excellent for (d,p) studies to highly excited states, since only protons of a rather broad range would be detected for given quadrupole settings. Similar applications for heavy ion reaction studies are anticipated.



L1
Q1
Q2
L2
HORIZONTAL PLANE
OFFSET SLIT
15
10
5 mr
5 mr
10
15
20
25
30
35
40
45
VERTICAL PLANE
DISTANCE (INCHES)
DISTANCE (INCHES)
HORIZONTAL PLANE
10 d 15
9 d 15
SLIT
10 d 10
9 d 10
10 d 5
9 d 5
11 p 15
11 p 10
11 p 5
10 MeV p
9 p 5
9 p 10
9 p 15
DETECTOR
SLIT
DISTANCE (INCHES)

[17]Karl Brown, Stanford Linear Accelerator, Stanford, California

4. Target Transfer System: Decay of ^{64}Ga

(L. Parks and C. Davids)

A pneumatic target transfer system ("rabbit") has been constructed for study of the decay of ^{64}Ga. The function of the "rabbit" is to remove the activated target to a shielded area several meters from the beam tube area in less than 1 second. All data acquisition by the detectors is done at this point. The purpose of this is to protect the detectors from high neutron fluxes and greatly reduce the background due to the activated beam tube. The "rabbit" tube was originally 17 feet long and enabled the detector station to be placed behind a brick wall in the experimental area itself. We have recently modified the tube to extend instead into an adjacent room, greatly improving the detector shielding, and shortening its transit time.

A sequential timer has been constructed to be used in conjunction with the "rabbit". It controls the timing of the bombardment and firing of the valves of the "rabbit", and also provides signals for routing data into the PDP-15 computer for the determination of half-lives. Spectra are collected in up to six successive time bins from which half-life calculations may be made.

The positron decay of ^{64}Ga produced by the $^{64}Zn(p,n)^{64}Ga$ reaction was studied in order to check out the "rabbit" and its associated electronics. Using the "rabbit" the half life of ^{64}Ga

was measured to be 154.1 ± 0.5 seconds. This is somewhat lower than values arrived at by previous work[1,2,3]. We performed the experiment two times, making modifications on the set-up after the first measurement. Both results are quite consistent (153.9 ± 0.8 seconds and 154.1 ± 0.5 seconds). We plan to measure the half life of the metastable state of ^{54}Co produced by the $^{54}Fe(p,n)^{54}Co$ reaction in order to further check for possible systematic errors in the system.

A gamma-gamma coincidence experiment was done, involving the decay of ^{64}Ga using the rabbit. This agreed with previous results.

1C.N. Davids and D.R. Goosman, Phys. Rev. C7, 122 (1973).
2J. Konijn, R. Van Lieshout, J.P. Deutsch, and L. Grenacs, Nucl. Phys. A91, 439 (1967).
3C.E. Moss, C. Detraz, and C.S. Zaidins, Phys. Rev. C5, 1122 (1972).

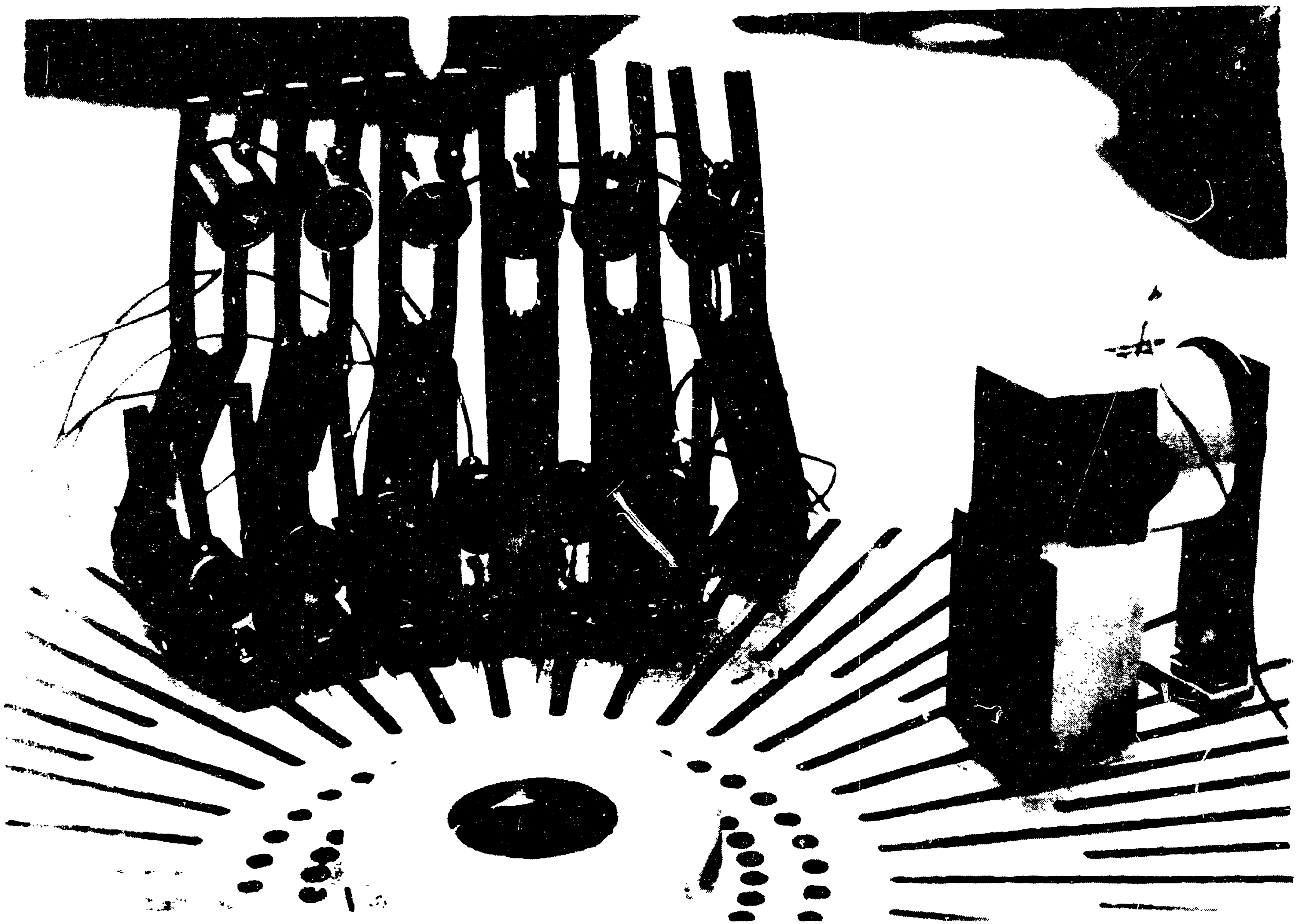
5. An Array of Alpha Detectors for Use in Spin Assignments

(W.J. Braithwaite, A.W. Obst, and C.H. King)

Figure 1 is a photograph of a 12-detector array of silicon detectors along with a conventional ΔE-E charged-particle telescope. This group of detectors is designed for use in measuring spins of alpha-unstable states in even-even nuclei using "A New Method for Spin Determinations Using Heavy-Ion-Alpha Angular Correlations", described elsewhere in this report (II. E. i.).

The charged-particle telescope in Figure 1 is used to measure the energy and to identify the MZ^2 of the heavy ion that emerges from the reaction that forms the alpha-unstable state. This detector is located at a non-zero angle with respect to the

Fig. 1



beam, so a scattering plane is defined by this FORMATION reaction. The 12 detectors for measuring the energies of each DECAY alpha from each excited nucleus are located out-of-plane at 12 laboratory (θ,ϕ) positions, corresponding to 12 different values of Φ (for fixed Θ) in the center of mass of the alpha-unstable nucleus.

In the detector arrangement of Figure 1, the charged particle telescope is set at an angle of -15^{o} LAB from the beam and the 12 detector array spans in-plane angles every 5^{o} from 35^{o} to 90^{o} LAB. The detectors in the array are spaced, alternatively, above and below the reaction plane in order to permit an in-plane angular spacing of 5^{o}. The out-of-plane angles are adjustable to allow for a variety of different spins to be measured for a variety of different states in a variety of different heavy-ion reactions.

6. Detector Fabrication Developments

(C. Doss)

A large number of lithium-drifted detectors were fabricated from p-type silicon with areas ranging between 30 and 200 mm^2. All were drifted in air without the use of fluorochemicals, the better detectors having resolution of approximately 16 KeV for 5.4 MeV alphas and 4-5 KeV for 1 MeV electrons.

About a dozen surface barrier transmission detectors were made from n-type silicon. Areas range from 50 to 350 mm^2 with some thicknesses as small as 50 microns. The front contact of these detectors was a common gold evaporation while the back heterojunction contact was made with a thin germanium and aluminum evaporation.

Another n-type silicon detector was made as follows: a shallow lithium diffusion (50-75 microns) was made on one side for the n-contact. This side was masked and the rest was etched. A surface barrier contact was put on the front. Twenty five round 100 mm^2 active area and eight rectangular detectors (10 mm x 20 mm x 1.3 mm) of this type were made. Resolution is typically 20 keV for these detectors for the 5.4 MeV alpha line.

Currently a split detector is being developed on a single silicon wafer which has a very thin lead strip between the two independent detectors.

7. A New Type of Position Sensitive Detector

(W.J. Braithwaite, C.R. Doss, and C.F. Moore)

Recently, we have utilized the idea that differences in pulse risetimes can be used to provide position determination in a solid state radiation detector, in direct analogy with conventional position-sensitive gas proportional counters[1]. In preliminary efforts we have found that fairly accurate position signals (≈ 1 mm) can be obtained for bursts of radiation using a specially constructed semiconductor detector (with a very high-resistance backing) which relies on a timing technique that senses the difference in risetimes of the two pulses (associated with one burst) that are collected at opposite ends of the detector's high-resistance backing.

These preliminary efforts were made possible by the purchase of a long cylindrical ingot of n-type silicon. Although we were able to obtain this ingot at a very low price, it unfortunately had a high etch-pit density and ordinary (small) silicon surface-barrier detectors made from this ingot were seriously inferior to those made from small n-type wafers that we had in stock. This ingot was cut longitudinally into strips to provide several large-area wafers capable of being made into silicon position sensitive detectors with a high resistance backings. A rough schematic diagram of our first such detector is shown in Fig. 1. The fabrication of this detector was accomplished as follows: (1) by polishing (lapping) each rectangular silicon wafer on a glass surface, using a slurry of alumina powder and water; (2) by etching the polished silicon wafer in a special solution of acid; (3) by mounting the wafer on a printed circuit board and evaporating a very thin layer of gold onto its front surface; and (4) by evaporating a thin layer of germanium onto the other (i.e. the reverse) side of the detector, followed by a layer (or layers) of carbon. The thickness of the carbon layer determines the resistivity of the detector backing. This thickness can be increased easily, between measurements of the position resolution, by successive carbon evaporations. It is more difficult to reduce the thickness of the carbon layer, when necessary. This is done by dissolving the germanium layer using a solution of hydrogen peroxide and hydrofluoric acid, followed by a re-evaporation of the germanium and carbon.

Initial tests have been performed using a very strong ThC' alpha source which provides two alpha groups: a doublet at 6.05, 6.09 MeV and a singlet at 8.78 MeV. Fig. 2 is a schematic diagram of the system used for testing the position resolution of the detector and Fig. 3 is a schematic of the electronics used in these tests. Fig. 4 is a typical spectrum of the number of detected alpha particles *vs.* the position at which they strike the detector. Our position resolution was between about 0.5 and 1.5 mm, depending primarily on the size of the detector.

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[1]C.J. Borkowski and M.K. Knopp, IEEE Trans. on Nucl. Sci. NS17, No. 3, 340 (1970); *ibid.*, Rev. Sci. Instr. 39, 1515 (1968); M.P. Baker, J.R. Calarco, N.S. Chant, J.G. Cramer, and S. Hendrickson, Nucl. Phys. Lab. Ann. Rept., Univ. of Wash. (1971) p. 49; P.L. Jolivette, H. Stocker, and A.F Hrejsa, Nucl. Structure Research Ann. Rept., Univ. of Notre Dame (1970) p. 190.

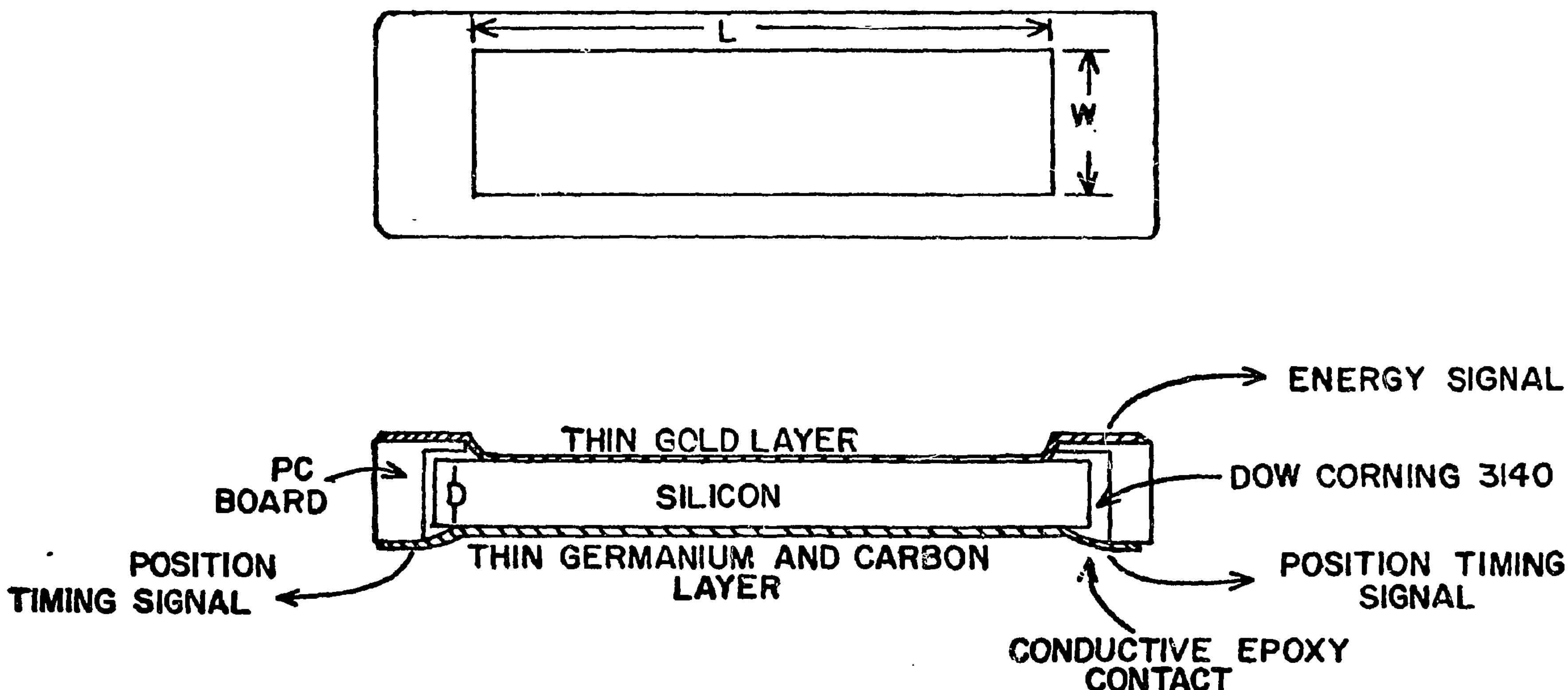


Figure 1 Detector Schematic.

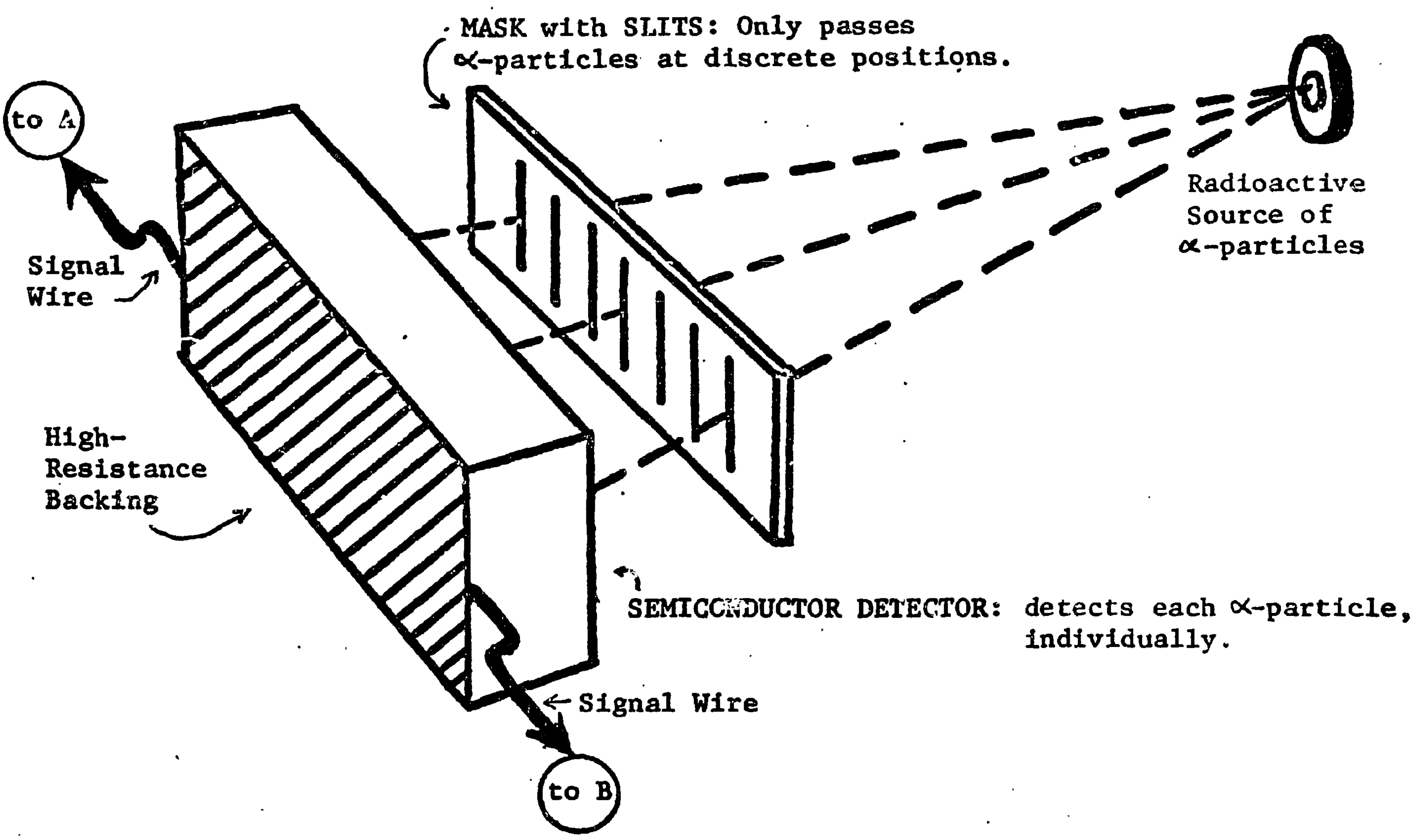
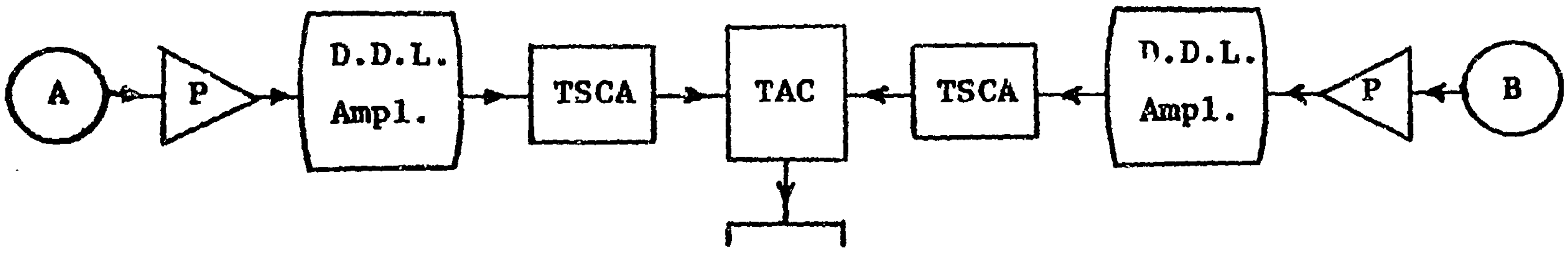


Figure 2 System Schematic.



(to the PDP 15 Computer)

P	Charge Sensitive Preamplifier	D.D.L. Ampl.	Double Delay Line Amplifier
TSCA	Timing Single Channel Analyzer	TAC	Time to Amplitude Converter

Figure 3 Electronics Schematic.

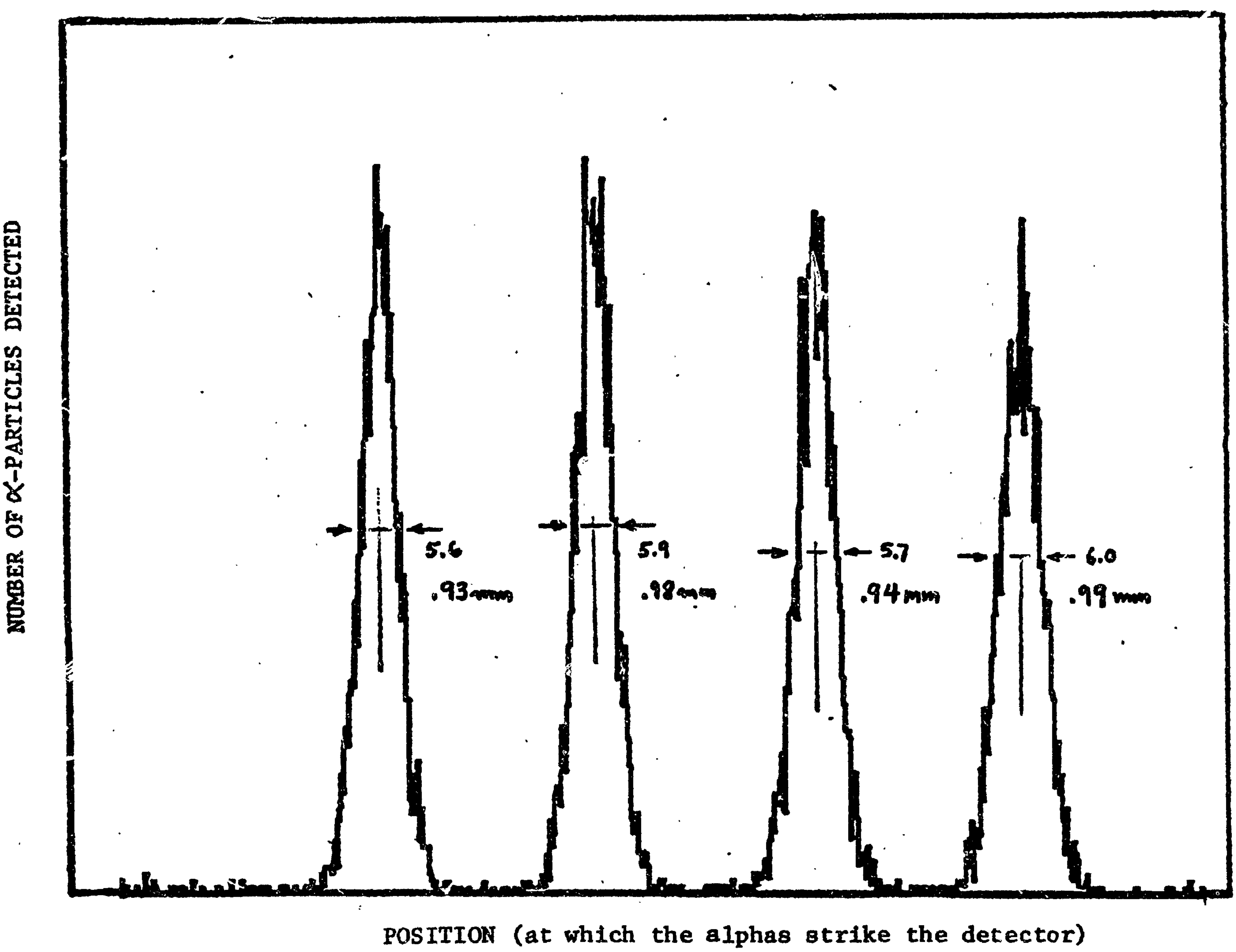


Figure 4 Histogram of counts versus position.

8. The Zero-Degree Magnetic Spectrometer System for Particle-Gamma Ray Angular Correlations

(W.J. Braithwaite, A.W. Obst, and C.H. King)

A double-focussing magnetic spectrograph[1] has been modified for particle detection at 0^o with respect to the beam. Figure 1 shows a rough schematic of this instrument, including a surface-barrier silicon detector located at the double-focussing point on the focal plane.

The reason for detecting the outgoing particles at 0^o is that a decay from a nuclear state formed by such a reaction must have symmetry around the beam axis. Litherland and Ferguson[2] have developed the angular correlation technique referred to as Method II which uses this idea to determine the spin of a nuclear state without requiring any knowledge of the reaction mechanism.

The gamma-ray angular distribution is taken in coincidence with the appropriate particle, detected at 0^o. This angular distribution is provided by an array of four 5" x 5" NaI detectors placed at 25^o intervals from 90^o to 165^o. Each detector is mounted in its own lead shielding as seen in Figure 2. This array is placed on a thick aluminum table top, which is supported by a heavy-duty gun mount capable of moving the detector array around the center of the scattering chamber (see Figure 2).

The correlation system, as described so far, is completed except for our new scattering chamber. We have been using a scattering chamber that had been constructed several years ago for a different purpose, but it proved inadequate for the zero-degree work. Figure 3 is a rough schematic of the chamber that the shop is building.

This drawing shows the general features of the chamber, but it is not quite the final version as some changes have been pencilled onto the shop's copy that don't appear here.

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[1]A.E.S. Green, R.J. Berkley, C.E. Watson, and C.F. Moore, Rev. Sci. Instr. 37, 415 (1966); E. Feldl, C. Fetrow, and C.F. Moore, Nucl. Instr. Meth. 44, 98 (1966).

[2]A.E. Litherland and A.J. Ferguson, Cau. J. Phys. 39, 788 (1961).

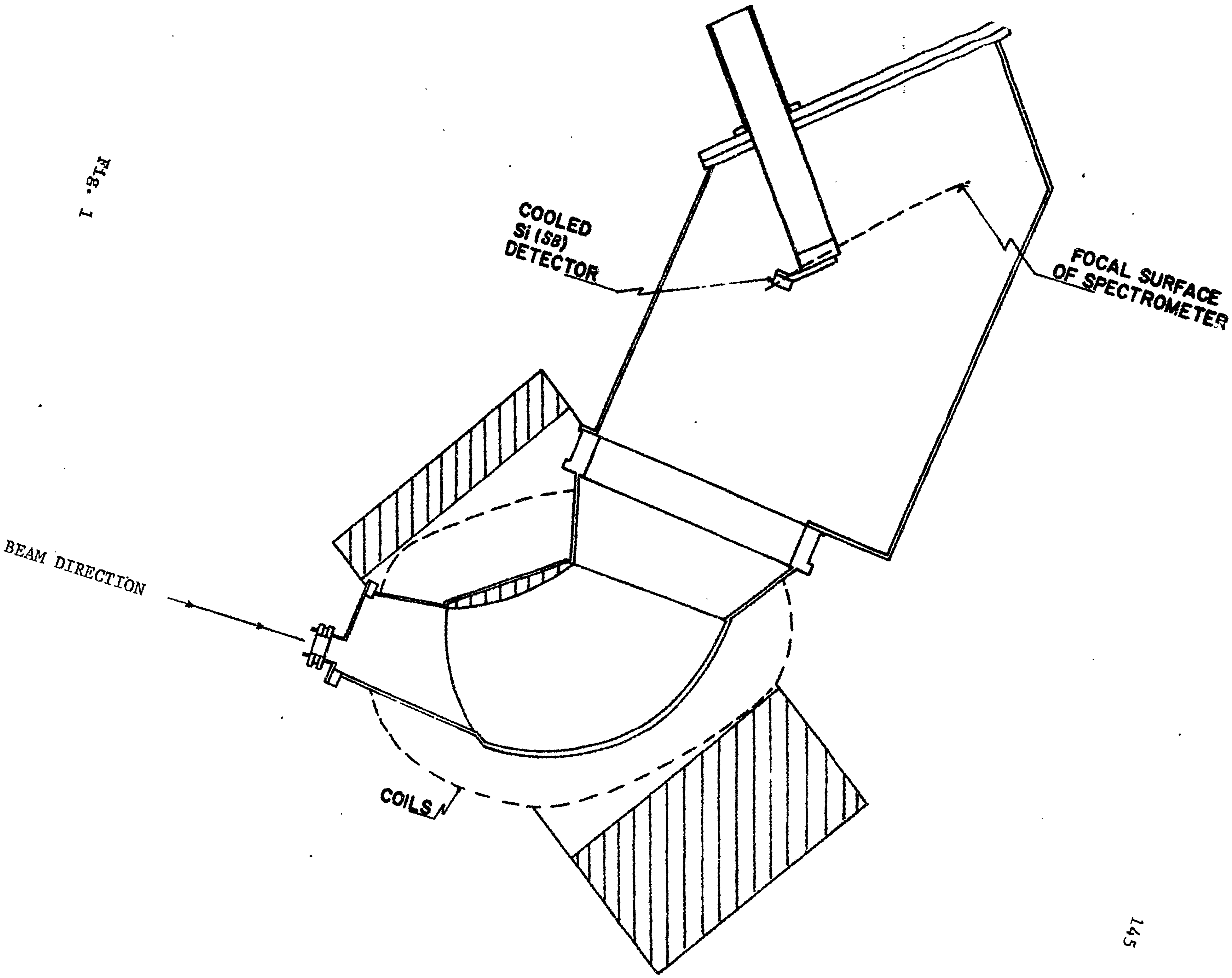
COOLED
Si (SB)
DETECTOR
FOCAL SURFACE
OF SPECTROMETER
BEAM DIRECTION
COILS

Fig. 1

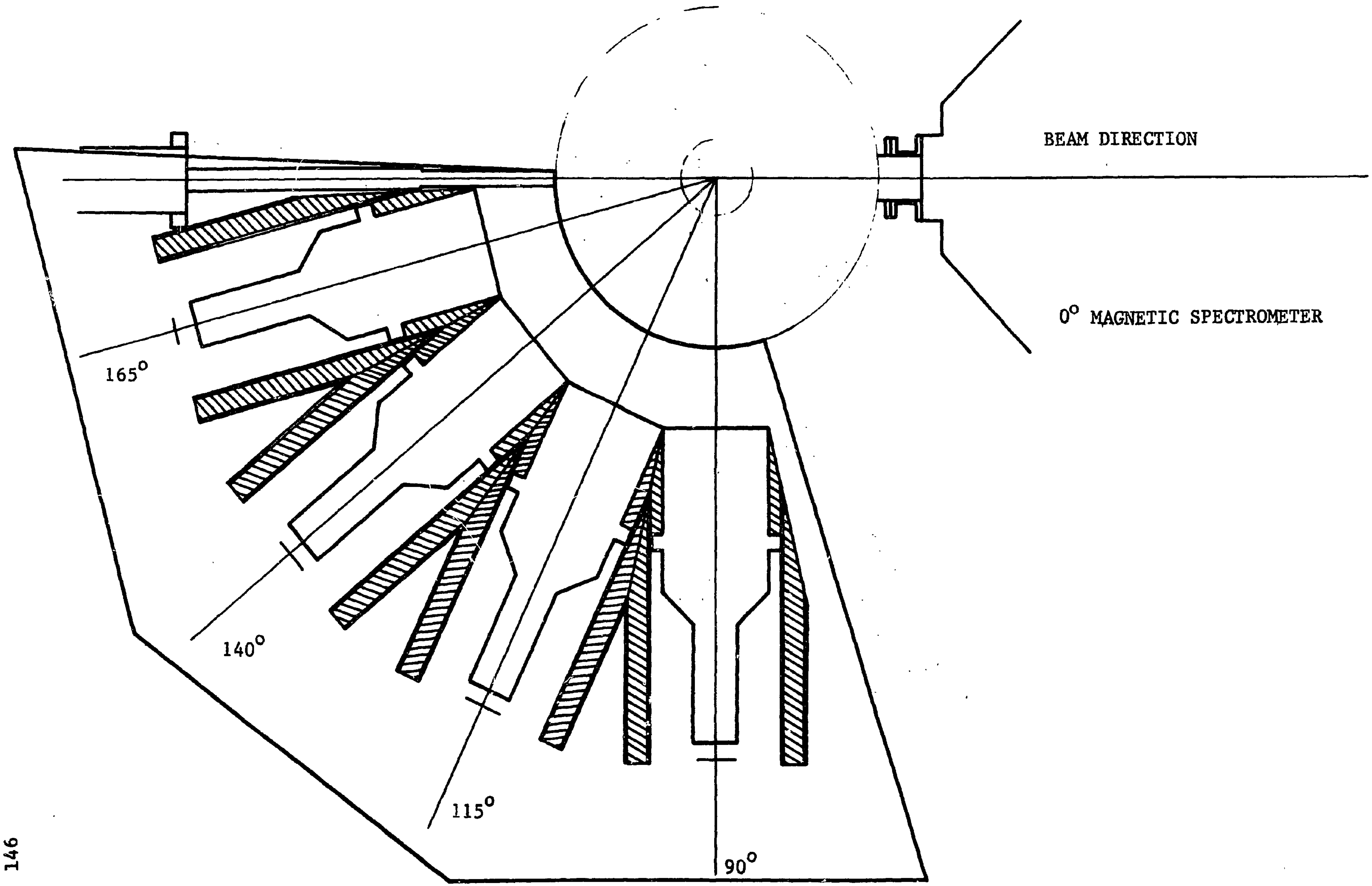

Fig. 2

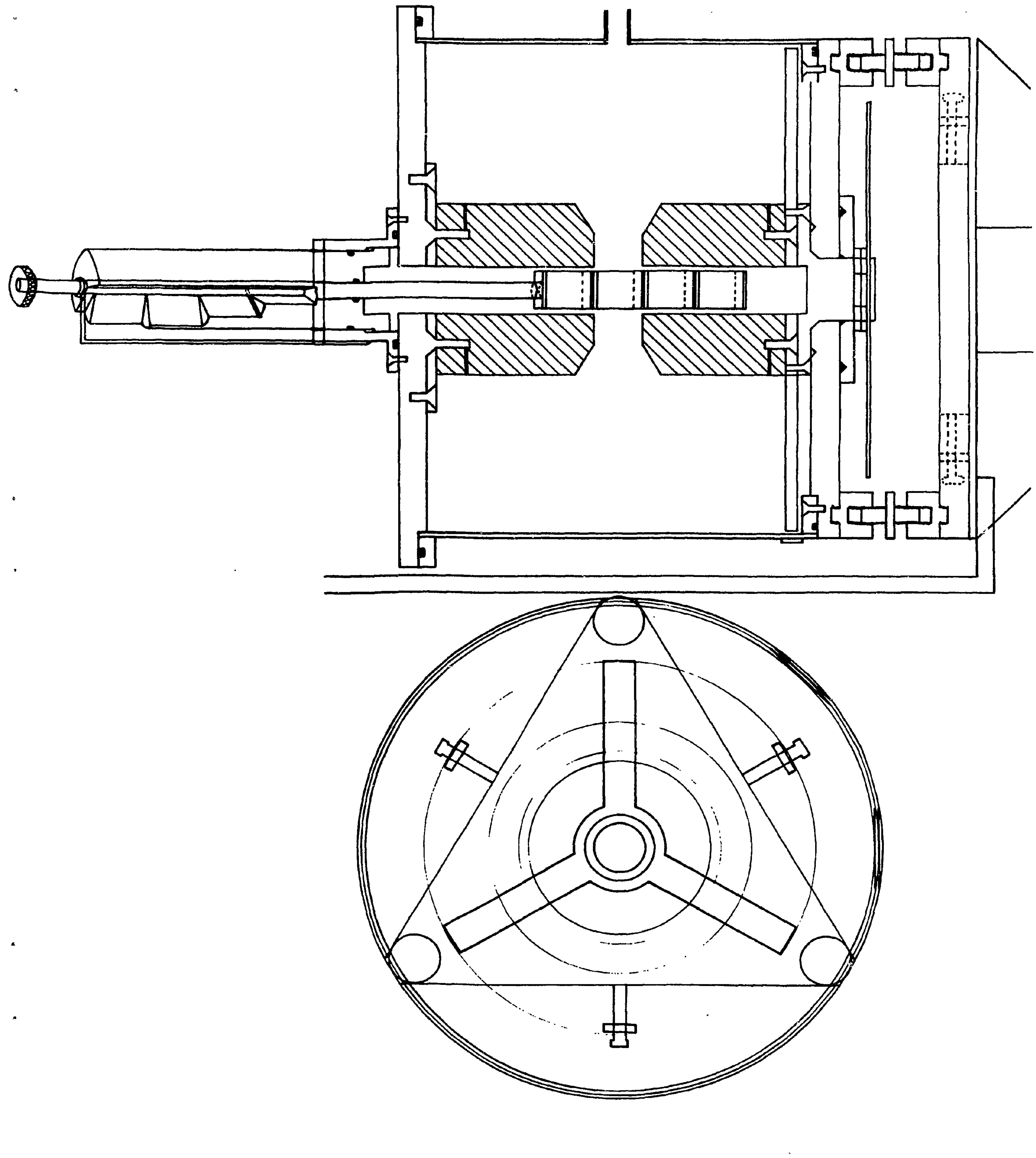

Fig. 3

II. G. LABORATORY FACILITIES

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1. Accelerators

(J. W. Jagger)

a. EN Tandem

During the period described by this report, the EN Tandem operated for 6080 hours. Since the installation of the rebuilt accelerator tubes in 1972, and the ^{137}Cs sources external to the tandem tank, the accelerator has run trouble free at 6 MV.

During the past year a drive motor failed due to faulty bearings. This failure resulted in the entire column structure, resistors, belt, and tank being coated with a thin film of carbon. Removing this film proved extremely difficult, and eventually, the column structure was washed with tepid water and detergent using a water hose pipe and pressure pump. This cleaning operation was far less time consuming than the old technique and resulted in far better cleaning. To avoid a recurrence of this problem, fast-operating adjustable current cutouts have been installed on the three-phase power input to the drive motor. In conjunction with the present temperature sensors, this arrangement should provide adequate protection against such burnouts.

The charging belt presently being used is one of the early "brown" belts. Contrary to other users' experience, this belt has been one of the most successful that we have ever used. It has run for two years, or 9890 hours, and is still in good condition.

b. 5.5 MV Negative Ion Injector

The accelerator tubes for this machine were rebuilt here during 1972. In order to save time, they were reconstructed in the conventional or straight configuration. Subsequent running of the machine shows this to be the wrong decision; it takes far too long to condition the tubes. We have now removed those tubes from the machine, and propose to construct a magnet-

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ically suppressed tube.

c. KN 4.0 MV Positive Ion Accelerator

In May of this year, the coils of the analyzing magnet developed a short circuit to ground, probably as a result of water condensation. The coils were removed and rewound here. The accelerator is now back in operation.

2. Ion Sources

(J. W. Jagger, B. K. Naumann, T. Majors)

a. Direct Extraction Sources

A new stabilized 100 KV injector power supply was purchased with University funds to replace the old unstabilized power supply used with the direct extraction sources. This has made the source much more usable in terms of beam position stability.

b. Middleton Source

(T. Majors, J. Jagger)

Construction of a Middleton type heavy ion source was began in August of this year. The source is now nearing completion and will probably be bench tested before the end of this year.

This source will be housed in a vacuum chamber that is compatable with the lithium-vapor charge-exchange source, or the old H.V.E.C. source. Thus, there will be two identical vacuum housings on separate beam legs of the source deflection magnet, so that each chamber can accomodate either the (a) HVEC source, (b) lithium charge-exchange source, or (c) Middleton source.

In addition, the lithium charge exchange source can be used with the duoplasmatron head, or the Sidineus hollow cathode head.

3. Machine Electronics

(J. Jagger, A. L. Mitchell)

a. Heavy Ion Beam Identification

With the increased use of heavy ion beams, the identification of the various ion species emerging from the ion source analyzer magnet has gotten to be more complex. To overcome this problem, a system using the PDP-15 computer has been tried out.

A computer display has been added to the ion source control panel. The computer drives the remote display using sampled values of the analyzing magnet current and ion-source faraday cup current. Sweeping the magnet current through the range of interest will cause the computer to display the various ion species on the output oscilloscope, and a selected bright spot will identify which particular peak is being magnetically analyzed. The computer program can then calculate the relative mass of the ion beam compared to hydrogen. At present the system is limited by the need to maintain constant ion source accelerator voltage, but we propose also to input this information to the computer and eventually to obtain a versatile beam identification system which can be extended to the output of the tandem accelerator.

b. Capacity Pickups and Slit Amplifiers

(A. L. Mitchell)

Capacity pick-up amplifiers for use with the EN Tandem capacity pick-up terminal monitoring system have been constructed. Originally, a wide-band MOSFET amplifier with input protection circuitry was installed. These amplifiers would not tolerate large tank sparks and repeatedly failed. A very simple nuvistor cathode-follower amplifier has been designed and will be installed for testing. It is felt that this new design will be much more tolerant to tank sparks.

A slit-amplifier system for the EN Tandem has been constructed and tested. A re-design of the current to voltage slit pre-amplifier stage has been necessary. This improved system is to be tested and, if acceptable, will totally replace the existing vacuum tube control system.

A preliminary investigation has been made as to the feasibility of installing a terminal voltage regulation system to remove higher frequency ripple components from the terminal. The slit driven corona load control system is good for approximately DC and low frequency terminal voltage regulation. A light pipe was installed along the low energy column of the EN Tandem. This remained in the machine for six weeks and was removed when several resistors had to be replaced along the same section of the machine. It was decided to postpone further investigation of this type of system.

4. Data Acquisition Facility and Data Processing

a. Data Acquisition Facility Additions

(A. L. Mitchell)

The data acquisition facility of the Center for Nuclear Studies has been expanded again this year by the addition of the following equipment to the PDP-7, PDP-15/20 digital computers:

NS 621 Northern Scientific ADC

NS 459A Northern Scientific MIXER

TDC 100 Time Digitizer (EG & G)

The NS 621 is an 8K ADC with a 50 MHz digitizing clock. When used with the NS 459A four input MIXER where two additional ID bits are added to the ADC output, the system can be run as a four input PHA system. This PHA system has been interfaced to our data acquisition computers for operation in the normal (PHA) mode or a special mode. The special mode allows a single detector input to be routed to different memory storage areas (blocks) when an external logic signal to the interface is provided. The external logic signals can be provided by a "sequence timer" which has been constructed to supply multiple gate outputs that can be "time-programmed" by means of a patch board. The interface's special mode is used for time decay studies of spectra associated with experimental astrophysics research.

The TDC 100 Time Digitizer converts time-interval data into a binary digital format with a time resolution of 125 pico seconds over a period that can be as long as 67 milliseconds. The instrument can be selected to operate in either a single-stop or a multiple-stop mode in which the time interval between a start pulse and an accepted stop pulse is measured, defined digitally as a 29-bit binary word, routed through an interface, and stored in either the PDP-15/20 or PDP-7 memory. The interface for the TDC 100 was designed to present either an 18 bit section of the 29 bit output or the full 29 bit output (broken up into two consecutive computer words of 18 bits each) to the computer for storage. In addition, the interface allows a parallel shift of up to four bit locations when selecting which 18 bits of the 29 will be used. This last feature effectively allows the user to select the time resolution that he needs and still keep an 18 bit range. The TDC 100 and associated interface are used in fission-time-of-flight research.

b. Related Instrumentation

The Automatic Priority Interrupt (KA-15) was installed by Digital Equipment Corporation on the PDP-15/20 computer during the summer. A two input API pulse counting interface has been installed to allow certain experiments to operate scaler count routines in the PDP-15/20 similar to those in use on the PDP-7 system. An additional pulse counting interface is also under construction and will be installed on the PDP-15/20 to allow more complex count routine experiments or multiple-users to operate with the scaler counting program.

A program-relocatable fast increment interface has been constructed for use on the PDP-15/20 data channel. This device contains a program loadable register whose output is added to the incoming ADC PHA histogram word. This hardware allows the program to select where the histograms will be built in the computer memory, thus allowing a fortran program to operate in a real-time data acquiring manner.

The memory increment channel on the PDP-7 has also been modified with a specially constructed adder card containing a program loadable four bit register. This modification allows the supervisor program, via operator keyboard command, to select the starting location in memory of the first data block. The starting location must be a multiple of 1 K because the adder card contains a four bit adder and can shift PHA information by 1 K, 2 K, 4 K, 8 K increments and their combinations.

5. Computer System Software
(Hunter Ellinger)

a. Computers

We have two computers; a PDP-7 with 20 K memory, which is used for data-taking and communication with the CDC-6600, and a PDP-15 with 32 K core and two 256 K disks, which is used for data-taking, analysis, and programming for both computers. Both computers have magtape and Dectape units, and have common interfaces to a card reader, an incremental plotter, and two line printers.

Data input hardware consists of hardware memory increment inputs, eight interrupt lines for use by experimenters, and an ADC list-mode interface on each computer. A special disk interface is used to build moderately fast (>1000 increments/sec) histograms on up to 256 K of disk space.

b. Analog/Digital Converters

We have two Tennelec PACE-8 ADC systems, with 5 μsec digitization and 13-bit precision. We also have a 4-input Northern Scientific ADC with a eight-way routing device, and a 125 picosecond precision time digitizer with a full range of up to 28 bits. We also have seven other ADC's which are not used as much as the PACE systems. All ADC's have interfaces permitting input to either computer, either preformatted (for hardware increment) or full precision (for list mode analysis).

c. Data-Taking Program

All experiments are supported by one general-purpose machine-language program, SUPERVISOR. Since the same program supports various different kinds of experiments, the number of simultaneous experiments is limited only by memory space needed and by availability of other experimental equipment. For three or more experiments to be done simultaneously is not unusual.

In addition to the capabilities described below, SUPERVISOR in the PDP-15 can call in a FORTRAN analysis program, after first saving a copy of itself and all core data on the disk. This program can then call back SUPERVISOR, which would then start the next run. The analysis program can use the core image of the data as input, and can change it to communicate with SUPERVISOR.

d. Modes of Data-Taking Available

i. Direct increment: ADC output can be used to form histograms by a hardware interface; no programming is required. However, the computer can control the increment input, enabling it for a chosen amount of time or charge.

ii. Interrupt inputs: The PDP-7 has six interrupt channels, and the PDP-15 has two. Some are used to monitor the current integrators for control of runlength or for normalization. The others are used as data inputs from single-channel analyzers, electron multipliers, and similar devices having a logic pulse output. The PDP-7 can support two independent pulse counting experiments simultaneously, the PDP-15 one.

There are three different modes for these experiments. In two modes, data pulses cause increments in successive channels in core. The modes differ in their methods of controlling the period during which each channel is incremented. In one mode, a channel is dwelled on for a chosen number of current integrator pulses. The data channel is then disabled while the computer gives out the chosen stepping motor pulses (with a settling delay between each pulse). The data channel is then reenabled on the first integrator pulse after the last settling delay. Then data pulses will cause increments in the next channel. This mode is useful for stepping-motor-controlled devices such as our X-ray spectrometer and variable high-voltage power supply.

The other mode, for use with devices that vary linearly with time (such as electronic ramps and turntables), dwells on each channel for a certain time, then normalizes the count by dividing by the number of current integrator pulses accumulated during that time.

In either mode, either pulse input can be replaced by a gate set on an area in the spectrum from an ADC. Then one pulse is simulated for each pulse digitized by the ADC that falls within the chosen range. If desired, the spectra can be accumulated in a differential mode, where the difference between successive (normalized) totals is accumulated.

In the third mode, two parameters are derived either from the ADC list or from the counting inputs for sample averaging, which is further described below.

iii. ADC list examination routines: In both computers, ADC data can be put into a circular input list for program examination. This input buffer derandomizes the ADC event processing, permitting a least-time-between-events of about 15 μsec for two-parameter coincidences. The average rate that the system can sustain depends on the complexity of the analysis, but is usually about 1000/second.

The main ADC list routine builds histograms of some detector pulse heights (or calculated parameters) sorted on peaks in the spectra of others. Decrementing gates can be associated with incrementing gates to give random correction (from the time spectrum) and/or to suppress the Compton contribution to sorted gamma-ray spectra. The raw data list can be dumped on magnetic tape in 1 K blocks for later analysis. This can be done in conjuction with preliminary on-line analysis. All analysis modes can be used with either on-line data or data from tape.

The experimenter can specify the number of parameters, the size of the total coincidence histograms, the size and number of sorted histograms, and various special modes. These include provisions for calculation of mass (from energy and time-of-flight), particle identification (for detector telescopes), and calculation of the sum of the two parameters or the ratio of one of the parameters to the sum. More than one parameter can be sorted on, if this is desired.

Other modes include array formation, sample averaging, and a singles mode. All these modes, as well as the sorting modes, can be directed into the disk increment system, which can build up to 262,144 words of histograms. In sort mode, up to 256 gates can be set, permitting exhaustive on-line analysis of virtually any experiment.

Recent additions include a mode which permits a singles spectrum of one or more parameters to be accumulated in one area, while the same ADC inputs send the data to the list analysis routine whenever a coincidence is detected. This enhances the value of on-line analysis, since the gates for sorting can be set on the singles spectrum as the peaks build up there, rather than having to take a separate singles spectrum, which might require a long time for the smallest peaks to appear. This has been used in

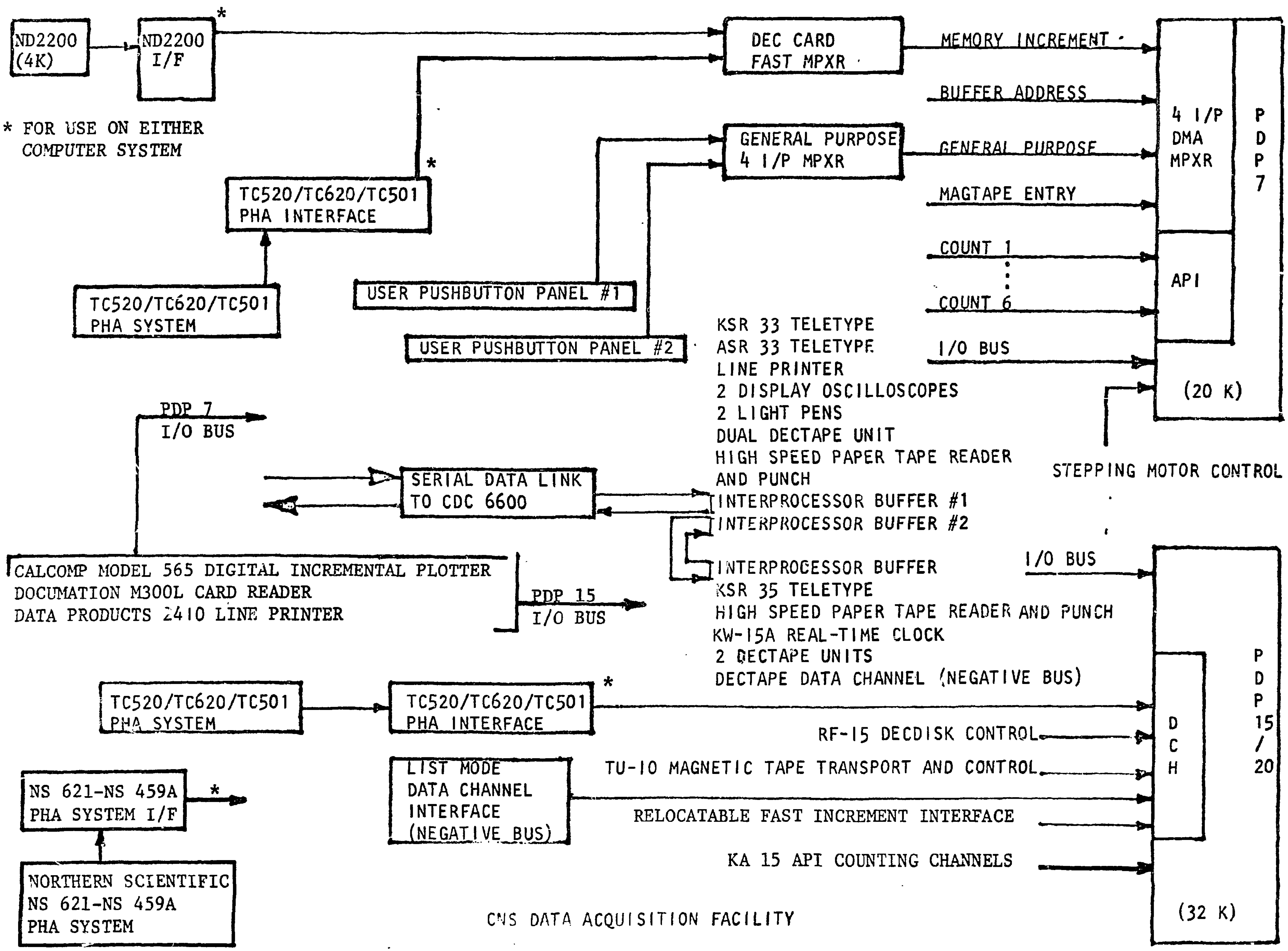
γ-γ correlation experiments.

The sample averaging routine has been expanded to permit the samples to come from voltage to frequency converters instead of one or both of the ADC samples of the input DC lines.

iv. Data-handling capabilities: In both computers, SUPERVISOR permits a wide variety of display, internal manipulation, and output commands. Data can be written on dectape, magtape, or disk (PDP-15), and can be printed on a line printer or graphed on an incremental plotter. Printer routines include both a line-printer graph and a two-dimensional printout. All output commands can be executed while data is being taken, and can overlap with the execution of output commands to other devices.

A list of sequential commands can be entered by the experimenter at any time. This "automatic program" will be executed sequentially each time the user types "DO program". This permits dependable end-of-run data handling.

In the PDP-15, SUPERVISOR can call in a FORTRAN program to analyze the core image before recalling SUPERVISOR; the FORTRAN program can either output its own results or change the core image. The FORTRAN call can be imbedded in the automatic program list, which will continue on return to SUPERVISOR. This gives great flexibility to end-of-run analysis.



CNS DATA ACQUISITION FACILITY

III. THEORETICAL RESEARCH

III. A. INTRODUCTION AND SUMMARY

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The theoretical activity in our center during the past year covered a few important areas in nuclear reactions and structure. They may be categorized as: (i) Population of unbound states in direct reactions; (ii) Study of analog states via (d,n$\bar{p}$) and (p,n) reactions; (iii) Successive nucleon transfer reactions; (iv) Coupled-channel Born approximation calculations for light-ion-induced reactions and (v) various analyses of heavy-ion-induced reactions. Several papers were published in each of these areas, and a number of others are under preparation. The work completed is briefly reviewed below in subsections III A (i) -- (v). A few other studies not in the above categories were also made and they are reviewed in subsection III A (vi).

Sections III B, III C and III D, respectively give the title page of the published papers, abstracts of papers submitted for publication, and abstracts of talks presented at meetings, while Section III E gives abstracts of work now under way.

(i) Population of Unbound States in Direct Reactions

A good deal of theoretical work at the Center for Nuclear Studies during the past few years has dealt with the description of isobaric analog resonances in nuclear reactions. Of particular recent interest has been the theoretical description of observed cross sections for population of isobaric analog states via direct proton transfer reactions, such as (d,n) and (h,d). Studies of analog resonances via proton elastic scattering, the most often used method, may be criticized for their inherent inaccuracies. The proton partial widths are small, and rapidly become unmeasurable as the proton's orbital angular momentum increases; further, the partial width cannot be directly extracted from the data --- its value depends on an estimate of the total width of the resonance. By contrast, direct proton transfer reactions populate isobaric analog states of high

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angular momentum strongly, because only for large angular momentum is there good momentum matching. Further, the extracted spectroscopic factors depend only on the proton partial width of the resonance. It has been shown by many workers, e.g. in ref. 1, that in order to extract reliable spectroscopic factors for analog resonances, the particle-unstable nature of the final state must be properly treated.[1]

A large number of approaches have been put forward to deal with the decay of the residual analog state[2-6], and most have been tested against the available data[2,5-9]. The analyses in the literature have ranged from those using simple potential resonances[2,4,7-9], to those using detailed microscopic descriptions of the analog state in the context of some shell-model theory of reactions[5,6]. A study of these analyses makes clear that the extracted spectroscopic information is largely independent of the way in which the resonance state function is computed, so long as it describes a proton resonance at the proper energy.

Coker has therefore proposed use of the Gamow function[9-11] as an elegant and simple description of both single-particle resonances[10] and analog resonances[9]. Coker and Hoffmann have shown that Gamow functions give proton single particle widths and spectroscopic factors for ^{92}Mo(h,d)^{93}Tc^{A} which are in excellent agreement with those obtained from ^{92}Mo(p,p)^{92}Mo and spectroscopic factors which agree very well with those obtained from ^{92}Mo(d,p)^{93}Mo to the parent states as is shown in Fig. III A - 1.

Gamow states have also been used by Coker to treat neutron resonances excited via ^{36,38}Ar(d,p)[10] and proton resonances excited via ^{54}Fe(d,n).[11] Although there are no adjustable parameters in these calculations, agreement both with expectations and with earlier work has been excellent. On the basis of these successes, we are now able to include the residual analog states properly in coupled-reaction-channel calculations of (h,t) and (p,n) reactions to analog states, as discussed in Section III. E.

(ii) Study of Analog States Via (d,n$\bar{p}$) and (p,n) Reactions

One of the more important experimental discoveries made in the Center for Nuclear Studies in past years was that of the threshold cusp in excitation functions of (d,p) reactions, at the threshold for the (d,n) reaction to the isobaric analog of the state populated in (d,p)[12]. As a complement to the wealth of data which now exist for the threshold cusp in (d,p), one needs information concerning the (d,n$\bar{p}$) reaction, where the delayed proton $\bar{p}$ is from the residual analog state.[13] Experimental data for ^{88}Sr(d,n$\bar{p}$) were obtained and analyzed in the Center during the past year. It was expected that the coupled-channel-Born-approximation approach[13] suggested some years ago for the description of such processes would be able to describe the data wery well, and this was indeed found[14] as is shown in Fig. III A - 2. Such a test of the approach is quite rigorous, since the (d,n$\bar{p}$) total cross section shows a very strong energy dependence, rising from threshold to maximum in only 0.2 MeV. These experiments and calculations were carried out by Hoffmann, Coker, and Zaidi.

Another study completed during the past year involves the observed energy dependence of the (p,n) cross section to the ground isobaric analog state. Such (p,n) cross sections for all nuclei studied, from mass 50 to mass 209, show the same distinctive and characteristic shape for the total (p,n) excitation function. Attempts to describe this total cross section, either with DWBA or by solving the coupled Lane equations[15], met difficulties due to the experimental uncertainties in the neutron optical potential and in the nucleon symmetry potential. Global potentials such as that of Becchetti and Greenlees[16] provide both a neutron potential and a nucleon symmetry term, but in general the neutron and proton potentials are inconsistent with one another and with the quoted symmetry term, both in the Becchetti-Greenlees potential and in all other global potentials known to the authors. Hoffmann has shown further that the Becchetti-Greenlees neutron potential cannot account for the observed (p,n) excitation functions unless the symmetry potential itself is given an energy dependence.[17]

As a way past this difficulty, Hoffmann has proposed for example a very strict interpretation of the Lane equations, which allows one to use any proton optical potential, global or not, which correctly describes elastic scattering, together with any appropriate neutron potential.[18] Charge independence is guaranteed, in the sense of the Lane model,[15] by generating the Lane potential in a self-consistent way from the nucleon potentials. Hoffmann was able to show that coupled channel and DWBA calculations with such a prescription are able to describe the observed energy dependence of (p,n) total cross sections, without any adjustable parameters, while simultaneously providing good fits to the (p,n) distributions at all available energies.

A modification of the prescription, which does not ignore the global significance of a given potential, and thus violates the spirit of the Lane model, was later suggested by Kunz, Rickertsen and Hoffmann[19]. They showed, however, that Hoffmann's excellent fits are not sensitive to any modification of the original prescription which changes the Lane potential but leaves the diagonal parts of the nucleon potentials alone. Thus the main conclusion has been that difficulties in describing the (p,n) reaction are mainly due to uncertainties in the neutron optical potentials used, and not to any particular uncertainties concerning their symmetry or Lane potential or the reaction mechanism itself.

(iii) Description of Successive Single-Nucleon Transfer in Nuclear Reactions, Using the Coupled-Reaction-Channels Formalism

The first concrete suggestions that successive single-nucleon transfer reactions were playing an observable and important role in nuclear reactions was made by Shaeffer and Bertsch and independently by Toyama, who pointed out that certain anomalous spectroscopic results obtained with (h,t) reactions might be explained if there were a significant contribution from (h,α)-(α,t) in the reaction[20]. Detailed calculations by Toyama using the second-order Born approximation and neglecting the direct (h,t) process indicated that (h,α)-(α,t) cross sections were indeed of the right order of magnitude to explain many of the observed anomalies.

Toyama's original calculations were open to some criticism. To study the problem in a more general and systematic way, Udagawa, Wolter and Coker wrote a very flexible computer program which could solve exactly, to all orders, a set of coupled equations for various reaction channels, treating the channel-coupling interactions in zero-range, and neglecting the non-orthogonality of the multichannel basis. This program, JUPITER-4, has been used in a very wide variety of direct reaction studies.

Our first numerical calculations were made for the case of $^{40}Ar(h,t)^{40}K$ to the isobaric analog and anti-analog 0^+ states, and for the same case as treated by Toyama, namely $^{48}Ca(h,t)^{48}Sc$ leading to the 0^+, 2^+, 4^+ and 6^+ states of the ($f_{7/2}$-$f_{7/2}^{-1}$) configuration. Both direct charge exchange and (h,α)-(α,t) mechanisms were included in all the calculations, which were done by solving the coupled equations both iteratively and exactly, and comparing. The results of these calculations, as well as details of the coupled-reaction-channel formalism, were reported in Phys. Rev. C.[21]

Further calculations, for $^{88}Sr(h,t)^{88}Y$ leading to the 4^-, 5^- states of ($p_{1/2}$, $g_{9/2}^{-1}$) and 2^+, 3^+ states of ($p_{1/2}$,$f_{5/2}^{-1}$), included the competing (h,d)-(d,t) process which was found to be quite comparable in importance to the (h,α)-(α,t) process for final states of high spin (e. g., 5^-).[22] The results of these calculations are presented in Fig. III. A - 3.

Most of our calculations were done neglecting coupling back to the entrance channel and in first iteration of the coupled equations, so that our results could be compared to the second-order DWBA calculations of other workers, including Toyama[20], Kunz[23], and de Takacsy[24].

The main results of our work may be summarized as follows. (i) As shown in Ref. 21, the higher-order terms in the DWBA expansion are not very important. For the case of ^{48}Ca(h,t)^{48}Sc(0^+ IAS), the exact solution of the coupled equations is found to differ very little from the results of a second-order DWBA solution. (ii) The interference between the direct and the two-step processes is generally destructive, which is both surprising and disturbing. If the phase of the interference were a free parameter (it is not) one would have chosen constructive interference in order to fit the available data for ^{48}Ca(h,t) for example. (iii) The (h,d)-(d,t) process cannot be safely ignored, although it plays a minor role for states of low J.

Further work has led us to suspect that the difficulties found in (ii) above perhaps lie in one of the simplifying assumptions used in all the numerical calculations made thus far by all group. The zero-range approximation and the neglect of non-orthogonality are among the most likely culprits, though workers have also made a poor approximation in treating residual analog states as bound.

To shed some light on the guilty assumption, Udagawa, Wolter and Olsen made calculations for (p,t) reactions leading to unnatural parity final states from 0^+ targets. The two-step processes which could compete are inelastic excitation, and successive (p,d)-(d,t) --- the direct transition is forbidden in zero range, and negligible in finite range[25]. Again, as expected, results were disturbing[26,27]. Consider as an example ^{22}Ne(p,t)^{20}Ne to the 2^- state at 4.97 MeV, which has been well described in terms of inelastic excitation using the CCBA (coupled-channel Born approximation). A CRC calculation assuming a (p,d)-(d,t) mechanism gave an angular distribution very different from the one observed experimentally,[27] but of the same order of magnitude. Indeed at very forward angles the CCBA and CRC predictions differ in the extreme. The CCBA calculation, which neglects spin-orbit coupling, goes to zero at 0^o, since only the $S = 1$ amplitude can contribute at 0^o and the CCBA amplitude is $S = 0$. On the other hand, the CRC amplitude is dominated by $S = 1$. Unfortunately experimental data does not extend to very forward angles. Data at angles less than 10^o could be used to decide almost conclusively between the CRC and CCBA predictions (see ref. 27).

These (p,t) results, coupled with the "wrong" direct-two step interference required by experiment in (h,t) reactions, led Udagawa, Wolter, and Coker to study the specific consequences of the neglected non-orthogonality corrections to the coupled reaction channels equations. Results of these studies will appear in ref. 28. There a fairly simple method is used to estimate the non-orthogonality corrections for (h,t) reactions in the CRC formalism, using the zero-range approximation and the second-order DWBA. They find that the effects of non-orthogonality amount to a renormalization of the direct, charge-exchange amplitude. The required renormalization is unexpectedly large. It completely cancels the direct term, and more than makes up for the "loss", producing a term having all the characteristics of the direct term, but with the opposite phase. The main effect in (h,t) comes from the (h,d)-(d,t) process, the contribution from (h,α)-(α,t) cancelling out in second order Born approximation. Thus the (h,d)-(d,t) process looms even greater in importance than the earlier work would have indicated.

The most serious defect of our estimate of the effects of these non-orthogonality terms is the use of the zero-range approximation. However, we are unlikely to have made more than an order of magnitude error in our estimate, and within this bound our conclusions would remain unchanged. Thus the mystery concerning the "wrong phase" for the direct amplitude seems to be solved.

We are presently working on a finite range version of the JUPITER 4 program, so that we can treat sequential processes in heavy ion transfer reactions, and better handle the non-orthogonality integrals which appear in the CRC equations.[28]

(iv) The Coupled-Channel Born Approximation Description of Nuclear Reactions

During the past year, the ongoing project to apply CCBA theory to nuclear reactions was greatly expanded. Detailed and elaborate numerical analyses of a very wide variety of data were carried out. The first example of such an analysis is that of the one-particle transfer reactions leading to the famous $7/2^+$ state at 1.6 MeV and the $9/2^+$ state at 3.9 MeV in the mass 25 nuclei. Population of these states is strongly forbidden on the basis of a single-step direct reaction mechanism, and thus the data provide a sensitive test of CCBA theory. Two earlier, independent CCBA analyses had previously been made, particularly for (d,p)[29,30]. Unfortunately, these two analyses reached conflicting conclusions! We thus intended to resolve the confusion with our work. Analyses were made of a variety of one-nucleon transfer reaction data, including (p,d), (d,t), (h,α), and (h,d), for which there were plentiful data. Results of the analyses have been reported in ref. 31, which concludes that all the data are reasonably well accounted for by CCBA. Some of the results of the calculations are presented in Fig. III.A - 4.

Another example studied extensively was the excitation of two-phonon vibrational states in nuclei, by means of the (p,t) reaction. Very good data recently became available for the Cd isotopes[32]. We thus analyzed the data for $^{116}Cd(p,t)^{114}Cd$ in great detail, with very careful treatment of the nuclear states involved. Results have already been presented,[33] and are presently in press.[34] The main conclusion from this study is that (i) The two-phonon 0^+ state is mainly populated by three-step inelastic processes such as $0_g^+ \rightarrow (p,t)\ 0_g^+ \rightarrow 2_1^+ \rightarrow 0_1^+$. (ii) The one and two phonon 2^+ states are excited mainly through a two-step process. (iii) The 4^+ state of the two-phonon is excited via the three-step process. All these results demonstrate the importance of the multistep inelastic processes. It was further found that the magnitudes of the cross sections of one- and two-phonon states relative to the ground state are all reproduced well by the calculations. Many characteristic features observed in the angular distributions, which could never be interpreted in terms of a single-step mechanism, are also well explained by CCBA.

One of the remarkable successes of CCBA is that the excitation of the unnatural parity 2^- state at 4.97 MeV observed in $^{22}Ne(p,t)^{20}Ne$ is explained by the theory. The work done on this reaction was already published a year ago.[35] Later, the analysis was extended to the cross sections of the rotational states of the ground band. A study was also made of the cross section of the 2^- state mentioned above, relative to that of the ground state. The results were reported in ref. 36, which concludes that the cross sections of the 0^+, 2^+ and 4^+ members of the ground band can be explained well by CCBA calculations employing the Nilsson-plus-pairing-force model in describing the nuclear wave functions involving in the process. The 2^- cross section relative to that to the ground state was also shown to be accounted for within the same description.

For the $^{22}Ne(p,t)^{20}Ne$ reaction leading to the rotational states of the ground band, a study was also made of the energy dependence of the cross section, finding that CCBA can explain the observed energy dependence better than DWBA.[36] This, together with the fit of the CCBA angular distribution with the observed data are shown in Fig. III A - 5.

A calculation was also made of the $^{11}B(h,\alpha)^{10}B$ reaction leading to the 3^+ ground state of the final ^{10}B. It was found that the inelastic scattering processes in both channels play an essential role in this case.[37] This work was done in collaboration with a group at Oak Ridge.

A calculation was also reported which attempted to describe the assymmetry of the proton in a (p,t) reaction from ^{176}Yb as target[38]. The data were taken by Igo et al. It is generally expected that the polarization is very sensitive to the details of the reaction mechanisms, and thus the theory can be better tested by these data. Unfortunately, the measured assymmetry of the $^{176}Yb(p,t)^{174}Yb$ reaction is not very large, and thus the data involve fairly large experimental uncertainties, thus making it difficult to carry out a sensitive test. Nevertheless, we found that it is somewhat difficult to find a consistent explanation of both the angular distribution and asymmetry data at the same time. A further search on various parameters used in the calculations may be needed.

(v) Heavy-ion Reactions

Our activity in heavy-ion reactions in the past has been somewhat limited; in fact only a few studies were made of the elastic scattering between heavy ions. By taking the opportunity, however, for Tamura and Low to spend the period of Sept. 1972 through May 1973 at the Argonne National Laboratory, a large scale involvement in heavy-ion reaction analysis was initiated, and already a few significant achievements have been made.

Chronologically the work began by preparing computer programs which can perform direct reaction calculations with the no-recoil approximation.[39] The original DWBA/CCBA program MARS, which can be used for calculations with the zero-range approximation can also be used, with very slight modifications, for those with the no-recoil approximation. Thus the major part of the work was to develop a new program SATURN for producing the form factor appropriate for the no-recoil rather than for zero-range approximation.

The first application of the program SATURN-MARS was made for the $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ reaction,[40] and was reported at the Argonne Symposium.[41] Since the major interest in the above data was to explain why the angular distribution for the case in which ^{20}Ne is in the 2^+ state is so much different from that in which ^{20}Ne is in the 0^+ state, and since the most likely reason for this to take place was thought to be the fact that ^{20}Ne is deformed, a CCBA rather than a DWBA calculation was made. As is seen in Fig. III A - 6, we indeed succeeded in fitting the data this way.

Since it has been known that the no-recoil approximation can in many cases give erroneous absolute cross sections (but often correct angular distributions) we then started to modify both SATURN and MARS so that exact-finite-range (EFR) calculation including recoil can be carried out with both DWBA and CCBA approaches. In the course of developing this version of the program, we found several important techniques with which the calculation can be carried out very fast.

Since our program[42] is quite fast, its running is fairly easy and thus a large number of calculations have already been made, though so far analysis has mostly been limited to one-nucleon transfer reactions. Thus we have analyzed $(^{16}O,^{15}N)$ reactions from ^{208}Pb,[43] ^{88}Sr,[44] and ^{64}Ni[45] isotopes as well as from Ca isotopes. One example of such analyses is presented in Fig. III A - 7. Also $(^{12}C,^{11}B)$ from ^{208}Pb[46] and ^{64}Ni,[45] and $(^{12}C,^{13}C)$[46] reactions from ^{208}Pb were analyzed. Through these calculations it has been confirmed that to include the recoil effect is vital in extracting correct spectroscopic factors from the data, and that the spectroscopic factors extracted by using EFR are very reasonable.[47,48] Indeed we may conclude that, as far as the one-nucleon transfer reaction is concerned, heavy-ion reactions can be used as a very dependable spectroscopic tool, so long as the data are analyzed with EFR calculations.

In spite of the success of our CCBA calculation shown in Fig. III A - 6, and discussed above, the situation of the analysis of the two-nucleon transfer reaction is much worse, particularly concerning the absolute magnitude, as compared with the one-nucleon transfer reactions. One of the reasons for this situation is that the theoretical cross section is sensitive not only to the parameters used in the calculation, but also to the models assumed; it is so sensitive that one may get cross sections which differ by two orders of magnitude from each other by using two models neither of which seem to be unreasonable.

Another source of the ambiguity is that there seems to exist a rather strong contribution from the process in which two one-nucleon transfer reactions take place sequentially. In fact we calculated,[49] by using the technique discussed in III A - (iii) above, the cross section, within the no-recoil approximation, of the process $^{18}O + {}^{40}Ca \rightarrow {}^{19}F + {}^{39}K \rightarrow {}^{20}Ne + {}^{38}Ar$, and found that the cross section is comparable with that of the one-step (simultaneous) transition $^{18}O + {}^{40}Ca \rightarrow {}^{20}Ne + {}^{38}Ar$, although of course the cross section of the sequential process also depends sensitively on the models as well as parameters.

In summary it seems that the one-nucleon transfer heavy-ion reaction is now under very good control, while the reactions that transfer more than one nucleon are not. We are planning to analyze these data in a much more systematic way so that a way is established to make the data useful for spectroscopic tool.

(vi) Miscellaneous Works

In addition to the works categorized in the above subsections (i)-(v), other projects were completed and published. Since the title pages of these papers are found in Section III B, and the abstracts there give basic ideas of what were made, we shall summarize these works very briefly here.

The work done in cooperation with Benenson and others[50] dealt with a resonance-like excitation function observed in a transfer reaction, one of a type of processes which had received much less attention, compared with similar phenomena observed in the scattering processes. To analyze the data we simply added Breit-Wigner-type term(s) to the DWBA amplitude and obtained a reasonable fit. Since the energy region we encounter lies within the range of the giant resonance of the compound system, a rather simple microscopic treatment may be possible to replace our approach which so far has been purely phenomenological.

The paper on Regge poles by Tamura and Wolter[51] dealt with an exact treatment of the Regge type description of the scattering phenomena, contrary to most of other papers, in which some assumptions were made, thus abandoning mathematical or numerical rigor. A few points which would be worth emphasizing would be that, when one has a Woods-Saxon type potential, it is vital to retain the background term, and a fairly simple analytical background term[52] works rather well under favorable conditions, though not always.

Two studies were made of the coupled-channel calculations. In one of them[53] discussions were made on how the nuclear collectivity affects the energy dependence of the total cross section of neutrons on various targets. In other inelastic scattering of very high energy (60 - 90 MeV) deuterons by ^{24}Mg and ^{89}Y was discussed. This work was initiated when Tamura visited Jülich in May, 1972.

The paper by Tamura and Kishimoto[55] reported on part of the results of applying Boson expansion technique to several nuclei, by taking into account the effect of the so-called particle branch to the collective branch in an approximate way. Surprisingly good fits to nuclear level schemes, particularly to those of Sm isotopes, was obtained; not only the transition of the level scheme, from spherical to rotational in going from ^{148}Sm to ^{154}Sm, was reproduced, but also the electromagnetic properties of lower states were reproduced in almost perfect agreement with experiment. The energies of higher levels, however, did not agree so well with experiment, and it was thought that the addition of the sixth order effect could improve the situation. Preliminary work with sixth order terms included was done by Braunschweig, and was reported in his Ph.D thesis. Further work along this line is now under way.

References

1. R. L. McGrath, N. Cue, W. R. Hering, L. L. Lee, Jr., B. L. Liebler, and Z. Vager, Phys. Rev. Letters 25, 682 (1970).
2. R. L. Kozub and D. M. Youngblood, Phys. Rev. C 4, 539 (1971).
3. C. M. Vincent and H. T. Fortune, Phys. Rev. C 2, 782 (1970).
4. B. J. Cole, R. Huby, and J. R. Mines, Phys. Rev. Letters 26, 264 (1971).
5. S. A. A. Zaidi and W. R. Coker, Phys. Rev. C 4, 236 (1971).
6. D. Agassi, N. Auerbach, and A. Moalem, Phys. Rev. C 6 385 (1973).
7. W. R. Coker and S. A. A. Zaidi, Nuclear Phys. A 188, 65 (1972).
8. D. Ashery, S. Alpen, A. Moalem, Y. Shamai, A. I Yavin, G. Bruge, A. Chameaux, M. Moinester, Phys. Rev. 729 (1972).
9. W. R. Coker and G. W. Hoffmann, Z. Phy[illegible], 179 (1973). (See also III B - 1)
10. W. R. Coker, Phys. Rev. C 7, 2426 (1973). (See also III B - 2)
11. W. R. Coker, to be published.
12. C. F. Moore et al, Phys. Rev. Lett. 17, 926 (1966); R. Hettner et al, Phys. Lett. 26B, 150 (1968); R. G. Clarkson et al, Phys. Rev. C2 1097 (1970); S. A. A. Zaidi, W. R. Coker, and D. G. Martin, Phys. Rev. C2, 1097 (1970).
13. W. R. Coker and T. Tamura, Phys. Rev. 182, 1277 (1969).
14. G. W. Hoffmann, W. R. Coker, S. A. A. Zaidi and D. O. Elliott, Jr., Phys. Lett. 41B, 47 (1972).
15. A. M. Lane, Nucl. Phys. 35, 676 (1962).
16. F. D. Becchetti and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).
17. G. W. Hoffmann, W. H. Dunlop, G. J. Igo, J. G. Kulleck, C. A. Whitten, Phys. Lett. 40B, 453 (1972); G. W. Hoffmann and W. R. Coker, Phys. Rev. Letts. 29, 227 (1972); G. T. Garvey and P. S. Miller, Phys. Lett. 28B, 243 (1968).

18. G. W. Hoffmann, Phys. Rev. C 8, 761 (1973). (See also III B - 3)

19. P. D. Kunz, L. D. Rickertsen and G. W. Hoffmann, to be published.

20. M. Toyama, Phys. Letters 38B, 147 (1972) and Nuclear Phys. A211, 254 (1973); R. Schaetter and G. F. Bertsch, Phys. Letters 38B, 159 (1972).

21. W. R. Coker, T. Udagawa, and H. H. Wolter, Phys. Rev. C 7, 1154 (1973). (See also III B - 4)

22. W. R. Coker, T. Udagawa and H. H. Wolter, Phys. Letters, 46B, 27 (1973). (See also III B - 5)

23. P. D. Kuntz, private communciation, and to be published.

24. N. B. DeTakacsy, Phys. Lett. 42B, 1 (1972) and Phys. Rev. Lett. 31, 1007 (1973).

25. B. F. Baymann and D. H. Feng, Nucl. Phys. A205, 513 (1973).

26. H. H. Wolter, T. Udagawa and D. K. Olsen, Proc. of the Intern. Conf. on Nuclear Phys., Munich, Aug. 1973, p. 492.

27. T. Udagawa and D. K. Olsen, Phys. Letters, 46B, 285 (1973). (See also III B - 6)

28. T. Udagawa, H. H. Wolter, and W. R. Coker, to be published.

29. D. Braunschweig, T. Tamura, and T. Udagawa, Phys. Lett. 35B, 273 (1971).

30. R. S. Machintosch, Nucl. Phys. A 170, 353 (1971).

31. A. K. Abdallaha, T. Udagawa, and T. Tamura, Phys. Rev. C 8, 1855 (1973).

32. J. R. Comfort, private communication, and J. R. Comfort, W. J. Braithwaite, Jr. Duray, and S. Yoshida, Phys. Rev. Lett. 29, 442 (1972).

33. T. Udagawa et al, Bull. Am. Phys. Soc. 18, 604 (1973).

34. T. Udagawa; to be published in Phys. Rev.

35. D. K. Olsen, T. Udagawa, T. Tamura, and R. E. Brown, Phys. Rev. Lett. 29, 1178 (1972).

36. D. K. Olsen, T. Udagawa, T. Tamura, and R. E. Brown, Phys. Rev. C 8, 609

(1973). (See also III B-7) Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, p.489.

37. W. R. Coker, J. Lin, J. L. Duggan, and P. D. Miller, Phys. Lett. 45B, 321 (1973). (See also III B - 10).

38. G. Igo, J. C. S. Chai, R. F. Casten, T. Udagawa, and T. Tamura, Nucl. Phys. A 207, 289 (1973). (See also III B - 9)

39. T. Sawaguri and W. Tobocman, J. Math. Phys. 6, 2223 (1967); F. Schmittroth, W. Tobocman and A. Golestaneh, Phys. Rev. C 1, 377 (1970).

40. K. Katori, C. L. Fink, G. C. Morrison, and J. L. Yutema, to be published; R. H. Siemssen, C. L. Fink, L. R. Greenwood and H. J. Körner, Phys. Rev. Letts. 28, 626 (1972).

41. K. S. Low and T. Tamura, Argonne Nat. Lab. Phys. Div. Informal Report Phy - 1973 B p. 655. (See also III B - 11)

42. T. Tamura and K. S. Low, to be published.

43. D. G. Kovar et al, Phys. Rev. Letts. 30, 1075 (1973).

44. N. Anantharaman, K. Katori and H. J. Körner, Phys. Letts. 46B, 67 (1973).

45. M. C. Lemaire, M. C. Mermaz, T. Tamura, and K. S. Low, to be published.

46. J. S. Larsen et al, Phys. Letts. 42B, 205 (1972).

47. T. Tamura and K. S. Low, Phys. Rev. Letts., to be published.

48. K. S. Low and T. Tamura, Phys. Letts., to be published.

49. K. S. Low, T. Tamura and T. Udagawa, to be published.

50. R. E. Benenson, I. J. Taylor, D. L. Bernard, H. H. Wolter and T. Tamura, Nucl. Phys. A197, 305 (1973). (See also III B - 12)

51. T. Tamura and H. H. Wolter, Phys. Rev. 6C, 1876 (1972). (See also III B - 13).

52. K. W. McVoy, Phys. Rev. C 3, 1104 (1971).

53. C. Y. Wong, T. Tamura, H. Marshak and A. Langsford, Particle and Nuclei, 4, 163 (1972). (See also III B - 14).

54. G. Hrehuss, A. Kiss, K. T. Knöpfle, C. Mayer-Böricke, M. Rogge, U. Schwinn, T. Tamura and P. Turek, Z. Physik 260, 172 (1973). (See also III B - 15)

55. T. Tamura and T. Kishimoto, Journ Phys. Soc. Japan, 34, 393 (1973).
(See also III B - 16)

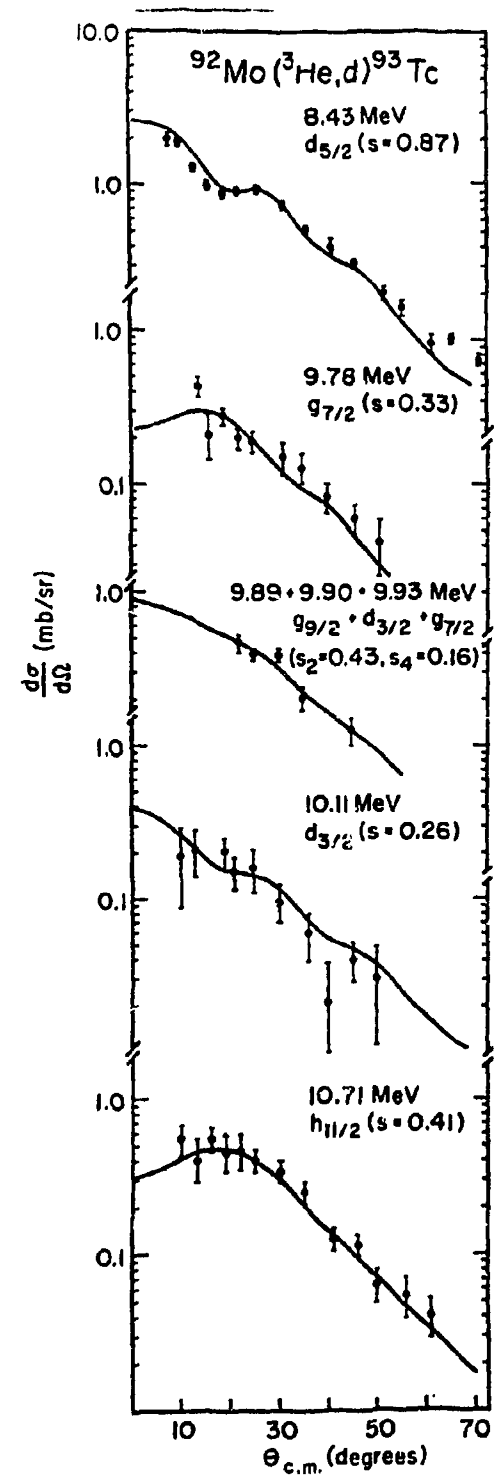


Fig. IIIA-1

Calculated angular distributions, using the DWBA program VENUS and Gamow-function form factors, as explained in the text, as compared to the data of Shamai, *et al.*, for ^{92}Mo(τ, d) to analog states in ^{93}Tc. The incident τ energy is 30.2 MeV. The analog states are identified by their excitation energy, l_j value, and the spectroscopic factor extracted from the fit shown

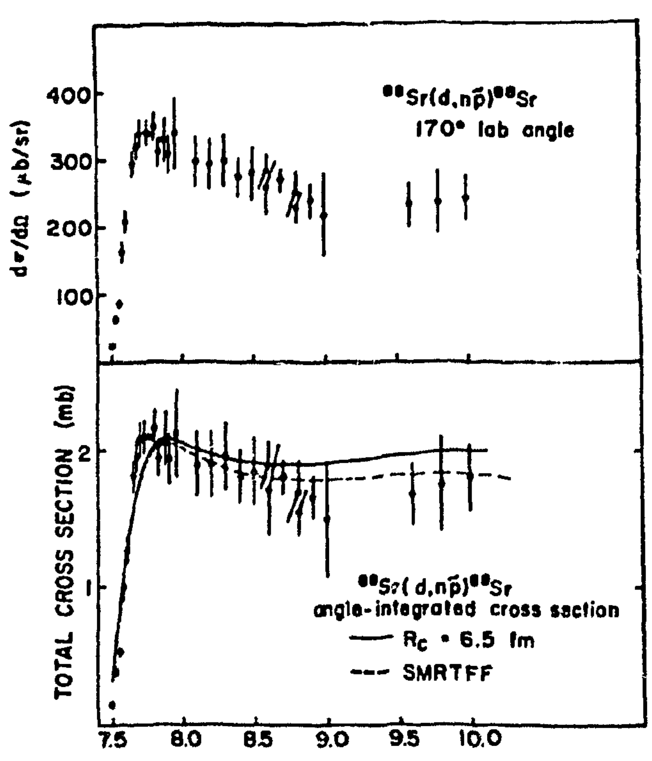


Fig. IIIA-2

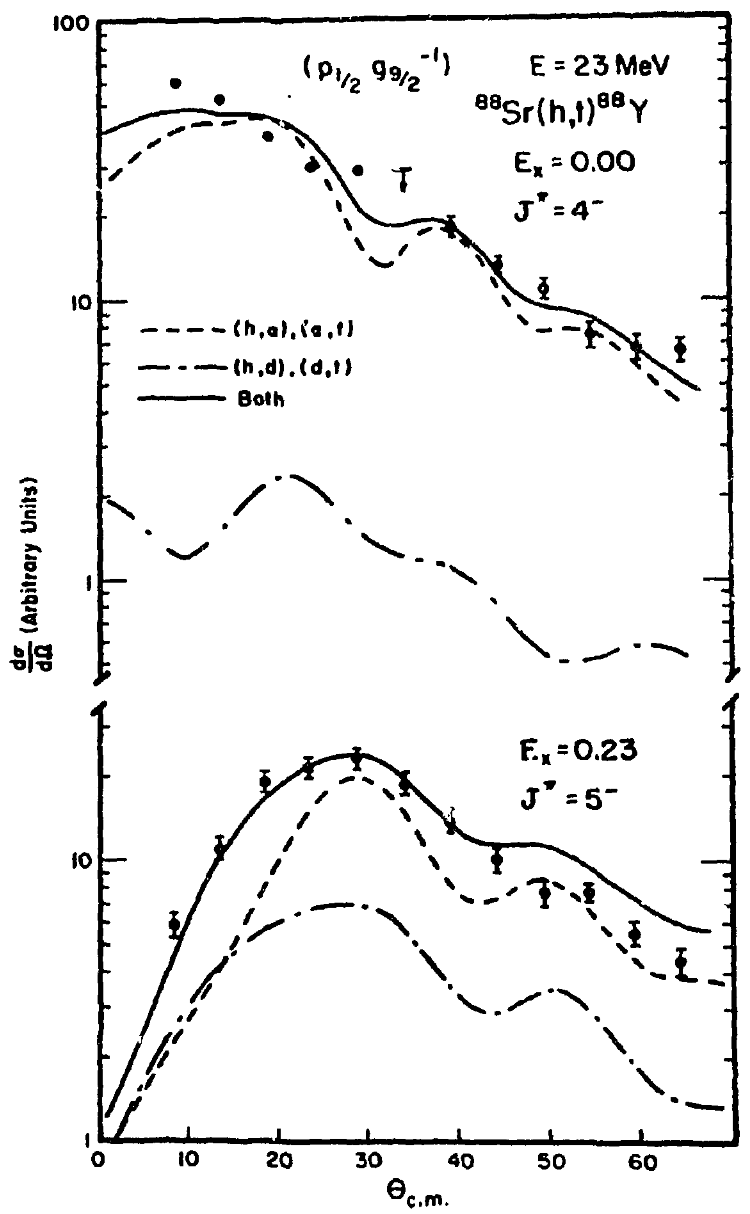
a

The differential cross section for ^{88}Sr($d, n\tilde{p}$) from threshold to 10 MeV, at 170°. Errors shown are due to counting statistics and peak-extraction procedures. Between 9.0 and 9.6 MeV the $\tilde{p}$ group was obscured by (d, p) protons from a light target contaminant

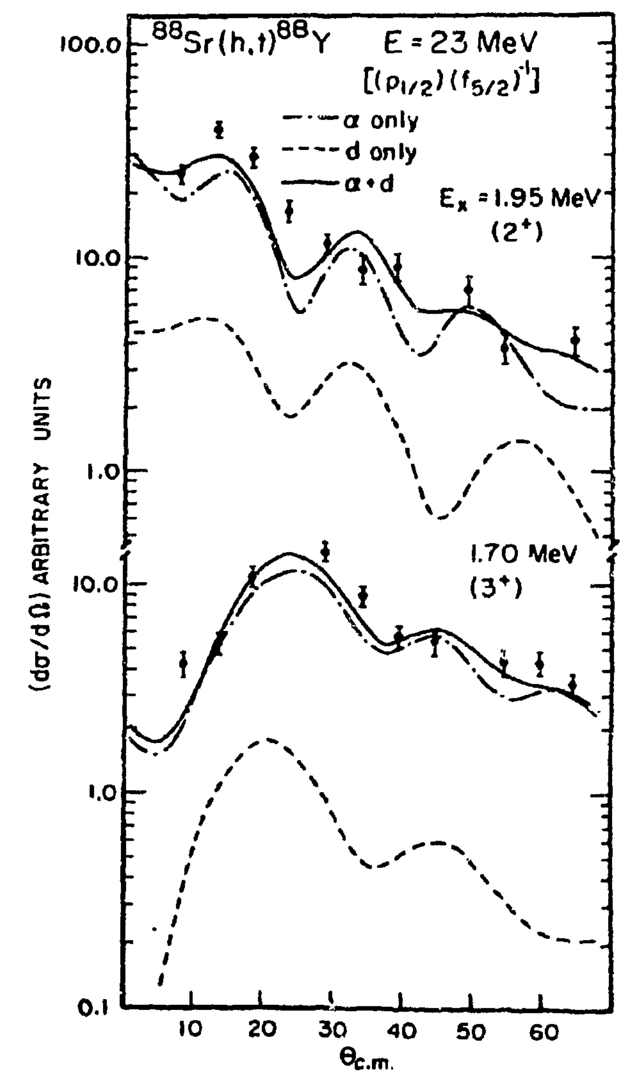
b

The integrated ^{88}Sr($d, n\tilde{p}$) cross section, obtained using the fractional substate populations determined by Cue and Richard. The solid line is the result of a CCBA calculation using a matching IAS form factor with 6.5 fm matching radius. The dashed line is due to an equivalent CCBA calculation using an IAS form factor computed from a simple shell-model theory of reactions (SMRT).

Fig.IIIA-3

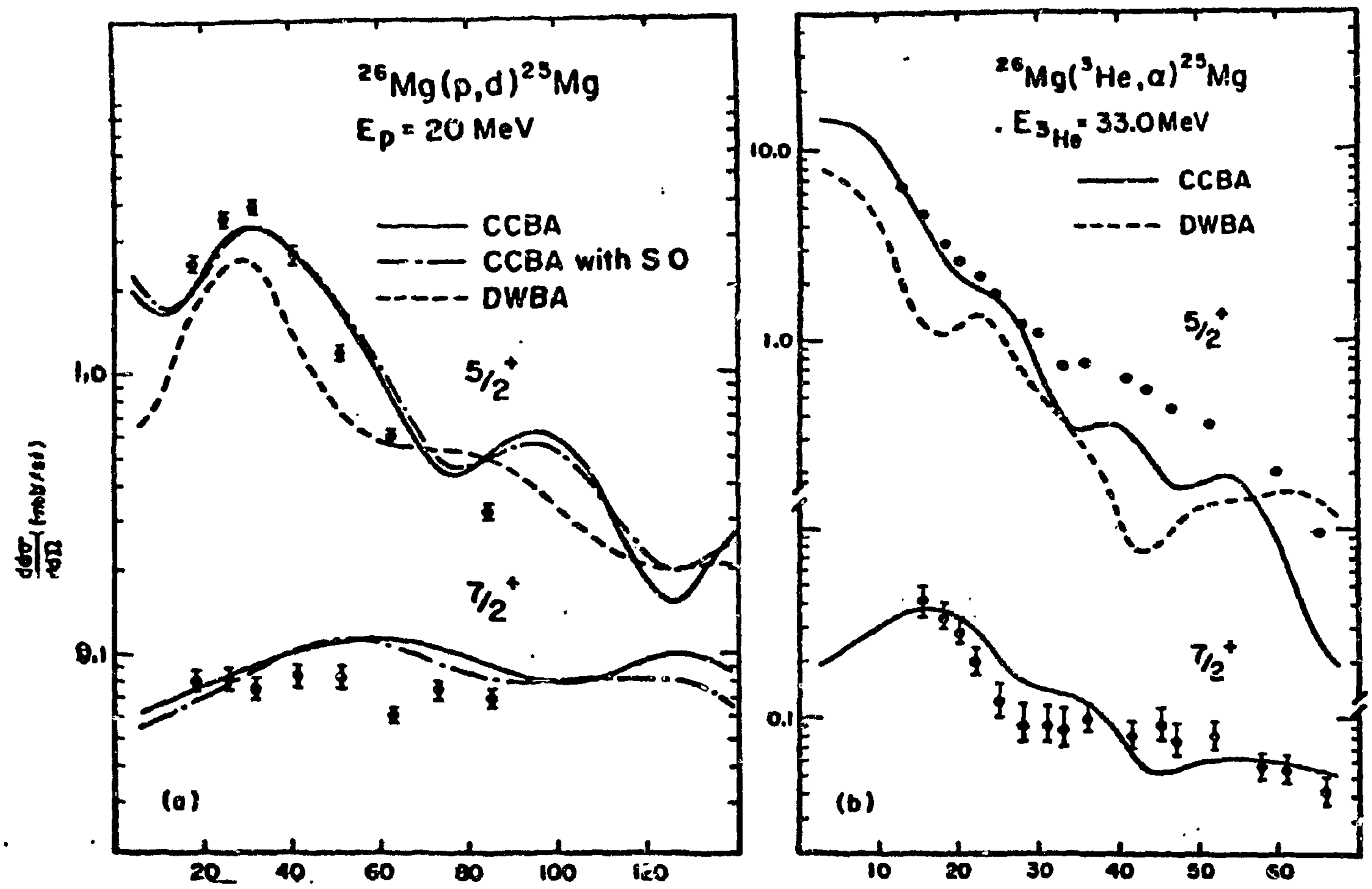


CRC calculations for $^{88}Sr(h,t)^{88}Y$ to the 4^-, 5^- doublet, compared to the data of ref. [5]. The dot-dashed curve is the result of considering only intermediate deuteron channels, while the dashed curve is the result of considering only intermediate ^4He channels. The solid curve is the result of including both types of intermediate processes, as discussed in the text.



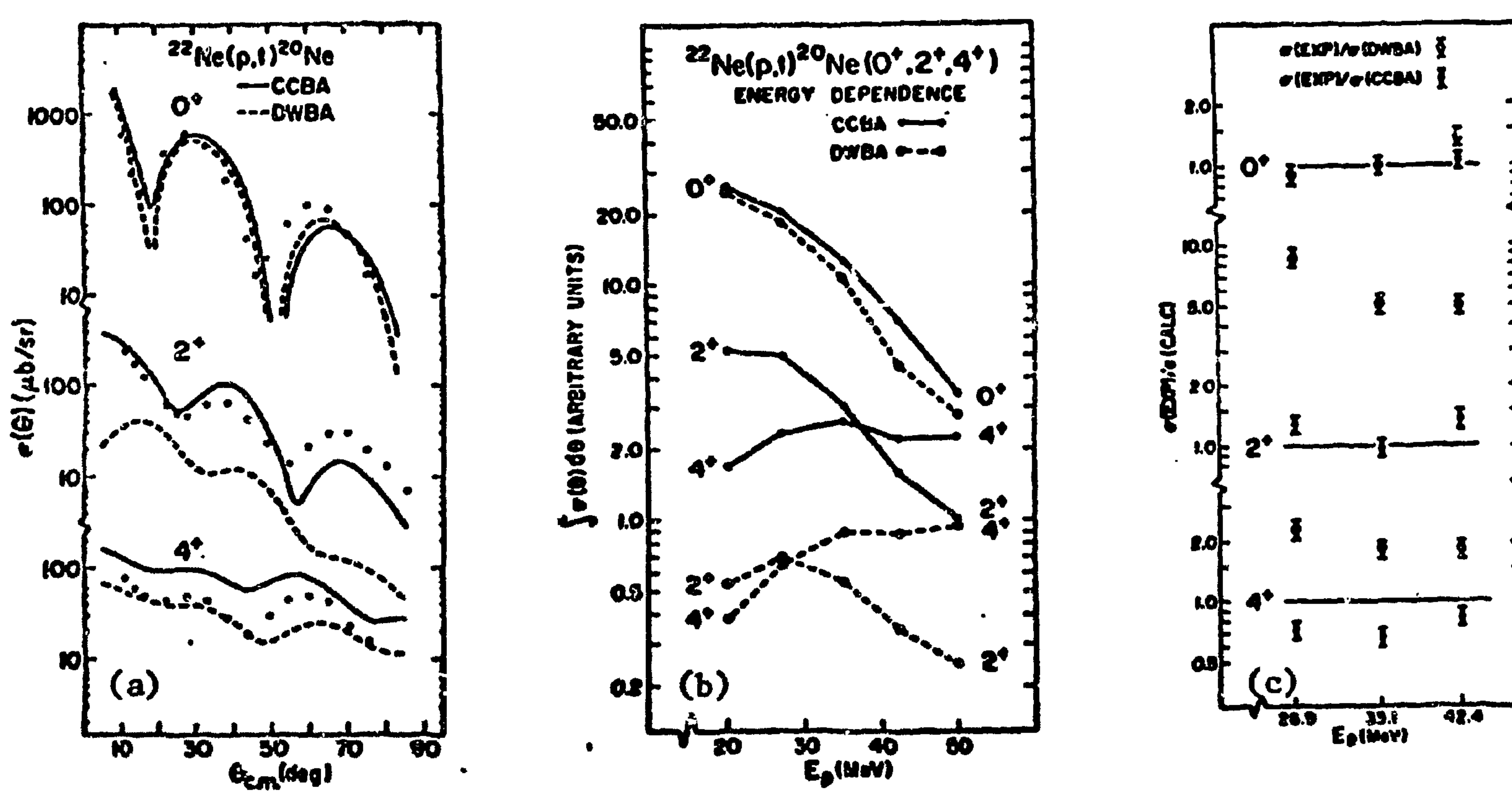
CRC calculations for $^{88}Sr(h,t)^{88}Y$ to the 2^+, 3^+ doublet, compared to the data of ref. [5]. The meaning of the various curves is similar to that in fig. 1.

Fig.IIIA-4



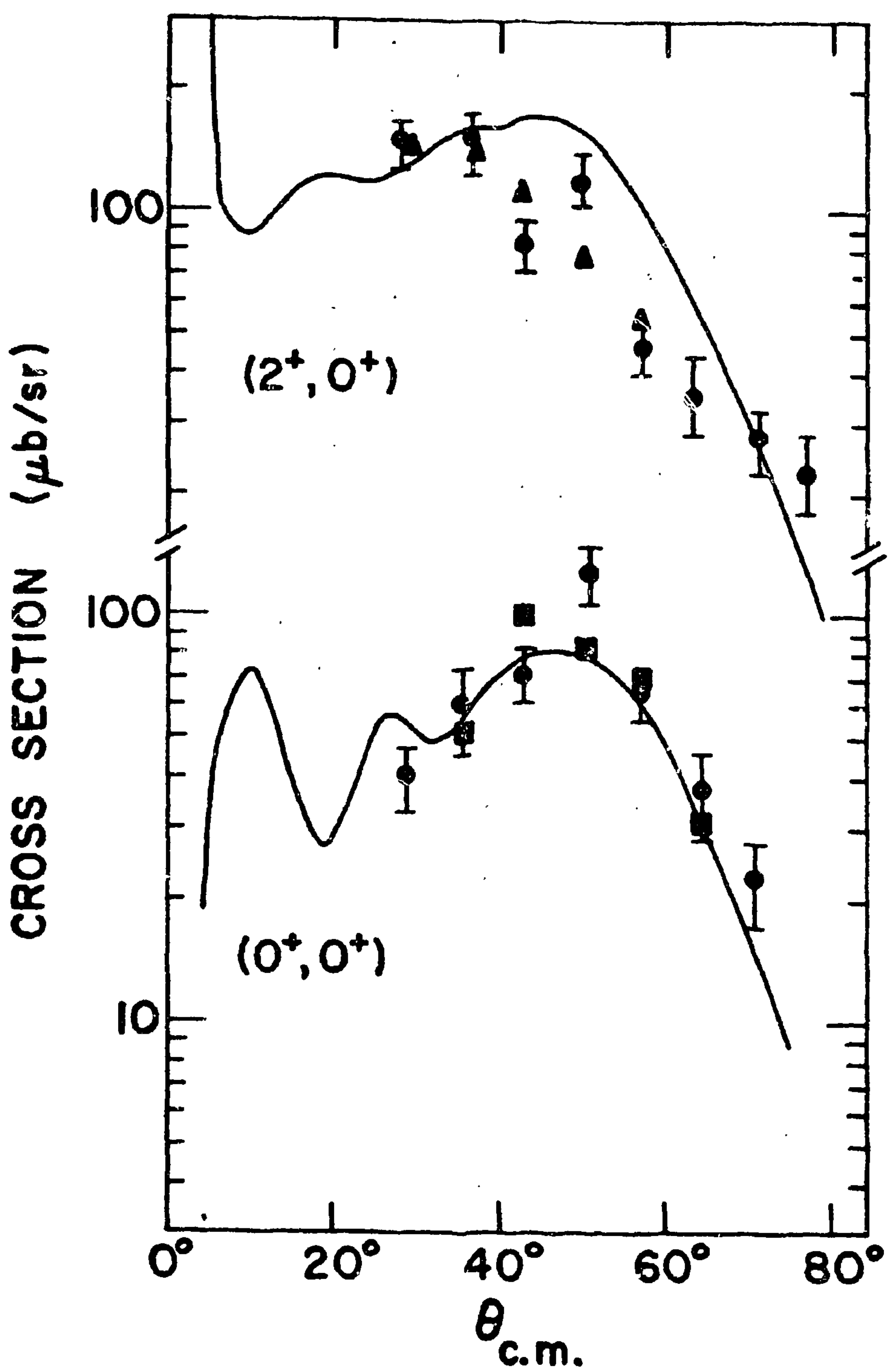
Cross sections for the ^{26}Mg(p,d)^{25}Mg and ^{26}Mg(^{3}He,α) reactions populating the 5/2$^+$ ground and 7/2$^+$ 1.61 Mev states.

Fig.IIIA-5



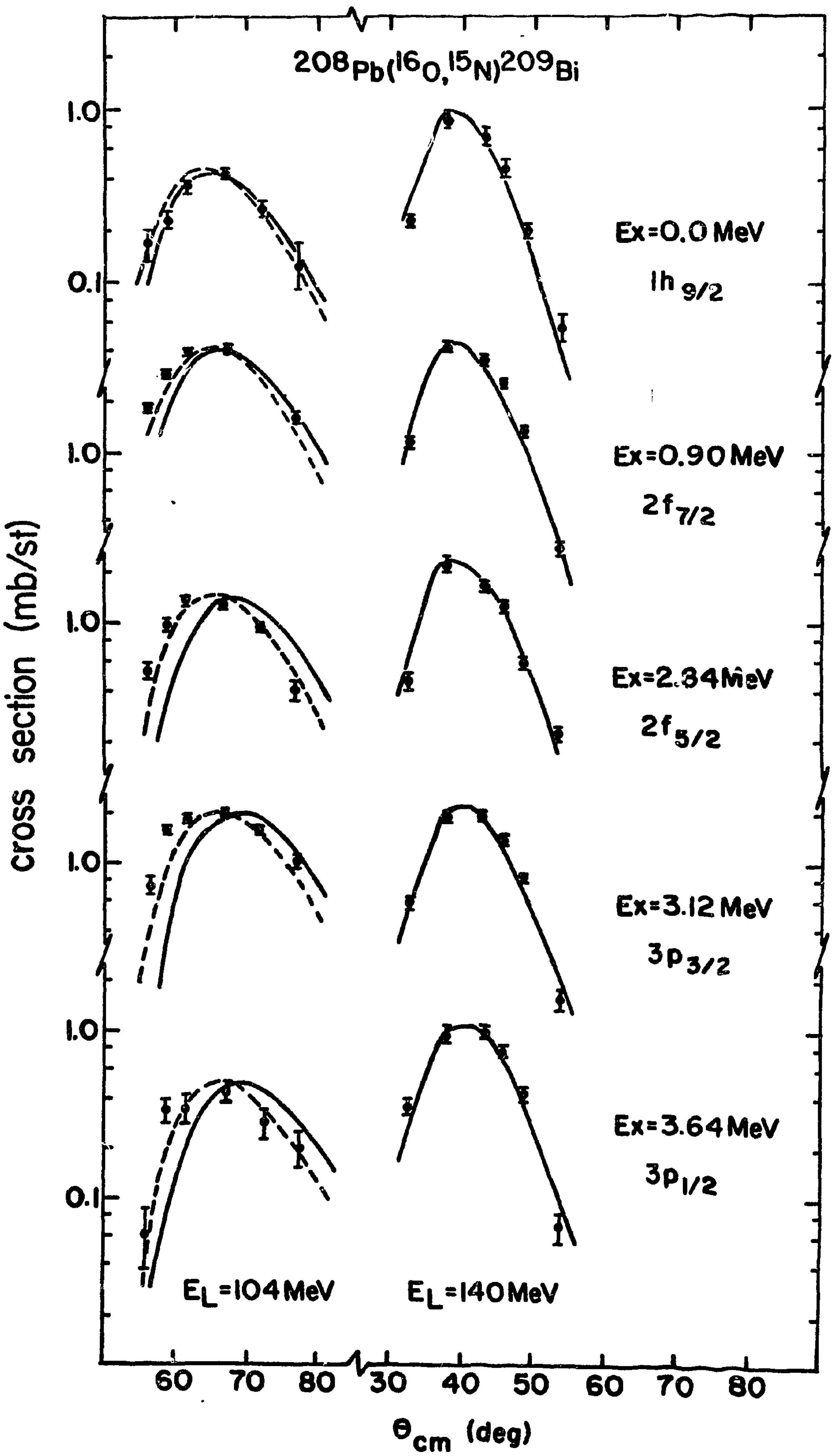
Cross sections for the ^{22}Ne(p,t)^{20}Ne reaction populating to the 0$^+$,2$^+$ and 4$^+$ ground rotational states. (a) The result of analysis of the angular distributions, and (b) and (c) the energy dependence.

Fig. IIIA-6



Best fit obtained with CCBA calculation for $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ reactions. The lower part of the figure is for the case in which both ^{20}Ne and ^{38}Ar are in 0^+ ground states. The upper part is for the case in which ^{20}Ne is in the 2^+ state.

Fig.IIIA-7



$^{208}Pb(^{16}O,^{15}N)^{209}Bi$
cross section (mb/st)
1.0
0.1
1.0
1.0
1.0
1.0
0.1
Ex=0.0 MeV
1h 9/2
Ex=0.90 MeV
2f 7/2
Ex=2.34 MeV
2f 5/2
Ex=3.12 MeV
3p 3/2
Ex=3.64 MeV
3p 1/2
EL=104 MeV
EL=140 MeV
60 70 80 30 40 50 60 70 80
θcm (deg)

III. B. COPY OF TITLE PAGES OF PUBLISHED PAPERS

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Z. Physik 263, 179—190 (1973)

III. B-1

Analysis of Stripping to Analog Resonances Using Complex Energy Eigenstates*

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An analysis is presented of 30.2 MeV ^{92}Mo(τ, d)^{93}Tc^A angular distributions for seven isobaric analog resonances in ^{93}Tc^A, using complex energy eigenstates to provide single-particle resonance state functions as form factors for the DWBA calculations. Details of the computation and use of complex energy eigenstates or Gamov functions are given, and results of the analysis are compared both with previous ^{92}Mo(d,p)^{93}Mo studies and with previous analyses of the isobaric analog resonances. It is stressed that Gamov functions make possible a simple and elegant description of direct reactions populating either single particle or isobaric analog resonances.

1. Introduction

Quite a large amount of experimental [1–4] and theoretical [5–10] work on population of isobaric analog resonances (IAR) by direct proton transfer reactions has been done over the past two years. Despite the number of papers in the literature, a conjunction of good theoretical analysis with good experimental data has been rare until recently.

It is becoming increasingly clear, however, that sophisticated calculations of the resonance state function yield spectroscopic information essentially identical to straightforward analyses utilizing optical model distorted wave functions as "form factors" [2, 3, 7, 8].

One could have foreseen that detailed form factor calculations including isospin mixing and a multichannel formulation were not strictly necessary, since the stripping reaction strongly populates only those residual states for which there is a good angular momentum matching, and the theoretical cross section is sensitive principally to the "neck" of the resonance form factor, in the nuclear surface region, where the "doorway" nature of the analog resonances is not felt.

Therefore, the simplest unambiguous method for analysis of direct reaction data, for population of IAR as residual nuclear states, should be identical to the simplest unambiguous method for analysis of direct reaction data, for population of fractionated single-particle resonances

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III. B-2

PHYSICAL REVIEW C VOLUME 7, NUMBER 6 JUNE 1973

Distorted-Wave Born-Approximation Analysis of $^{36,38}Ar(d,p)$ to Neutron Resonances in $^{37,39}Ar$

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$^{36,38}Ar$ (d,p) angular distributions at 9- and 10-MeV incident energy, for 13 neutron-unbound states in $^{37,39}Ar$, are described in terms of conventional distorted-wave Born-approximation theory using complex-energy eigenstates as form factors, and spectroscopic information is extracted which is consistent with previous studies of the bound neutron states of $^{37,39}Ar$.

I. INTRODUCTION

In studies of the reaction $^{36}Ar(d,p)^{37}Ar$ at 9.16 MeV,[1] and $^{38}Ar(d,p)^{39}Ar$ at 10.06 MeV[2] it has been found that a number of neutron unbound states in ^{37}Ar and ^{39}Ar are populated. Sen *et al.*[1,2] were able to obtain angular distributions for these states in 5° steps over c.m. angles from 26 to 146°; specifically, data are available for states at 8.89 and 9.01 MeV in ^{37}Ar, and at 6.79, 7.00, 7.06, 7.14, 7.22, 7.34, 7.40, 7.50, 7.56, 7.63, and 7.73 MeV in ^{39}Ar.

Presented here are distorted-wave Born-approximation (DWBA) analyses of these 13 angular distributions, making use of complex-energy eigenstates to described the resonance states. It is shown that use of complex-energy eigenstates permits extraction of spectroscopic factors consistent with the usual bound-state single-particle spectroscopic factors.

II. COMPLEX-ENERGY EIGENSTATES

The complex-energy eigenstate, often called a Gamow state, is either of two equivalent facto. making up the residue of the Green's function of the system, at the pole corresponding to a given resonance.[3-5] Thus it is closely analogous to the bound-state function, which is again either factor of the residue of the Green's function of the system at the pole corresponding to a given bound state. It is straightforward to show that complex-energy eigenfunctions have normalization and orthogonality properties analogous to bound states,[6] and can form part of a basis for eigenstate expansion, in the sense that a quantum mechanical state Ψ can, under weak restrictions, be expanded as a sum over discrete bound and Gamow states, plus a contour integral over continuum states.[7] The choice of contour determines the number of Gamow states included in the discrete sum, and also the set of functions Ψ which may be so expanded. The situation is quite reminiscent of Regge-type representations of the scattering amplitude, in many ways.

Some confusion has resulted over the connection of Gamow states to the familiar Hilbert spaces of scattering theory. Berggren[8] has shown that norms can be introduced for Gamow states such that many analogous mathematical properties,

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Exact Macroscopic Charge-Independent Analysis of Quasielastic (p, n) Reactions*

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A technique is described in which a strictly charge-independent optical potential for nucleons is derived from empirical neutron and proton potentials which provide optimum fits to the available data. Predictions for the (p, n) charge-exchange reaction on ^{208}Pb and ^{209}Bi are made by solving the coupled Lane equations exactly. It is found that both angular-distribution and excitation-function data are fitted quite well, without adjustable parameters.

I. INTRODUCTION

In this paper some inadequacies of the standard approach to determination of the isospin-dependent part of the nucleon optical-model potential, from global neutron and proton optical-model analyses, are discussed. An alternative procedure is presented, in which a strictly charge-independent optical potential for nucleons is derived from given empirical neutron and proton optical potentials which provide optimum fits to the available data. The isospin part of this charge-independent potential is complex and can have a rather complicated energy-dependent form factor, when rather different neutron and proton optical potentials are used as generating potentials. Predictions using the results of the analysis are made for the quasielastic (p, n) charge-exchange reaction, which is directly sensitive to the isospin part of the nucleon optical-model potential, by solving the coupled Lane equations exactly. It is found that both the neutron angular distributions from quasielastic (p, n) reactions and the rapid energy dependence of the corresponding (p, n) excitation functions are fitted quite well, *without adjustable parameters*.

II. DISCUSSION OF OPTICAL SYMMETRY POTENTIAL

Satchler and Perey[1] remarked that, in the Becchetti-Greenlees[2] (BG) search for global neutron and proton optical potentials, the parametrization of the neutron potentials was based on the proton analysis and included a forced dependence on both energy and symmetry parameter, $(N-Z)/A$. In the search on the neutron data most parameters were fixed at the values obtained from the proton study, very few parameters being determined solely from the neutron data. In part this bias is unavoidable, since extensive 30- and 40-MeV proton data were available for the determination of the proton parameters, but most all of the neutron data was for energies below 15 MeV, except 3 cases at 24 MeV. Thus, in the BG analysis, an important compound-elastic contribution to the neutron cross sections was simply adjusted to obtain the best fit. It is not surprising to find, therefore, that the experimental total and reaction cross sections for neutrons are poorly described by the BG potentials.[1] It is important to note that the BG potentials are significantly different in strengths and geometries from those obtained from other analyses of neutron data at low energies.[3,4]

The ambiguities of the BG analysis, as well as many others less careful and complete, leave the $(N-Z)/A$ dependence (or "symmetry" dependence) of the difference between neutron and proton potentials very unclear. If one adopts the BG global analysis, then the symmetry-dependent potential is taken to be complex with a real volume strength of 24 MeV and an imaginary surface strength of 12 MeV.

However, for example, there is evidence from an extensive study of neutron scattering, on targets from Al to Bi at 1.5 to 8 MeV, of a dependence of the real potential alone on the symmetry parameter $(N-Z)/A$, with no dependence of the imaginary potential on symmetry.[5] Here the real potential strength was found to be 12.5 ± 2.5 MeV, which is about half the value found in the BG analysis. Other total cross-section measurements have been reported which imply that for neutrons the real symmetry potential has a strength of 17 MeV, while the imaginary potential has a strength of about 26 MeV.[6] Independent analysis by Perey of 14-MeV data is consistent with a symmetry potential of zero.[1]

Thus, detailed knowledge about the symmetry potential as obtained from elastic scattering remains clouded. However, if the symmetry potential found from optical-model analyses of nucleon elastic scattering data is as usual identified with the contribution to the effective elastic scattering potential from a more generalized nucleon optical potential which contains a term such as $V_1 \vec{t} \cdot \vec{T}_0/A$,

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III. B-4

PHYSICAL REVIEW C VOLUME 7, NUMBER 3 MARCH 1973

Coupled-Reaction-Channels Study of (h, t) Reactions*

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(Received 19 October 1972)

We have developed a formulation of the theory of multichannel nuclear reactions which permits practical and realistic numerical calculations in which a number of different reaction channels are coupled, assuming a zero-range approximation for the effective coupling and neglecting effects arising from the non-orthogonality of different reaction channels. A computer program, JUPITER-4, has been written embodying this coupled-reaction-channel formulation, and as a specific application we present analyses of the (h,α)-(α,t) or pickup-stripping contributions to (h,t) reactions, for the specific cases of $^{48}Ca(h,t)^{48}Sc$ and $^{40}Ar(h,t)^{40}K$. We pay particular attention to the interplay and interference of direct and pickup-stripping amplitudes, and try to identify general tendencies. Finally, we give simple sum rules which aid in predicting the nature of the interference for specific spins of intermediate and final nuclear states.

I. INTRODUCTION

The reactions (h, t) and (p, n) at reasonable energies have customarily been interpreted as occurring through a direct, one-step charge-exchange process.[1-4] Evidence for this mechanism is the strong population of isobaric analog resonances by such reactions. However, much recent experimental evidence suggests that a simple direct-reaction process is not necessarily the dominant reaction mechanism, particularly for (h, t) and that the usual distorted-wave Born approximation (DWBA) is inadequate.[5-11] (The symbol h stands for the helion, the nucleus of the mass-3 helium atom.)

For example, the angular distributions for (h, t) population of the $J^\pi = 0^+$ antianalog state in a variety of nuclei do not have an $l=0$ pattern, but can be fitted in shape by an $l=1$ DWBA calculation.[6] A persistent shift, to backward angles, of the experimental angular distributions relative to DWBA calculations has been observed generally for residual $T_<$ states of any J.[6-8] A serious anomaly in magnitude is observed, such that (h, t) cross sections for 4^+ and 6^+ $T_<$ states have magnitudes 1 or 2 orders greater than expected on the basis of DWBA calculations, using microscopic form factors.[5] These discrepancies are not removed by more sophisticated DWBA approaches including a tensor force, exchange terms, etc.[9] Further, a strong energy dependence is noted in the microscopic or macroscopic form factor when angular distributions are fitted at several energies.[10] Finally, it is noted that arbitrarily introducing a complex part to the microscopic form factor often improves the calculated DWBA angular distribution in shape, relative to the data.[11]

All such observations point to a multistep mechanism for (h, t).[12-14] Toyama,[13] and the present authors[14] have investigated the effect of the pickup-stripping mechanism for (h, t), namely, (h, α), (α, t) processes. Toyama calculated cross sections for $^{48}Ca(h, t)^{48}Sc$ leading to the $(f_{7/2}^{-1}f_{7/2})$, 0^+ to 6^+ states in ^{48}Sc, assuming a pure (h, α), (α, t) mechanism. He was able to account for the relative magnitudes of all four states, as well as to obtain excellent shape fits to the available data at two incident energies. He also found a negligible contribution from (h, d), (d, t). We have previously shown that to explain the angular shift in the $^{40}Ar(h, t)^{40}K$ 0^+-antianalog-state angular distribution, and the relative magnitudes of 0^+-analog-state and 0^+-antianalog-state cross sections, one has to assume both direct *and* pickup-stripping mechanisms, with careful treatment of the interference between them.[14]

The (h, t) cross sections are generally 1 or 2 orders of magnitude smaller than typical inelastic scattering cross sections for population of collective states, and typical single-nucleon-transfer-reaction cross sections. It is then not surprising if two-step processes can play an important role in (h, t). Important contributions from inelastic processes in entrance and exit channels have previously been found for (p, t) reactions, which have cross sections comparable in magnitude to (h, t) reactions.[15] The possibility of successive single-nucleon-transfer mechanisms for two-nucleon-transfer reactions has not to date been studied, though (p, h) and (d, α) reactions could have important contributions from such mechanisms.

It is of great interest to investigate in a systematic way the contributions of successive specific nuclear reactions to a given reaction. We have developed a program JUPITER 4 which solves a set of coupled radial Schrödinger equations for

MULTISTEP CONTRIBUTIONS IN ^{88}Sr(h, t) ^{88}Y ☆

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Received 19 June 1973

Using a coupled-reaction-channels (CRC) description of nuclear reactions, we have studied the reaction ^{88}Sr(h,t) ^{88}Y to 4^-, 5^-, and 2^+, 3^+ doublet states. The data, taken at 23 MeV, show angular distributions with anomalous shapes, which cannot be explained by simple distorted-wave Born approximation calculations; our calculations, including (h,α) – (α,t) and (h,d) – (d,t) intermediate processes, but neglecting the direct (h,t) mechanism, give a good description of the shapes and relative magnitudes of the angular distributions. Effects of configuration mixing are also studied.

It has been shown recently that (h, t) angular distributions for population of the 0^+ isobaric analog state in ^{40}K and ^{48}Sc, and natural parity 2^+, 4^+, 6^+ states in ^{48}Sc, can be understood in shape and magnitude in terms of a multistep reaction mechanism involving, principally, (h,α)–(α,t) and direct (h, t) processes [1–4]. Further, the anomalous shape of the (h, t) transition ot the 0^+ antianalog state in ^{40}K can be understood as a result of interference between (h,α)–(α,t) processes through various contributing intermediate states in ^{39}Ar, considered together with a direct process [2,4].

In the present work, we treat the reaction ^{88}Sr(h,t) at 23 MeV incident h energy, populating four states in ^{88}Y: the 4^-, 5^- ground state doublet, which has principally the configuration $(p_{1/2}g_{9/2}{}^{-1})$, and the 3^+, 2^+ doublet at 1.70, 1.95 MeV which has principally the configuration $(p_{1/2}f_{5/2}{}^{-1})$ [5]. The states of ^{88}Y have been the subject of a number of recent, detailed spectroscopic studies, involving ^{88}Sr(h, t), ^{87}Sr(α, t), ^{87}Sr(h,d), ^{89}Y(h,α) and ^{90}Zr(d,α) [5–7]. Thus a large amount of information is at hand upon which to base realistic multistep reaction calculations.

The four states mentioned are the only strong candidates, on the basis of the single nucleon transfer studies, for membership in the multiplets to which they have been assigned. Yet the shapes of the (h, t) angular distributions for these states are inconsistent with the usual singel-nucleon transfer assignments, if the usual distorted-wave Born approximation description of direct (h, t) reactions is employed [5, 8, 9]. Most anomalous is the shape of the 4^- ground state transition, which bears no resemblance to the prediction of DWBA calculations, without tensor force terms in the form factor, as is seen in fig. 1, 2 of ref. [5]. The general nature of the anomaly, for all the transitions, is an apparent mixing of non-allowed l-transfers and has been described, with a number of examples, by Comfort et al. [9].

In the present work, we show that the shapes of the 4^-, 5^-, 2^+ and 3^+ angular distributions follow naturally from a treatment in which intermediate single-nucleon transfer processes are included in the theoretical description of the (h, t) reaction mechanism [1–4]. Our calculations have been done in terms of a coupled-reaction-channel (CRC) formalism [4, 10], with the program JUPITER 4. Details of the formalism and numerical methods have appeared elsewhere [4]. Optical potentials used for the h, t, d and α channels are those called H1, D1 and A1 by Comfort and Schiffer [5]. The nonorthogonality of the various mass partitions is neglected, as in ref. [4].

The usual separation-energy method was used to compute single-nucleon-transfer form factors. Spectroscopic amplitudes were computed, or deduced from experiment [5, 11], using the phase convention defined in eqs. (14) and (25) of ref. [4]. The spectroscopic amplitudes relevant to the present calculations are given in table 1.

Three types of reactions were considered. (1) Direct (h, t) amplitudes were computed using a microscopic form factor, without a tensor term [8]. A gaussian

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III. B-6

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NOTE ON THE "FORBIDDEN" (p, t) EXCITATION OF UNNATURAL PARITY FINAL STATES FROM 0^+ TARGETS VIA MULTISTEP PROCESSES*

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An estimate of the (p-d-t) successive single-neutron pickup cross section is shown to be in disagreement with experimental data for the "forbidden" ^{22}Ne(p, t)^{20}Ne(4.97 MeV, 2^-) transition. Furthermore, it is shown that cross sections at very forward angles are important to distinguish whether a "forbidden" transition proceeds via inelastic excitations or successive single-neutron pickup.

There has been considerable interest [1,2] in the (p, t) excitation of unnatural parity states from 0^+ targets because such transitions are forbidden in the usual zero-range, distorted-wave-Born-approximation (DWBA) formalism [3]. This selection rule results from the following three assumptions: (i) the reaction mechanism is a direct single-step process, (ii) the two neutrons in the triton wave function are in a spin-singlet state with zero relative orbital angular momentum, (iii) the perturbing interaction depends only on the distance between the proton and c.m. position of the two neutrons. Recently Bayman and Feng [4] have relaxed assumptions (ii) and (iii) by including finite range effects and calculated the "forbidden" ^{22}Ne(p, t)^{20}Ne(4.97 MeV, 2^-) cross section to be two orders of magnitude smaller than its experimental strength. This result leads to the conclusion that the (p, t) excitation of unnatural parity states proceeds primarly through multistep paths if the reaction is a direct process. Hence, such transitions allow the study of multistep process without the complications of a competing single-step path.

Two distinctly different multistep processes appear to be significant for (p, t) transitions. One multistep process proceeds via inelastic scattering in the entrance and exit channels, and is reasonable well understood in terms of the couple-channel-Born-approximation (CCBA) formalism [5]. In particular both the relative strength and shape of the "forbidden" ^{22}Ne(p, t)^{20}Ne(2^-) transition is predicted correctly by the CCBA [2]. The other process arises from successive single-neutron pickup, that is, a (p-d-t) mechanism. This process is not well understood, and so far only one preliminary calculation has been reported for "allowed" transitions [6]. In this letter we estimate the (p-d-t) cross section for the above 2^- transition, and discuss a characteristic difference between the forward angle cross sections from inelastic excitations and successive single-neutron transfer.

We estimate the ^{22}Ne(p-d-t)^{20}Ne(2^-) cross section with the second-order Born approximation [6–8] using the coupled-reaction-channel (CRC) formalism of ref. [7]. We assume simple BCS vacua states for the ^{22}Ne and ^{20}Ne ground states, and assume a simple particle-hole (two-quasi-particle) state with the neutron configuration $p_{1/2}^{-1} d_{5/2}$ for the ^{20}Ne, 2^- wave function. Two (p-d-t) paths are then possible to connect the ^{22}Ne ground state to the ^{20}Ne, 2^- excited state. One path goes through the ^{21}Ne, $5/2^+$ state at 0.35 MeV of excitation, whereas the other path goes through a ^{21}Ne, $\frac{1}{2}^-$ state at 5.00 MeV of excitation. The absolute calculated cross section including both paths are compared with the 39.8 MeV Minnesota data in fig. 1. In addition, a similar calculation is shown for the "allowed" transition to the 5.63 MeV, 3^- state. *Both* cross sections (solid curves) are from a (p-d-t) process only and do not include direct (p, t) amplitudes.

The proton, deuteron, and triton optical model parameters used are from ref. [9–11], respectively, and the neutron spectroscopic amplitudes (A_{lj} of ref. [7]) are given in table 1. Zero-range force con-

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Coupled-Channel-Born-Approximation Analysis of "Allowed" and "Forbidden" $^{22}Ne(p,t)^{20}Ne$ Transitions*

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The effects of inelastic excitations on the $^{22}Ne(p,t)^{20}Ne$ reaction are investigated. Differential cross sections at a proton energy of 39.8 MeV were measured for $^{22}Ne(p,t)^{20}Ne$ transitions to the 0^+, 2^+, and 4^+ members of the ground-state rotational band, to the 2^- and 3^- members of the excited $K^\pi=2^-$ band; and to the 0^+ and 2^+ members of the first excited $K^\pi=0^+$ band. The cross sections to members of the ground-state band are compared with distorted-wave Born-approximation (DWBA) and coupled-channel-Born-approximation (CCBA) calculations using both pure Nilsson and pairing-mixed Nilsson rotational wave functions. Only the CCBA calculation with pairing provides a reasonable description of the experimental data. The effects of multistep processes are found to be as large for neon as for rare-earth nuclei. The shape and relative strength of the measured cross section to the 2^- state, a transition which is forbidden by a direct single-step process, are reproduced well by the CCBA calculation, which allows the excitation of the 2^- state by inelastic processes in the entrance and exit channels.

I. INTRODUCTION

Recently it has been shown that multistep processes which arise from inelastic excitations make very significant contributions to (p,t) cross sections. The coupled-channel-Born-approximation (CCBA) theory for explicitly calculating such effects was first formulated by Penny and Satchler.[1] They extended the usual distorted-wave Born-approximation (DWBA) formalism to include contributions from indirect processes. The amplitudes for these indirect processes add to the direct single-step DWBA amplitude and therefore contribute coherently to the cross section. Using formulations equivalent to that of Penny and Satchler,[1] CCBA calculations for (p,t) reactions have been reported for both spherical[2] and deformed[3-5] nuclei.

Even-even nuclei in the rare-earth region have been of particular interest for the initial investigation of these effects.[3-5] The magnitudes of the indirect amplitudes depend both upon the parentage of the states of interest and the strengths of the inelastic excitations, and both of these factors are large for rare-earth ground-state rotational bands. In addition, the basic simplicity of the nuclear structure of these bands allows accurate wave functions to be calculated. In these studies, initial and final state rotational wave functions of the adiabatic form have been used with intrinsic wave functions constructed from the mixing of a large number of Nilsson orbits by a simple pairing force.[6] CCBA calculations using such wave functions have reproduced both the experimental shapes and relative transition strengths remarkably well for such transitions.[4] In contrast, DWBA predictions have been in gross disagreement with the measured cross sections.

Neon is in another region of strong permanent deformation giving rise to rotational bands. In fact, the quadrupole deformations of the ground-state bands of ^{20}Ne and ^{22}Ne are considerably larger than those of rare-earth nuclei. Figure 1 shows all the low-lying levels of ^{20}Ne grouped into five rotational bands.[7] The adiabatic approximation appears to be valid, at least for the low-spin members of rotational bands in ^{20}Ne and ^{22}Ne. The ratios of electromagnetic matrix elements for the low-spin members of both ground-state bands and for the $K^\pi=2^-$, ^{20}Ne excited band have been shown to be consistent with these states being generated from rigid rotations.[8] In addition, shell-model wave functions for these states overlap well with the corresponding wave functions projected from a single intrinsic state.[9] Hence transitions to low-spin members of the ^{20}Ne rotational bands provide excellent examples with which to investigate the effects of multistep processes on (p,t) reactions.

In this publication we report the measurement of $^{22}Ne(p,t)^{20}Ne$ differential cross sections at 39.8 MeV. In particular, angular distributions of transitions to the following ^{20}Ne states were obtained: the 0^+, 2^+, and 4^+ members of the $K^\pi=0^+$, ground-state band; the 2^- and 3^- members of the first excited $K^\pi=2^-$ band; and the 0^+ and 2^+ members of

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Coupled-Channel-Born-Approximation Analysis of One-Nucleon Transfer Reactions to ^{25}Mg and ^{25}Al

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A simple formulation of the coupled-channel Born approximation is presented, for the case where the spin-dependent term in the optical potential can be ignored. The formalism is particularly useful in reducing the computer time required when numerical calculations are carried out for one-particle transfer reactions.

The formalism is then applied to calculate one-particle pickup and stripping reactions such as (p,d), $(^3\mathrm{He},\alpha)$, (d,t), and $(^3\mathrm{He},d)$, all leading to the 1.61-MeV $\frac{7}{2}^+$ and the 3.4-MeV $\frac{9}{2}^+$ states, together with the $\frac{5}{2}^+$ ground states in mass-25 nuclei. It is shown that the observed cross sections are all well reproduced by the Coupled-Channel-Born-approximation calculations.

I. INTRODUCTION

Much interest has been concentrated on the excitation of the 1.61-MeV $\frac{7}{2}^+$ states in ^{25}Mg and ^{25}Al by means of one-particle pickup and stripping reactions.[1-8] Note that these reactions are almost completely forbidden on the basis of a direct single-step mechanism, since the admixture of the $g_{7/2}$ single-particle state into the initial- and final-state wave functions is extremely small,[1] while experimentally observed cross sections are almost two orders of magnitude greater than that resulting from the above simple theoretical estimate.[1-6] Further, the shape of the observed angular distributions is generally found to disagree with the distorted-wave Born-approximation (DWBA) prediction with $l=4$.[1-4]

These experimental facts seem to show that the $\frac{7}{2}^+$ state is primarily excited through processes other than those of the direct single-step type. Since the nuclei involved in the reactions are strongly deformed, it is quite natural to expect that the multistep processes involving the inelastic scattering in both the incident and exit channels play an important role. Studies along this line have actually been made recently, in which the (d,p) reaction data for $E_d=13.5$ MeV[7] and 10.1 MeV[8] were specifically analyzed in terms of the coupled-channel Born approximation (CCBA).[9,10] Unfortunately, the conclusions obtained in the two independent works[7,8] contradicted with each other; in Ref. 7, the observed data (at $E_d=13.5$ MeV) were well reproduced in the calculations, while in Ref. 8, it was not possible to reproduce the data ($E_d=10.1$ and 12.3 MeV). The failure of the later work, however, could be attributed to the fact that the deuteron energy with which the author is concerned is not sufficiently high so that the measured cross sections involve a large contribution from compound processes.[8] Indeed, (d,p) data taken at small intervals of deuteron energy ranging from 6 to 13 MeV exhibited a rather marked variation with the incident energy, though the excitation function became comparatively smooth near 13 MeV.[11]

In order to get a clearer answer to the question of whether the forbidden transition to the $\frac{7}{2}^+$ state is indeed explained in terms of the CCBA, we have undertaken a systematic analysis of various one-particle transfer reaction data.[12] Experimental data are available for reactions such as (p,d), $(^3\mathrm{He},\alpha)$, (d,t), and $(^3\mathrm{He},d)$,[1-4] and we analyzed all of these data. Our analysis further included another forbidden transition, to the $\frac{9}{2}^+$ state at 3.4 MeV.

One problem in the CCBA analysis is that the calculation requires a large amount of computer time, particularly when the particle (the projectile or the outgoing particle) has a nonzero spin. However, under circumstances, such as those here, in which the spin-orbit part of the optical potential can safely be ignored, one can assume in the major part of the calculations that the incoming or outgoing particle has a vanishing spin, and thus one can speed up the calculations greatly. In Sec. 2, we thus present the reformulation of CCBA needed in carrying out this type of calculation.

Numerical results obtained by using the computer program MARS[13] are given in Secs. 3 and 4. In Sec. 3, the calculations are made of the ground $\frac{5}{2}^+$

2.B:2.G

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THE ASYMMETRY IN THE ^{176}Yb(p, t)^{174}Yb REACTION USING POLARIZED PROTONS AT 16 MeV

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Abstract: The vector analyzing power, as well as the differential cross sections, were measured for the ^{176}Yb(p, t)^{174}Yb reaction with $E_p = 16$ MeV, leading to the 0^+, 2^+, and 4^+ states of the ground band. It was found that the CCBA explains both measurements rather well, while the DWBA also explains the data for the analyzing power, but not the (p, t) angular distributions particularly those for the excited states.

E | NUCLEAR REACTIONS ^{176}Yb(p, t)^{174}Yb, polarized proton beam, $E = 16$ MeV; measured $\sigma(E_t, \theta)$, analyzing power $P(\theta)$.

1. Introduction

Recently proton beams having both large polarization and high intensity have become available, making it possible to study the asymmetry of the (p, t) reaction despite the small magnitude of the cross section. The present paper reports on one of the first studies of vector analysing power in a two-nucleon transfer reaction. We were motivated by the experience gained in understanding the differential cross section obtained from the reaction ^{176}Yb(p, t)^{174}Yb [ref. [1]]. The nucleus ^{176}Yb has a large deformation; consequently the (p, t) reaction proceeds by two modes, the one-step two neutron transfer and the two-step process, inelastic scattering plus two neutron transfer. The second mode including its interference effects, significantly changes the relative magnitudes of the differential cross sections of the 0^+, 2^+, and 4^+ states [2,3]. In the present work, an investigation is therefore made of the effect of the second mode on the asymmetry based on the coupled channel Born approximation (CCBA) [refs. [2,3]].

In sect. 2, the experimental procedure is briefly reviewed and in sect. 3, the experimental results are presented. In sect. 4, a CCBA theoretical analysis is made and in sect. 5, final conclusions are given.

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MULTISTEP CONTRIBUTIONS TO $^{11}B(h,\alpha)^{10}B$ FROM 8.0 TO 12.0 MeV

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Various improvements to the usual distorted-wave Born approximation description of direct reactions on light nuclei are investigated, using $^{11}B(h,\alpha)^{10}B$ as an example, and including finite-range effects, compound nuclear contributions, and deformation as well as inelastic process in the entrance and exit channels. It is found that only the inelastic processes and deformation play an important role, and that their inclusion, via the coupled-channel Born approximation, very satisfactorily describes the available data in shape and magnitude.

Part of the hoariest lore of nuclear physics is the observation that particle-transfer reactions on the lighter nuclei cannot be well described by the usual distorted-wave Born approximation (DWBA) calculations. Spectroscopic factors are found to be strongly energy- and reactions-dependent [1–3]. Generally the experimental cross sections have slopes much less steep than the DWBA predictions, the discrepancy increasing with decreasing incident energy. Vague, accusatory comments regarding the compound nucleus or the optical model are often found in the literature, as something of an excuse for the failure of direct reaction theory, but these accusations have not been followed up.

In this note, we present a study of the $^{11}B(h,\alpha)$ reaction to the ground state of ^{10}B, at h energies of 8, 10 and 12 MeV. Helions were produces by the 6 MV Van de Graaff accelarator at ORNL and used to bombard a self-supported ^{11}B target. Targets of thickness ranging from 20 $\mu g/cm^2$ to 50 $\mu g/cm^2$ were used. The details of the method for preparation of the targets, as well as the electronic arrangement for the charged-particle identification system, have been described earlier [1]. Data were accumulated for five states in ^{10}B: 3^+ ground state, 1^+ 0.717 MeV, 0^+ 1.74 MeV, 1^+ 2.15 MeV, and 2^+ 3.59 MeV. Only the 3^+ results are discussed here.

In analysis of these data we have considered the following improvements over the usual DWBA approach: (1) finite range of the effective interaction [4]; (2) coherent contributions from compound nuclear states [5]; and, (3) inelastic excitations and/or deformation in initial and final channels [6].

Finite range effects were investigated using the program FRVENUS [7] which performs an exact, finite-range DWBA calculation [4]. The optical potentials used were A and C of the table, and the interaction range was 1.5 fm [8]. There was no significant difference in shape or magnitude between these calculations and conventional zero-range calculations with the program VENUS [9], confirming earlier results of Drisko and Satchler [8].

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FINITE-RANGE COUPLED-CHANNEL BORN APPROXIMATION FOR HEAVY-ION TRANSFER REACTIONS

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The two proton transfer reaction data of $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ obtained by Katori et al[1] as shown in Fig.1 revealed a striking difference in angular distribution to different final states of the reaction products. The $(2^+,0^+)$ cross section* has the peak apparently shifted by about 10^o to the forward direction compared with $(0^+,2^+)$ as well as $(0^+,0^+)$ cross sections. DWBA calculations made with finite range but with norecoil approximation[2], however, cannot predict such a difference, since as also shown in Fig.1, all the theoretical cross sections have the characteristic bell-shaped distribution, with the peaks appearing at about the same angle.

Since ^{20}Ne is a well deformed nucleus , it would be quite natural to investigate the contribution from the two- (or multi-) step processes which have been found very important for a number of light-ion reactions[3]. Still using the norecoil approximation we thus have performed two CCBA calculations, one with and the other without Coulomb excitations, and the results are given in Fig.2. In this figure it should first be noted that the DWBA curves have been shifted to the larger angle, as compared with the corresponding curves in Fig.1. The reason is that we now consider the deformation of ^{20}Ne, and thus even the central part of the optical potential has been modified[4].

Compared with the DWBA cross section, the CCBA $(2^+,0^+)$cross section has a markedly different angular distribution with sizably increased magnitude in the forward angles and gets closer to the experimental distribution, though not yet sufficiently. Before trying to get a better agreement with experiment,

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* When the two nuclei ^{20}Ne and ^{38}Ar in the exit channel are, respectively, in states with spins I^+ and I'^+, the corresponding cross sections are denoted as (I^+,I'^+) cross sections.

III. B-12

1.E.1: 2.A.1

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THE REACTION ^{20}Ne(^{3}He, n)^{22}Mg AT ^{3}He ENERGIES BELOW 6 MeV

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Abstract: The ^{20}Ne(^{3}He, n)^{22}Mg reaction has been studied with particular emphasis on some unusual angular distributions observed at bombarding energies between 4 and 6 MeV. A satisfactory explanation of the ground state group differential cross sections is given by assuming interference between direct interaction and compound-nucleus formation. The ^{22}Mg half-life was measured to be 3.97 ± 0.09 s, and an excitation curve for the ^{22}Mg(β^{+}) activity was obtained.

E | NUCLEAR REACTIONS ^{20}Ne(^{3}He, n), $E = 4$ to 5.6 MeV; measured $\sigma(E, E_n, \theta)$, Q. ^{22}Mg deduced levels. Reaction mechanism discussed. Enriched target. RADIOACTIVITY ^{22}Mg {from ^{20}Ne(^{3}He, n)^{22}Mg}; $E = 3$-5.6 MeV. $T_{\frac{1}{2}}$ deduced; $\sigma(E)$. Enriched target.

1. Introduction

The particular shapes and strong energy dependence of the neutron differential cross sections in the ^{20}Ne(^{3}He, n)^{22}Mg reaction at $\bar{E}_{^3\mathrm{He}} < 6$ MeV focus interest on the reaction mechanism. Two-nucleon transfer DWBA programs did not provide satisfactory fits to the angular distributions, yet direct interaction (DI) features were obviously present.

A satisfactory explanation of the n_0 angular distributions has been obtained by adding amplitudes from a DWBA program to amplitudes from two assumed resonances in ^{23}Mg.

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Regge Description of Optical-Model Scattering

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The analytic continuation of the S matrix into the complex angular momentum plane is performed exactly for the Woods-Saxon-type optical potentials, describing the elastic scattering of spinless but charged particles. The properties of this S matrix, such as the nature of the pole trajectories and the behavior of the background integral, are investigated for several specific cases. Based on these exact calculations, the validity of various approximations made in the Regge theory is assessed. It is found that approximations which retain only the pole terms are generally poor, being quite sensitive to the number and the positions of the poles and converging very slowly with an increasing number of poles. On the other hand, models using a simple analytic background term, in addition to one pole term, are found to reproduce the exact Regge amplitude quite accurately under favorable conditions. Suggestions are made for the possibility of extending this idea into a background-plus-several-pole model, when the background–one-pole model fails.

I. INTRODUCTION

Since the complex angular momentum approach was first introduced by Regge *et al.*,[1] it has been applied mostly to the relativistic rather than the nonrelativistic domain, in spite of the fact that various mathematical manipulations basic to the approach can be made rigorously only in the latter domain. The reason for this could have been that in nuclear and atomic physics, very little seems to be gained from this approach beyond what can be obtained by more conventional methods. However, interest has been revived recently, perhaps in relation to an increased investigation of heavy-ion-induced nuclear reactions. One finds that the scattering of such strongly absorbed particles can be described more easily and more uniquely in terms of a smooth cutoff S matrix, in contrast to optical-model fits which suffer from many discrete and continuous ambiguities.[2] More recently it was shown that the strong backward rise seen in heavy-ion scattering cross sections

III. B-14

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EFFECTS OF NUCLEAR COLLECTIVITY ON THE TOTAL NEUTRON CROSS SECTION

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A study is made of the effect of the nuclear collectivity on the variation of the total neutron cross section with respect to the incident energy ranging from 4 to 20 MeV. It is found that the higher the collectivity, the smoother is the excitation function, for both deformed and vibrational nuclei. This feature is understood qualitatively in terms of the nuclear Ramsauer effect and is explained quantitatively by coupled-channel calculations. These calculations further reveal that deformed nuclei have larger total cross sections and smoother variations than do the vibrational nuclei. For vibrational nuclei, it is also found that the quadrupole deformation has a slightly larger effect on the smoothness than does the octupole deformation, if they have the same deformation parameter.

I. INTRODUCTION

Much information has been obtained from the measurements of the dependence of the total neutron cross section σ_t on the orientation of deformed nuclei [1-6]. In particular, it is now known that an optical model analysis using adiabatic coupled-channel calculations (ACC) gives a satisfactory explanation of both σ_t and the quantity $\Delta\sigma_{(def)}$ defined as σ_t(oriented) - σ_t(unoriented) for ^{165}Ho over an energy range from 1 to 135 MeV [4,5]. It has also been shown that

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Z. Physik 260, 179–184 (1973)

Optical Model and Coupled-Channel Analysis of 60–90 MeV Deuteron Scattering from ^{24}Mg and ^{89}Y

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Angular distributions of deuterons scattered from ^{24}Mg and ^{89}Y in the angular range 12° → 100° have been measured at E_d = 60, 77 and 90 MeV. With some exceptions the elastic and inelastic data were found to be described consistently by the optical model approach and by coupled-channel analysis, respectively. Collective model features of ^{24}Mg are derived from the inelastic scattering results.

To date systematic investigations of deuteron scattering exist up to about 50 MeV [1]; in addition results for 80 MeV deuteron scattering have been reported recently from Orsay [2]. In a first approach to extend the systematics in the energy range above 50 MeV, using the variable energy isochronous cyclotron JULIC, the elastic and inelastic deuteron scattering from ^{12}C, ^{24}Mg, ^{27}Al, ^{89}Y, ^{115}In and ^{197}Au has been measured at 60, 77 and 90 MeV; for ^{24}Mg and ^{89}Y additional data were taken in 2 MeV steps from 60 to 80 MeV.

In this first communication we present part of the experimental ^{89}Y and ^{24}Mg data together with the first results concerning their interpretation.

The measurements were performed with $\Delta E - E$ telescope counters, consisting of a 0.5 mm thick standard surface barrier ΔE counter [3] and a 20 mm long Ge(Li) diode as E counter which had been developed in this laboratory [4]. The counters were mounted in cryostats around a 20 cm diameter scattering chamber which has been described elsewhere [5].

The resolution obtained in the particle spectra was ≈250 keV corresponding to the 3‰ beamspread in the unanalysed beam of JULIC.

Figs. 1, 2 and 3 show the angular distributions of elastic deuteron scattering on ^{89}Y and ^{24}Mg at 60, 77 and 90 MeV. As can be seen from the data the shapes of the angular distributions vary smoothly with incident deuteron energy and their overall slopes increase gradually with increasing energy. The measured absolute cross sections in the region of forward angles do not exhibit any remarkable variation with energy.

* On leave of absence from University of Texas, Austin, Texas, USA, May–July, 1972.

III. B-16

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 34, SUPPLEMENT, 1973
PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON NUCLEAR MOMENTS AND NUCLEAR STRUCTURE, 1972

V.h. Nuclear Moments and Related Structure of Vibrational and Transitional Nuclei

T. TAMURA and T. KISHIMOTO†

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(Presented by T. Tamura)

It is shown that the Boson expansion technique describes quite well the transition from vibrational ^{148}Sm to deformed ^{154}Sm. It is also shown that it predicts large quadrupole moment of the 2_1^+ state of ^{114}Cd, without making the $2_1^+ \rightarrow 0_1^+$ transition probability too large.

To explain the properties of the so called vibrational nuclei has been one of the pending problems of the theoretical nuclear physics in the past two decades, and in fact many attempts have been made with different degrees of success.[1] However, recently our qualitative understanding of these nuclei has been modified significantly, motivated by two major types of experiment. One is the discovery of the large static quadrupole moment, Q_2, of the first excited 2^+ state in these nuclei,[2] while the other is the measurement of the energies of the yrast 0^+, 2^+, 4^+, 6^+ . . . states, which showed that $\Delta E_I = E_I - E_{I-2}$ continue to increase with increasing I.[3] Both of these experiments show that the vibrational nuclei, believed to be basically spherical, have features that resemble rather strongly those of deformed nuclei.

This fact does not of course mean however that a theory which successfully describes deformed nuclei can also explain the vibrational nuclei. Rather it means that one should attempt to construct a theory which can describe vibrational and deformed nuclei, and consequently transitional nuclei, on one footing, rather than to construct a theory which is specifically attempting to explain only the vibrational nuclei. In this regard it is worthwhile to note two recent works reported by Bes, Greiner and their co-workers[4] who showed that, if a Hamiltonian for an quadratic oscillater is supplemented with appropriate unharmonic terms and if this whole Hamiltonian is diagonalized in a large multiphonon space, it is possible to obtain theoretical spectrum that have a nature of that of well-deformed nuclei. Since the same theory of course gives purely vibrational spectrum, if the unharmonicity term is suppressed, we see that a theory which we were seeking for has been found. Only task remains is to derive an appropriate Hamiltonian, the derivation being made in some microscopic way.

Since it seemed to us that the Boson expansion technique was one of the best ways, known to date, to serve this purpose we started to work on it some two years ago. The basic idea of this technique was first proposed by Belyaev and Zelevinsky,[5] and later was extended and applied by Sørensen[6] to a fairly large number of nuclei. In many respects our approach[7] follows very closely that of Sorensen. However, we have succeeded in solving the equations for the Boson expansion coefficients exactly. This has been done so far to sixth order and to continue it further, if necessary, does not offer any unsurmountable difficulty. Because of this

* Partially supported by the U. S. Atomic Energy Commission.

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III. C. ABSTRACT OF PAPERS SUBMITTED FOR PUBLICATION

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1. Gamow-State Analysis of $^{54}Fe(d,n)$ to Proton Resonances in ^{55}Co

(W. R. Coker)

DWBA calculations are performed for $^{54}Fe(d,n)$ angular distributions at 10 MeV populating five proton resonances in ^{55}Co, at 5.17, 5.54, 5.74, 5.86 and 6.07 MeV excitation, using Gamow states as form factors. Results of the calculations are compared with previous DWBA analyses in which bound state functions were used.

(Submitted to Phys. Rev. C)

2. Non-Orthogonality Effects in Successive Particle-Transfer Reactions

(T. Udagawa, H. H. Wolter, and W. R. Coker)

It is demonstrated that non-orthogonality effects can play a very important role in multistep processes involving successive particle-transfer reactions. This is shown for the particlular example of the (h,d)-(d,t) process, where non-orthogonality terms can be included as a renormalization of the effective interaction for the direct (h,t) charge-exchange process. A simple order-of-magnitude estimate shows that the non-orthogonality correction is of a size such that the effective interaction, incorporating the correction, can become negligibly small or even attractive.

(Submitted to Phys. Rev. Lett.)

3. Coupled-Channel-Born-Approximation Study of (p,t) Reactions Leading to Two-Phonon States of Vibrational Nuclei

(T. Udagawa)

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A coupled-channel-Born-approximation (CCBA) study is made of (p,t) reactions leading to two-phonon states of vibrational nuclei. A detailed numerical analysis is performed, particularly for the $^{116}Cd(p,t)$ ^{114}Cd reaction with the incident energy E_p = 28 MeV. It is shown that many features observed in the reactions, which cannot be explained by DWBA, can successfully be accounted for by CCBA. It is also shown that three-step processes play an essential role in the successful explanation of the observed data, particularly the cross sections of the 0^+ and 4^+ two-phonon states.

(Submitted to Phys. Rev. C)

4. <u>Exact Finite Range DWBA Calculation for $^{208}Pb(^{16}O,^{15}N)^{209}Bi$ and $^{88}Sr(^{16}O,^{15}N)^{89}Y$ Reactions</u>

(T. Tamura and K. S. Low)

A straight forward, fast approach to exact finite range DWBA calculations is developed, and is applied to the analyses of $^{208}Pb(^{16}O,^{15}N)$ ^{209}Bi and $^{88}Sr(^{16}O,^{15}N)^{89}Y$ reactions.

(Submitted to Phys. Rev. Lett.)

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III. D. ABSTRACTS OF TALKS PRESENTED AT MEETINGS

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APS Washington Meeting Apr. 1973

DL 1 Coupled-Channel-Born-Approximation Analysis of (p,t) Reactions, Leading to Two-Phonon States of Even Vibrational Nuclei.* T. UDAGAWA, T. TAMURA, W. J. BRAITHWAITE, University of Texas, J. R. COMFORT, University of Ohio, and J. R. DURAY, Princeton University.--Data were obtained for (p,t) reactions on ^{112,114,116}Cd, with E_p = 27.9 MeV, showing that the angular distributions for the 0^+ and 2^+ two-phonon states differ markedly in phase from those of the ground (0^+) and one-phonon (2^+) states, respectively.[1] An analysis of this data is made, based on the coupled-channel-Born-approximation (CCBA) method. It is shown that the phase difference in the angular distributions as well as the observed magnitude of the cross section is well accounted for by the CCBA.

*Work supported in part by the U. S. Atomic Energy Commission and the National Science Foundation.
[1]J. R. Comfort, et al., Phy. Rev. Letts., 29, 442 (1972).

APS Washington Meeting Apr. 1973

JK 14 Coupled-Channel Calculation for the Sub-Coulomb Transfer Reaction ^{238}U(d,t)^{237}U at 8.5 MeV.* J. R. ERSKINE and T. TAMURA, Argonne National Laboratory.— The effects of including inelastic-scattering terms in a sub-Coulomb transfer reaction on an actinide nucleus have been calculated with the CCBA program MARS.[1] In the ^{238}U(d,t)^{237}U reaction at 8.5 MeV bombarding energy, we find that the inclusion of the coupling causes a 10—15% modification in the magnitude of the cross section for the transfer reaction to the $J = \frac{1}{2}, \frac{3}{2}$, and $\frac{5}{2}$ levels in the ground-state band. This relatively small change in the cross section indicates that inelastic-scattering effects are not the explanation of the factor of 2—4 between the measured and the calculated absolute spectroscopic factors observed in the ^{238}U(d,t)^{237}U reaction.[2] Some detailed results of bound-state coupled-channel calculations will be presented.

*Under the auspices of the U.S. Atomic Energy Commission.
[1]T. Tamura and T. Udagawa, Technical Report Number 30, Center for Nuclear Studies, University of Texas.
[2]J. R. Erskine, Phys. Rev. C 5, 959 (1972).

APS Washington Meeting Apr. 1973

EJ 4 Regge Parametrization of Optical Model Scattering.* H. H. WOLTER and T. TAMURA, University of Texas at Austin.-- Recently we have investigated in detail[1] a model to parametrize optical potential scattering in terms of Regge poles and of an analytical background term.[2] Here we present applications of this procedure to experimental data of α and heavy ion scattering. Good fits are obtained in general, however, in many cases it is necessary to consider more than one pole term. The significance of these parametrizations is discussed.

*Work supported in part by the U. S. Atomic Energy Comm.
[1]T. Tamura and H. H. Wolter, Phys. Rev. C 6, 1976 (1972).
[2]K. W. McVoy, Phys. Rev. C 3, 1104 (1971).

APS Bloomington Meeting Oct. 1973

AD7. Exact Finite Range DWBA Calculations of (^{16}O,^{15}N), (^{12}C,^{13}C) and (^{12}C,^{11}B) Reactions on ^{208}Pb.* T.Tamura and K.S.Low, University of Texas.--Using a recently completed computer code SATURN-MARS, exact finite range DWBA calculations have been performed for ^{208}Pb(^{16}O,^{15}N)^{209}Bi reaction.[1] Contrary to the analysis made with no-recoil approximation[1], the spectroscopic factors extracted were found to be independent of the incident energy of the projectile and to be free from $j_> - j_<$ fluctuations, indicating the general applicability of EFR-DWBA analysis of heavy ion transfer reactions as a spectroscopic tool. Calculations are being extended to other reactions; in particular to the analysis of the ^{208}Pb(^{12}C,^{13}C)^{207}Pb and ^{208}Pb(^{12}C,^{11}B)^{209}Bi reactions.[2] Preliminary results indicate that the cross sections predicted are too small. The sources of this difference are being investigated including the possibility that the deformed nature of ^{12}C gives rise to the need of different bound state geometry and/or different optical parameters.

*Work supported in part by the U. S. Atomic Energy Comm.
[1]D.G.Kovar et.al.,Phys.Rev.Letts.,30,1075(1973).
[2]J.S.Larsen et.al.,Phys.Letts.,42B,205(1972).

APS Washington Meeting Apr. 1973

GG 7 Boson Expansion Techniques in the Description of Nuclear Collective Motion.* D. BRAUNSCHWEIG and T. TAMURA, Argonne National Laboratory and University of Texas at Austin, and T. KISHIMOTO, Niels Bohr Institute, Copenhagen. --Recent exploratory calculations using boson expansion techniques applied to Sm isotopes in particular, gave very encouraging results but there appeared to be a systematic tendency to locate states in excited bands too high. The present calculations were undertaken in the hope that this deficiency could be resolved by extending the original fourth-order calculation to include the sixth-order contributions. Since the sixth-order terms are proportional to β^6, it would make the outer portion of the potential well less steep than otherwise and thus lower the energies of the band heads. In preliminary calculations we are indeed getting such effects.

*Work supported in part by the U.S. Atomic Energy Commission.

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APS Bloomington Meeting Oct. 1973

BD8. Complex Microscopic Effective Interaction for (p,n) Reactions.* G. W. HOFFMANN and W. R. COKER, Center for Nuclear Studies, Univ. of Texas--A simple recipe for generating a complex effective interaction for distorted-wave Born approximation calculations of (p,n) cross sections to isobaric analog states, from the usual microscopic charge exchange form factor, is investigated. Such interactions are tested against a variety of angular distribution data for $^{90}Zr(p,n)$, $^{208}Pb(p,n)$ and $^{209}Bi(p,n)$ from 22 to 50 MeV incident proton energy, and are also compared to effective interactions resulting from a charge-independent Lane-model formalism[1] and from coupled-reaction-channels calculations including multi-step (p,d)-(d,n) contributions[2].

*Research supported in part by the U. S. Atomic Energy Commission.

[1] G. W. Hoffmann, Phys. Rev. C8, Aug. 1973.
[2] L. D. Rickertsen and P. D. Kunz, Phys. Letters (in press); H. H. Wolter, private communication.

APS Bloomington Meeting Oct. 1973

CD7. Coupled-Channel-Born-Approximation Analysis of 20Ne(p,t)18Ne Transitions.* DAVID K. OLSEN and TAKESHI UDAGAWA, University of Texas at Austin and RONALD E. BROWN, University of Minnesota.--A coupled-channel-Born-approximation calculation is performed for the 20Ne(p,t) reaction to the $J^\pi = 0_1^+, 2_1^+, 4_1^+, 0_2^+$, and 2_2^+ states in 18Ne at 0.00, 1.89, 3.38, 3.58, and 3.62-MeV of excitation respectively. Shell-model wave functions with both spherical (two-particle) and deformed (four-particle two-hole) components are used for 18Ne.[1] The inelastic excitations are described by a $0^+ - 2^+ - 4^+$ ground-state rotational coupling in 20Ne and both rotational and vibrational couplings schemes are consider for 18Ne. A comparison of the results with 39.8-MeV, experimental differential cross sections will be discussed. Preliminary results indicate that the effects of the inelastic excitations are large and improve the agreement with experiment.

*Work supported in part by the U.S. Atomic Energy Commission.
[1]H. G. Benson and B. H. Flowers, Nucl. Phys. A126, 305 (1969).

APS Bloomington Meeting Oct. 1973

CD8. Multistep Mechanism for (d,α) Reactions.* W. R. COKER and T. UDAGAWA, Univ. of Texas, Center for Nuclear Studies--The successive one-nucleon transfer processes, (d,t), (t,α), and (d,^{3}He), (^{3}He,α) are investigated for the specific example of $^{98}Mo(d,\alpha)^{96}Nb$. Interference between the direct and two-step processes is discussed, as well as consequences of basis nonorthogonality(1) in the coupled-reaction-channels approach(2) used in the calculations.

*Research supported in part by the U. S. Atomic Energy Commission

(1)T. Udagawa, H. H. Wolter, and W. R. Coker (in press)
(2)W. R. Coker, T. Udagawa, and H. H. Wolter, Phys. Rev. C7, 1154 (1973).

APS Bloomington Meeting Oct. 1973

EE7. $^{40}Ca(p,p')$ at 35 MeV,* J.A. NOLEN, JR., R.J. GLEITSMANN, G. HAMILTON, A. MOALEM, AND T. UDAGAWA,+ Mich. State Univ.— New higher resolution data on the $^{40}Ca(p,p')$ reaction have been recorded in order to resolve some questions raised in a recent microscopic analysis of the reaction.[1] A resolution of 4.5 keV FWHM was obtained at a bombarding energy of 35 MeV with the MSU cyclotron-magnetic spectrograph system. In particular, the 4^-(T=0) and 4^-(T=1) particle-hole states at 5.615 and 7.655 MeV excitation energies have been clearly resolved from nearby energy levels. The predicted yields to these unnatural parity levels are very sensitive to the details of the tensor and spin-orbit parts of the nucleon-nucleon force used in the microscopic analysis. The new data indicate that the excitation of these levels is experimentally ~2-5X stronger than predicted by reference 1. Coupled channel calculations show that indirect processes should be included in the analysis of some of the T=0 levels.

* Work supported by the National Science Foundation.
+ Permanent address, Univ. of Texas, Austin, Texas
1. F. Petrovich, et al., to be published.

5.75 Pro. of Intern. Conf. on Nucl. Physics, Munich
Aug. 1973

MACROSCOPIC CHARGE-INDEPENDENT ANALYSIS OF QUASI-ELASTIC (p,n) REACTIONS*

G. W. Hoffmann and C. F. Moore, Center for Nuclear Studies, University of Texas

Generally, macroscopic analyses of (p,n) charge-exchange data are done in ways which do not preserve charge-independence of the nucleon-nucleus force. This violates the spirit of the Lane model [Nucl. Phys. 35 (1962) 676] proposed to explain such quasi-elastic reactions. Lane generalized the nucleon-nucleus optical potential to contain explicitly a term involving the scalar product of the isospins of the target and the projectile, specifically, V=V0+V1(t·T)/A. The prescription for determining the potentials V0 and V1 is contained within the coupled Lane equations. V0 and V1 are related through the relations V0=(1/2)[VpC(Ep)+VnC(En)] and V1=(A/T0)[VnC(En)-VpC(Ep)], where the potential VpC(Ep) is essentially the full proton optical potential for the target nucleus at energy Ep, and the potential VnC(En) is, by definition, the full neutron optical potential for the target nucleus at energy En, which is less than Ep by the Coulomb displacement energy. Thus, the charge-independent Lane potential should be constructed from available realistic proton and neutron optical potentials. Since geometries, strengths, and energy dependences of proton and neutron optical potentials are generally very different, both V0 and V1 will in general be complex. Thus, energy dependent form factors of complicated shapes can be obtained for the Lane potential, V1. Such a procedure is thus a departure from the standard approximate treatment of (p,n) charge-exchange, where V1 is approximated from symmetry terms of global optical potentials, and given a simple, fixed geometry.

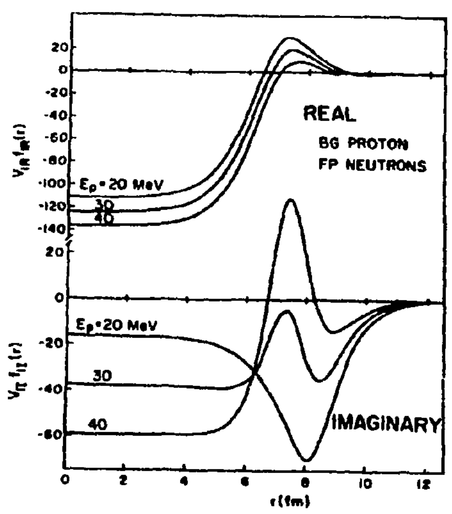

Fig. 1. Generated Lane potential for 208Pb(p,n)208Bi(IAS) as discussed in the text.

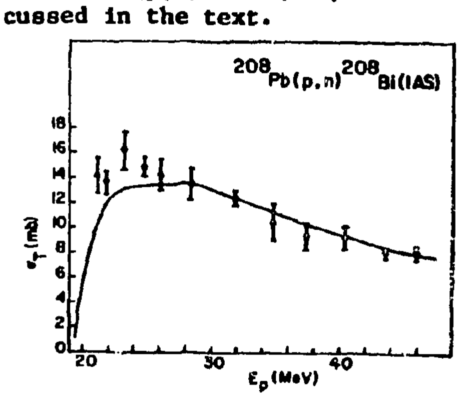

Fig. 2. Coupled-channel calculations compared to the data [G. W. Hoffmann et al., Phys. Lett. 40B (1972) 453] as discussed in the text.

The coupled Lane equations were solved exactly using potentials V0 and V1 generated from the Becchetti-Greenlees (BG) [Phys. Rev. 182 (1969) 1190] proton and Fu-Perey [unpublished, Oak Ridge National Laboratory Report ORNA-4765 (1972) 30] neutron optical potentials for the case of 208Pb(p,n)208Bi-IAS. The generated potential V1 is shown in fig. 1. Note in particular the complicated shape and energy dependence of the imaginary component. The shapes of the predicted angular distributions are in good overall agreement with both available data, and DWBA and CC calculations using the usual complex charge-exchange form factor extracted from the Becchetti-Greenlees potentials. Of course this is expected since the shape of the angular distribution is dominated by the Q-value and Δℓ=0 nature of this transition. On the other hand, the shape of the total (p,n)-IAS cross section is remarkably similar to the data for the present calculation as shown in fig. 2, while all other attempts to fit this shape fail unless one empirically parameterizes the Lane potential itself [Hoffmann and Coker, Phys. Rev. Lett. 29 (1972) 227; Phys. Rev. Lett. 30 (1973) 249]. In the present charge-independent treatment no arbitrary phenomological parameters need to be introduced to fit the data.

*Work supported in part by the United States Atomic Energy Commission

Pro. of Intern. Conf. on Nucl. Physics, Munich, Aug. 1973 5.160

COUPLED-CHANNEL-BORN-APPROXIMATION ANALYSIS OF (p,t) TRANSITIONS TO THE GROUND-STATE ROTATIONAL BAND OF ^{20}Ne*

David K. Olsen, Takeshi Udagawa, and Taro Tamura, Center for Nuclear Studies, University of Texas at Austin, U.S.A., and Ronald E. Brown, John H. Williams Laboratory of Nuclear Physics, University of Minnesota, U.S.A

Using the CCBA it has been shown that indirect transitions which proceed via inelastic excitations are important for (p,t) transitions to members of rare-earth, ground-state rotational bands. In the present work both DWBA and CCBA calculations are compared with experimental cross sections for the 22Ne(p,t) reaction to the 0^+, 2^+, and 4^+ rotational members of the 20Ne ground-state band.

Rotational wave functions of the adiabatic form are assumed for 22Ne and 20Ne with the usual BCS intrinsic states constructed from ten Nilsson levels in the 1s, 1p, and 2s-1d shells with a simple pairing force whose strength reproduces the odd-even neutron mass difference of 2.0 MeV in this region. A 0^+-2^+ coupling with intrinsic deformation parameters of $\beta_2 = 0.45$ and $\beta_4 = 0.05$ was allowed in the entrance channel, and the exit channel contained a 0^+-2^+-4^+ coupling with $\beta_2 = 0.45$ and $\beta_4 = 0.25$. Energy dependent global proton (Watson, Singh, and Segel, Phys. Rev. 182 (977) 1969) and triton (Becchetti and Greenlees, Madison Polarization Conference, 1971) optical model parameters were used.

Figure 1 shows both DWBA and CCBA results compared with the 39.8-MeV differential cross sections (solid points) of Olsen (Ph.D. Thesis, University of Minnesota, 1970). Note how the large effect of the indirect transitions is required to fit both the shape and relative magnitude of the 2^+ cross section. Figure 2 shows DWBA and CCBA calculated integrated cross sections from 11° to 91° for these transitions in arbitrary units for 20.0, 26.9, 35.1, 42.4, and 50.0-MeV proton beam energy. Figure 3 compares these results at the three intermediate proton energies with the differential cross sections of Falk, Kulisic, and McDonald (Nucl. Phys. A167 (157) 1971). Ratios of integrated experimental cross sections to integrated calculated cross sections are shown with both the DWBA and CCBA ratios normalized to unity for the 35.1-MeV, 0^+ transition. In contrast to the DWBA, the CCBA reproduces the experimental data reasonably well.

*Work supported in part by the United States Atomic Energy Commission.

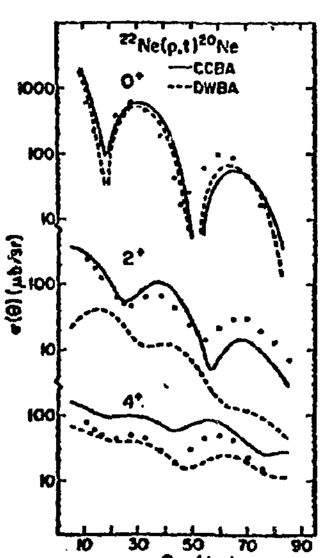

Figure 1

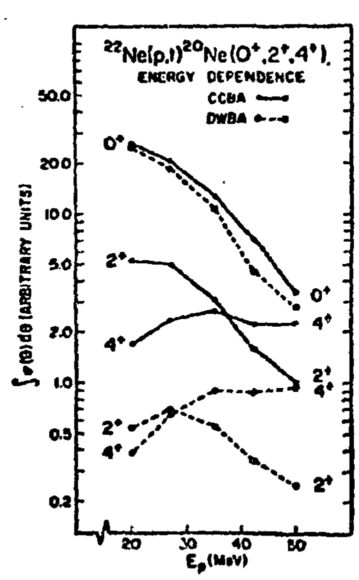

Figure 2

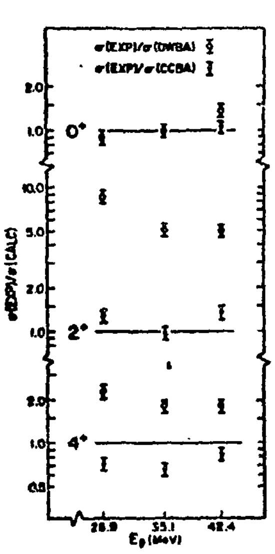

Figure 3

5.163 Pro. of Intern Conf. on Nucl. Physics, Munich Aug. 1973

STUDY OF TWO-STEP REACTION MECHANISMS FROM THE $^{58}Ni(p,t)^{56}Ni$ REACTION TO UNNATURAL-PARITY STATES*

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Center for Nuclear Studies, University of Texas, Austin, Texas 78712

Recently there has been considerable interest in the study of the excitation of unnatural-parity states in the (p,t) reaction because these transitions are forbidden in the usual direct, zero-range DWBA approximation [Glendenning, Phys. Rev. 137B(1965)102], and were recently shown to be too small even if finite range and other effects are included [Bayman and Feng, Nucl.Phys. A205 (1973) 513]. Thus these transitions appear to proceed predominantly by two-step processes and form a good case to study such reaction mechanisms.

There are essentially two kinds of two-step processes, those proceeding through inelastic excitations in the incident and final channels (CCBA), and those arising from successive one-neutron pick-up (CRC) [Coker, Udagawa, and Wolter, Phys.Rev. C7 (1973) 1154], i.e. the (p-d-t) reaction [Kunz and Rost, BAPS 10 (1972) 903]. We first present an experimental criterion to distinguish between these different two-step processes, namely that the cross section goes to zero at zero degrees for the two-step process via the inelastic channel, whereas it remains finite in general for the (p-d-t) process. This stems from the fact, that the former process involves mainly a total S=0 transfer and the latter proceeds mainly through S=1.

An example, where the inelastic two-step mechanism explains the data well and where also the above criterion is satisfied, has recently been found in the excitation of the 2^- state in the $^{22}Ne(p,t)^{20}Ne$ reaction [Olsen et al., Phys. Lett. 29 (1972) 1178]. Here we shall discuss the case of the reaction $^{58}Ni(p,t)$ ^{56}Ni, studied by Bruge and Leonard [Phys.Rev. C2 (1970) 2200]. The experimental data indicate that the cross sections rise at forward angles, suggesting that successive neutron transfer is predominant. Thus we performed a calculation of the (p-d-t) process using the CRC formalism. We assume that the final states in ^{56}Ni are particle-hole states of the type $(p_{3/2}f^{-1}_{7/2})$. There are two possible paths corresponding to first picking up the $p_{3/2}$ neutron or the $f_{7/2}$ neutron. The two contributions interfere destructively for the unnatural parity states in such a way, that the reaction is mainly an S=1 process. The cross sections obtained are of the order 1-10 μb/sr, which is about the correct magnitude when compared with the experimental cross sections. The angular distributions are relatively structureless and reproduce the data fairly well. We therefore believe that the (p-d-t) process can account for the excitation of the unnatural parity states.

However, one should note two uncertainities in these calculations which should be clarified before a consistent picture is obtained. First one should include the intermediate S=0, T=1 deuteron state, but it is not clear how to do this in the zero-range approximation. If one treats both deuteron channels in the same way, they cancel each other for S=1 transfer, and therefore have a significant effect on the results. Secondly, the calculations are done, neglecting effects of non-orthogonality between different reaction channels [Goldfarb and Takeuchi, Nucl.Phys. A181 (1972) 609]. An observed sensitivity of the magnitude of the cross sections to the deuteron parameters and significant contributions from the nuclear interior might be due to this problem.

* Work supported by the United States Atomic Energy Commission.

III. E. RESEARCH IN PROGRESS

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1. Microscopic Calculation of Nuclear Reactions Using Projection Operator Techniques

(S. A. A. Zaidi and Y. L. Tyan)

We have developed a description of nuclear reactions, which we believe could be used to calculate simple reactions on light nuclei. The main idea is to introduce an auxiliary Hamiltonian that has a much deeper single-particle potential than the actual Hamiltonian. The problem of diagonalizing the original Hamiltonian is tackled using the basis of eigenfunctions of the auxiliary Hamiltonian. The formulation can be most easily accomplished using the projection operator techniques introduced by Feshbach. Preliminary calculations to check the accuracy of this method have been performed for the $C^{12} + n$ system within the framework of the phenomenological collective model. This model is exactly solvable as it leads to the problem of solving coupled ordinary differential equations. It is planned to apply this method to light nuclei.

2. (p,n) Reaction on Deformed Nuclei

(G. W. Hoffmann, T. Udagawa, and W. R. Coker)

The (p,n) reaction on deformed nuclei is known to populate 2^+ excited analog states with an intensity comparable to the population of ground 0^+ analog states. Despite evidence that the (p,n) reaction has to some degree a contribution from successive particle transfer reactions (p,d)-(d,n)[(1)] the most likely mechanism for population of the 2^+ analog is via inelastic excitation of the target or residual nuclei. We are initiating a program of coupled-channel Born aaproximation analyses of the available (p,n) data for 2^+ analog states, in order to shed more light on this question.

[(1)] L. D. Rickertsen and P. D. Kunz, Bull. Am. Phys. Soc. 18, 1392 (1973).

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3. The Decay of the Final State in "Charge Exchange" Reactions

(W. R. Coker and G. W. Hoffmann)

The mechanisms of the charge "exchange reactions" (p,n) and (^{3}He,t) are considerably more complicated than was originally believed.[1] Important contributions to the observed cross sections, particularly for (^{3}He,t), are found to come from successive pickup-stripping and stripping-pickup processes. In performing detailed analyses of these reactions, it is important to take into account the fact that the residual nuclear states are unbound to proton emission. So far, this has been considered only in a single case[2] and it was found that the effect is small. However, the calculations were made only for the direct term, and it remains to investigate the effects of the residual decay on the final stripping or pickup contributions. From independent work in which isobaric analog resonances are populated by stripping or pickup reactions, it is known that the magnitude of the observed cross sections cannot be explained by DWBA calculations using bound states form factors.[3] Thus it is important to perform detailed calculations treating the decaying residual state correctly and realistically, in the context of a coupled-reaction-channel formalism.[1] We are initiating such calculations using complex energy eigenstates to describe the residual analog states.[4]

(1) W. R. Coker, T. Udagawa, and H. H. Wolter, Phys. Rev. C 7, 1154 (1973).
(2) G. W. Hoffmann and W. R. Coker, Phys. Lettrs. 40B, 81 (1972).
(3) S. A. Zaidi and W. R. Coker, Phys. Rev. C4, 236 (1971).
(4) W. R. Coker and G. W. Hoffmann, Zeits. fur Physik 236, 179 (1973).

4. Effective Form Factors for Charge Exchange Reactions

(G. W. Hoffmann and W. R. Coker)

For reactions such as (p,n), second-order Born approximation calculations have led to the conclusion that a significant contribution to the observed cross section arises from higher-order processes such as (p,d)-(d,n). Such processes can be included phenomenologically in DWBA by making the effective interaction used in the usual DWBA calculation complex. Studies of the effective coupling potential which appears when the coupled reaction channel equations for (p,n) are truncated(1) as well as experience with effective form factors for nucleon inelastic scattering calculations(2) have led us to a prescription for generating an effective form factor with no adjustable parameters, which fits in shape and magnitude the available (p,n) data from target ^{90}Zr to ^{208}Pb. A paper describing this form factor is in press. We are presently extending the calculations to cover other nuclei.

(1) H. H. Wolter, private communication.
(2) G. R. Satchler, Phys. Lettrs. 35B, 279 (1971).

5. Kinematical-Factor-Dependence of Effects of Inelastic Scattering Processes on Nucleon Transfer Reactions

(T. Udagawa, A. K. Abdallah, and T. Tamura)

Evidence has been accumulated which shows the importance of effects of inelastic scattering processes on nucleon transfer reactions. The dependence of the effects on the nuclear structure aspects such as the deformation or the spectroscopic factor, is fairly transparent and easy to understand. It is not, however, so easy to understand the dependence of the effects on kinematical aspects of the reaction such as the type of reactions, or the reaction Q-value, momentum transfer, angular momentum mismatch etc. involved in the reaction. In order to understand these aspects, it is important to decipher in some detail the behavior of various quantities, that appear only in the intermediate steps in the normal calculations with a computer; e.g. the radial dependence of the distorted waves, and of the contribution to the overlap integral.

6. High Energy Single Nucleon Transfer Reactions (^{12}C, ^{13}C) (^{12}C, ^{11}B) on ^{208}Pb

(T. Tamura and K. S. Low)

Analysis of the $^{208}Pb(^{16}O,^{15}N)^{209}Bi$(1) reaction indicated that angular distributions to different final states can only be fitted if the exit radius parameter is increased compared to that of the incident channel. It would therefore be interesting to investigate whether a similar situation occurs for the single neutron and proton transfer reactions induced by ^{12}C on ^{208}Pb(2). We have therefore analyzed the two reactions at three incident energies using our exact finite range DWBA program SATURN-MARS. Preliminary results indicated that the (^{12}C,^{13}C) data can be fairly well described using the same set of optical parameters in both the incident and exit channel. For the (^{12}C,^{11}B) reactions, use of the same optical model parameters in both the incident and exit channel would result in a similar shift in the peak of the angular distribution with increased excitation energies of the residual nucleus. However, spectroscopic factors obtained in these calculations are fairly consistent with respect to different projectile energies as well as different final states. We are continuing more detailed studies with regard to the discrepancies in the angular distributions for the proton transfer reactions.

(1) T. Tamura and K. S. Low, to be published in Phys. Rev. Letts.
(2) J. S. Larsen, J. L. C. Ford, Jr., R. M. Gaedke, K. S. Toth, J. B. Ball and R. L. Hahn, Phys. Letts., 42B, 205 (1972).

7. Multi-step Processes in Two Nucleon Transfer Reactions

(T. Tamura, K. S. Low and T. Udagawa)

The two nucleon transfer reactions $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ was first analyzed(1) in a CCBA formalism using "no-recoil" form factors. Results indicated that angular distribution to the ^{20}Ne 2+ first excited state is very much improved compared to a straight forward no-recoil DWBA calculation. We have since modified our program to perform an exact finite range CCBA calculation for the above reaction and results confirmed the importance of coupling to inelastic channels. We are also at the same time investigating the possible contribution from sequential transfer processes. The reaction code JP4 has since been modified to handle no-recoil from factors and preliminary results indicated that such contributions are at least of the same order of magnitude as the direct process. Modification of the program to perform exact finite range calculations is at the present being carried out.

(1)K. S. Low and T. Tamura, Argonne Nat. Lab. Physics Div. Report, March 1973.

8. Single Proton Transfer Reactions (^{16}O, ^{15}N) and (^{12}C, ^{11}B) on ^{64}Ni

(T. Tamura and K. S. Low)

No-recoil DWBA studies of these reactions by M. C. Lemaire and M. C. Mermaz indicated that consistent spectroscopic factors cannot be obtained, indicating the need of an exact finite range calculation. Of particular interest is the fact that the (^{16}O, ^{15}N) spectroscopic factors in this no-recoil calculation are fluctuating much more than the (^{12}C, ^{11}B) spectroscopic factors. We have performed an exact finite range DWBA calculations which showed that the recoil effect is particularly important for (^{16}O, ^{15}N) involving the transfer of a proton in a $j_<$ state in ^{16}O to the different $J_<$ final states in ^{65}Cu. For the (^{12}C, ^{11}B) reactions, recoil effects are minimized due to the transfer of a proton in a $j_>$ state in ^{12}C. This effect can be understood qualitatively but a more detailed argument has to be advanced. This work will be reported in a joint paper with M. C. Lemaire and M. C. Mermaz.

9. Finite Range DWBA Calculations for Deuteron Stripping Reactions

(R. J. Kulkarni and E. V. Ivash)

In order to take into account in a consistent manner the effect of the deuteron d-state on (d,p) and (d,n) stripping cross sections, polarizations, and tensor analyzing powers it is essential to include the effects of finite range in an appropriate DWBA calculation. Work has continued on the development of a suitable computer program based on the formalism of Delic and Robson.[1] It is planned to investigate among other things how the effects obtained using a hard core potential differ from those for a soft core potential. We have also given some consideration to the possibility of developing a simplier and faster computational method.

[1] G. Delic and B. A. Robson, Nucl. Phys. A156, 97 (1970).

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IV. DIRECTORY OF COMPUTER PROGRAMS

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An * indicates the program was written or developed at the Center for Nuclear Studies (CNS). All listed programs have been modified to some extent by CNS users. Where extensive modifications have been made, the modifier's name is appended. All programs are available on request. A number of spectrum fitting, plotting, or data manipulating programs are in use in the Center but are not listed because of their specialized nature. The final year in parenthesis is the year in which the program was written.

*ASTARTE (R. G. Clarkson)
Calculates isospin mixing 2nd order contribution to PWBA (d,p) stripping amplitude, due to dipole term of Coulomb interaction. See CNS Technical Report #4 for details. (1967)

*ATHENA (K. Lambrakos)
Calculates differential cross sections σ^+ and σ^0 for electroproduction of positive and neutral pi mesons by electron bombardment of protons. Exists in two versions. (1968)

*BACCHUS (P. Moore, S. Sen)
Calculates theoretical angular distribution of protons scattered inelastically through isobaric analog resonances. Required input: resonance parameters, optical phase shifts, residual state spin. Searches on inelastic partial widths to fit by χ^2 criterion. See CNS Technical Report #5 for details. (1969)

BD3 (H. Wolter, A. Faessler, P. Sauer)
This program was written to supply the two body matrix elements for the Hartree-Fock-Bogoliubov program HFB3, but it has much wider application. It calculates the two-body matrix elements of the nucleon-nucleon interaction in harmonic oscillator states. In these matrix elements the two-nucleon states may be coupled to total angular momentum J or not. The nucleon-nucleon interaction is specified either analytically or by the reduced relative matrix elements. In the first case (e.g. for the Coulomb interaction) the method of Horie and Sasaki is used, in the second the Moshinski transformation.

*BODY3 (W. J. Braithwaite)
Generates a table of (fully relativistic) kinematic information for the "kinematically-complete" description of three particles in final state. See Computer Physics Communications 4 (1972). (1970)

*CATHEN-LUB (W. R. Coker)
This program computes microscopic form factors for charge-exchange reactions, using a Yukawa effective two-body interaction. The residual state in the charge exchange process is correctly treated, in a shell-model approach to reaction theory, as a bound state in the continuum. The program PLATO is used as a subroutine to calculate this decaying nuclear state. The resulting charge-exchange form factor is complex. (See Phys. Lettrs. 40B, 81 (1972) and Phys. Lettrs., in press) Based in part on subroutines from DWUCK. (1972)

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*CORKIN (W. J. Braithwaite)
Provides a table of those kinematic parameters particularly important for use with the new angular correlation method for determining nuclear spins, as described in Physical Review Letters 31, 401 (1973). These parameters include laboratory and recoil-center-of-mass kinetic energies and emission angles (θ,ϕ), as well as the ratio between the differential solid angles in these two frames, for both the decay particle and the residual particle. (1973)

*COULOM (H. Wolter, T. Tamura)
Calculation of the regular and irregular Coulomb functions $F_\ell(\eta,\rho)$ and $G_\ell(\eta,\rho)$ and their derivatives for real η and ρ, i.e. for real energy. Contrary to other Coulomb function programs, which require $\eta^2 \ll \rho$, this one will calculate the functions with high accuracy in the entire (η,ρ)-plane ($-500 \le \eta \le 500$, $\rho \ge 0$). This is achieved by using different numerical methods in different regions of the (η,ρ)-plane. (1971)

*CROSS3 (W. J. Braithwaite)
Different versions calculate $(d\sigma/d\Omega_1 d\Omega_2 dE_1)_{LAB}$ for final state interactions and quasifree scattering, respectively. Finite geometry effects are handled approximately using Monte-Carlo techniques. (1970)

*DPPOL (M. A. A. Toosi, E. V. Ivash)
Calculates polarization and differential cross section for (d,p) or (d,n) reactions in the zero range and local energy finite range approximations for a general admixture of volume and surface Woods-Saxon potentials. (1966)

*DWAR (S. A. A. Zaidi)
Calculates decay widths of analog resonances according to the expressions given by Zaidi and Darmodjo. This short and fast running program may readily be modified to calculate widths in accordance with other prescriptions. (1972)

*DWARF (R. G. Couch)
This program was written in order to study the evolution of strongly degenerate stellar objects. For a given density the equations of hydrostatic equilibrium and mass continuity are integrated outward to determine the structure and total mass of the object. The code allows several options for the equation of state, including general relativistic effects. A version of this program is used as a subroutine in a nucleosynthesis code used to study degenerate carbon burning. There an iteration is performed to find the central density which reproduces the known mass of the carbon-oxygen core. (1973)

*DWBA-VENUS (T. Tamura, W. R. Coker, F. J. Rybicki)
In conjunction with program NEPTUNE, calculates zero range, spin-orbit-coupled DWBA cross sections for single nucleon transfer to single particle states. Has options for inelastic scattering and for particle-gamma angular correlations. (Comp. Phys. Comm. 2 (1971) 94-106.). (1971)

*DWBAOO (W. J. Braithwaite)
A short program that calculates zero-range DWBA cross sections for particles having zero-spin. Form factors (other than "collective") must be provided by the user. (1970)

*DWRES (H. H. Wolter, T. Tamura)
A modification of the DWBA program VENUS, which handles the interference of direct and compound nuclear processes. The compound amplitude is added in the form of an arbitrary number of multichannel resonance terms of Breit-Wigner shape. The overall phase of the resonance term is as in Fano theory, while the other resonance parameters are input quantities. (1972)

DWUCK (J. R. Kunz)
A zero-range DWBA program with spin-orbit coupling, and numerous options. (1969)

*EDITA (S. A. A. Zaidi)
A short, fast-running program that solves the Lane equations both above and below the (p,n) charge exchange threshold. (1972)

*FEXKRP (K. H. Liu, E. V. Ivash)
Calculates differential cross section for (p,n) knockout reactions for a general exchange mixture for the n-p interaction, taking into account finite range via a Yukawa potential, and for a volume Woods-Saxon nucleon-nucleus interaction. (1969)

*FFINEL (T. Udagawa)
Calculates microscopic form-factors for the inelastic and charge exchange reactions, assuming the gaussian form for the radial dependence of the two body force. Inputs are parameters for the two body force and spectroscopic factors for the particle-hole pairs that are excited in the reactions. (1971)

*FINITE (W. J. Braithwaite)
Two-dimensional energy spectra are generated from kinematic calculations of several direct three-body breakup rings and from kinematic calculations of the energy locations of several sequential decay peaks. Monte Carlo sampling of the finite geometry, the target thickness effects, and the natural widths, make this program useful in optimizing the experimental design for spin determinations, using the new angular correlation method described in Physical Review Letters 31, 401 (1973). (1973)

*FRVENUS (S. H. Suk, W. R. Coker)
An exact finite-range DWBA program, with stripping and knockout options. The program evaluates the finite range DWBA integrals in the formalism of Austern and Satchler, using a Gauss-Legendre quadrature. Spin-orbit coupling is used. (1971)

*GAMOW (W. R. Coker)
Computes Gamow functions for single particle resonances in an optical model potential. Automatic search provision for pole position as a function of real well depth. Uses COULOM (or COUCAM from REGGE) as a subroutine. Exists in 3 versions. (1972)

*GPMAIN (S. A. A. Zaidi)
Calculates theoretical elastic proton partial widths, as given in Phys. Rev. Letters 19, 1446 (1967). Required input: Nucleon optical parameters. Based on program NEPTUNE. Used in conjunction with JULIUS to analyze elastic IAR data. Exists in several versions. (1967)

HFB3 (H. Wolter, A. Faessler, P. Sauer)
Program to perform self-consistent calculations of the ground states of nuclei including pairing correlations (Hartree-Fock-Bogoliubov). The program allows to treat pairing not only between like nucleons, but also T = 0 and T = 1 pairing between protons and neutrons. It can describe axially symmetric deformations. It is designed to use a large set of harmonic oscillator basis states and uses two-body matrix elements supplied by the program BD3.

*HFS (H. Wolter)
Program for Hartree-Fock-Slater calculations for atoms, following the general method of a program by Herman and Skillman. The program will calculate the self-consistent potential of the atom, the single particle energies and wave functions and the total energy for any specified atomic configuration. Relativistic corrections are included in perturbation theory. The program can also calculate X-ray energies and transition probabilities for any atom or ion and also the shift in these quantities due to additional electron vacancies. (1970)

*JULIUS (S. A. A. Zaidi, S. Darmodjo, R. Alders)
Calculates theoretical excitation curve for elastically scattered protons, with resonance terms. Required input: proton optical parameters, resonance parameters. Based on an optical model program by F. G. Perey. (1967)

JUPITOR-1 (T. Tamura)
Calculates coupled-channel scattering of nucleons or light ions by nuclei, outputs angular distributions of elastic and inelastic processes. See ORNL Report 4152 and Rev. Mod. Phys. 37, 679 (1965) for details. (1965)

JUPITOR-2 (T. Tamura)
Compact version of JUPITOR-1, modified, among other things, to solve the Lane equations above and below the charge exchange threshold. See Physics Letters 25B, 186 (1967). (1966)

*JUPITER-2B (G. W. Hoffmann)
Modified specifically for charge-exchange reactions using a complex Lane potential, generated in a charge-independent way from proton and neutron optical potentials. (1972)

*JUPITOR-4 (W. R. Coker, T. Udagawa, H. H. Wolter)
Program to perform Coupled-Reaction-Channel calculations involving channels with different mass partitions. Channels involving transfer reactions as well as inelastic processes may be included. Direct reactions are treated in the zero-range approximation. The program is flexible and can include many different types of two-step processes. The organization of the program follows the general scheme of the JUPITOR-1 Coupled-Channel program. However, the solution of the coupled equations may be performed by an iterative method, which is especially useful, when the solutions of the coupled equations are compared to results of the Second-Order Born Approximation. A finite range version of the program, JUPITER-4F, is in preparation. (See Phys. Rev. C1, 1154 (1973)). (1973)

*LANE (R. D. Alders)
Calculates theoretical elastic proton partial widths of analog resonances from Lane equations. Required input: proton optical model parameters, resonance parameters. (1970)

*LSCWOP (D. Matthews)
A program for fitting arbitrary curves. Uses up to order 300 orthogonal polynomials for the purpose of least squares fitting a curve. Particularly useful for determining and accurately tabulating the calibration data for γ-ray spectra. (1970)

*LVDENS (T. Tamura, K. S. Low)
Calculates level densities separately for every possible set of values of spin, parity and excitation energy of a given nucleus. Inputs are spin, parity and energy of the single-particle orbits for both protons and neutrons, filled and/or vacant in the ground state of that nucleus. (1971)

*MARS (T. Tamura, T. Udagawa)
Performs a coupled-channel Born approximation (CCBA) calculation for direct transfer reactions. The multi-channel distorted wave is calculated using JUPITOR-1 as a subprogram of MARS. The versatility of JUPITOR-1 allows MARS to treat a wide variety of multi-step transfer reactions. (1971)

*MIA (R. Hiddleston, E. Sheldon)
Calculates the angular distribution for a resonant reaction proceeding through two levels at the same energy. (1970)

NEPTUNE (T. Tamura)
Calculates bound state radial wave functions for single particle states in spherical and deformed nuclei, coupled states, and analog states. Input: shell model parameters. (1966)

*OPTICS (W. J. Braithwaite)
A short program that calculates elastic differential scattering cross sections and polarizations from optical parameters, for particles having spin = 0, 1/2, 1. (1970)

*PI-NU (P. Dyer)
Modification of SHELMO allowing shell model generation of isobaric analog states as bound states in the continuum. (1968)

*PLATO (H. Bledsoe, T. Tamura, W. R. Coker)
Computes theoretical elastic total and partial widths of IAR using a modified phenomenological Fano Theory. Input: proton and neutron potentials, resonance parameters. Another somewhat specialized version exists, called JP-3. (1970)

RAYTRACE (G. Hoffmann)
Ray tracing of charged particles through arbitrary magnetic system. (1969)

RANGEN (C. F. Williamson)
Computes a table of ranges and stopping powers for light projectiles on target materials of varying chemical complexity.

*REGGE (H. Wolter)
Calculation of Regge trajectories and of pole terms and background integral for the Regge representation of the scattering amplitude of an optical model potential. The S-matrix for complex ℓ-values is obtained by solving the nonrelativistic Schrodinger equation for complex values of the orbital angular momentum and fitting the interior solution to Coulomb functions of complex order. The path of the background integral may be chosen arbitrarily in the complex ℓ-plane. (1971)

*RESFIT, A AND B (W. R. Coker)
A fitting program for resonant elastic scattering. A Breit-Wigner resonance phase is added to the optical model scattering phase shift, to generate experimental total and partial widths, and resonance energies, independent of any particular theoretical model. A has target thickness and compound elastic corrections, B has a least-squares automatic fitting provision. (Based on an elastic scattering program by Perey.) (1970)

*ROOTD (W. J. Braithwaite, J. G. Cramer)
Computes the roots of the reduced rotation matrix. See Computer Physics Communications 3 (1972) 318 and Nuclear Data Tables A10 (1972) 469. (1969).

*SATURN-MARS (T. Tamura, K. S. Low)
This program is written expressly for heavy-ion reactions. It calculates exact finite range DWBA and CCBA cross sections for various transfer reactions between light or heavy ions. SATURN calculates the form factor, either with or without recoil effects. MARS, which is a modification of the standard CCBA program of the same name, then calculates the finite range cross section. When a CCBA calculation is done, only $0^+ - 2^+$ coupling in the exit channel is available at present if the calculation is made including recoil. Extension to more general cases is underway (1973).

*SHELCAL (C. Watson, D. Wright)
Calculates the two nucleon matrix elements for a realistic velocity-dependent interaction due to Green. Matrix is diagonalized to give eigenvalues and eigenvectors for nuclei which have two nucleons outside a closed shell. (1970)

*SHELMO (P. Dyer)
Shell model program using Woods-Saxon bound states basis function, and Gaussian-type two-body residual interaction. Diagonalized residual interaction to yield eigenvalues and eigenvectors. Input: single particle quantum numbers and binding energies, two body force parameters. (1968)

*SNO (C. Watson, T. Ragland)
Calculates the elastic and inelastic scattering cross section for any spin using the phase shifts due to a phenomenological potential in the entrance and exit channels plus a Breit-Wigner resonance term. A background term due to direct scattering is also included. There is provision for searching on the partial widths for a best fit (a modern version of program SNOW). Also called ESOT in a later version. (1971)

SNOW (C. F. Moore, P. Richard)
Fits analog resonant proton elastic scattering data in BRIGIT fashion, without restriction to spin-zero target. (1964)

*SPRO (R. G. Couch)
This program was designed for studies of s-process nucleosynthesis. The evolution of abundances is followed in two ways. First, the neutron source and sink reactions are handled by a standard finite differencing scheme. Included in the reaction matrix is a dummy nucleus which reproduces the neutron absorption of all the s-process nuclei and serves as a repository for neutrons removed from the system. Using the free neutron abundance determined by this scheme, the abundances of the s-process nuclei are then integrated forward in time using a Runge-Kutta method which includes options for branching by beta decay to (n,p) and (n,α) reactions. Normally the size of the time step is kept small enough that the fractional change in abundance of any species with a mass fraction greater than 10^{-12} is less than 0.1 Mass is conserved to better than one part in 10^{+10}. (1973)

*TIGER (D. Ward)
Computes neutron yields from quasi-free proton-deuteron scattering ($d^3\sigma/dE_n d\Omega_n d\Omega_p$), using Arndt-MacGregor p-n phase shifts, an optical model distorted wave function for the $\ell = 0$ di-proton system, and plane waves for $\ell > 0$. (1971)

TRANSPORT (Karl Brown)
A computer program for designing beam transport systems.

TRIM (John Colonias)
A general purpose, two-dimensional magnetostatic code capable of solving mathematical models of two-dimensional magnets and includes the effects of finite permeability of the iron.

*TWOBOD (W. J. Braithwaite)
Generates a table of fully relativistic two-body kinematic information. See Computer Physics Communications 4 (1972). (1969)

*UNIFYC1 (Y. L. Tyan, S. A. A. Zaidi)
This program computes nuclear reaction cross sections using a shell-model reaction theory and the Feshbach formalism. The S-matrix is generated by placing a microscopic many-body system of bound interacting fermions into the continuum. The advantage of the technique is that reactions such as inelastic scattering can be treated using realistic, microscopic two-body interactions between each pair of nucleons in the system. (1973)

*VENUS (P. Moore, W. R. Coker)
A forerunner of DWBA-VENUS which allows use of local energy approximations for finite interaction range and optical potential nonlocality. Outputs absolute differential cross sections and excitation functions for reactions with deuterons, tritons, or helions. Exists in several versions. (1967)

*VENUS C (T. Tamura, W. R. Coker)
A forerunner of DWBA VENUS allowing long-range (<40 fm) overlap integrals and including a shell-model calculation of the distorted wave function of a proton in an analog resonance, for use in Hamburger-Effect calculations with direct reactions, and for stripping to unbound states (Phys. Rev. C4, 236 (1971)). (1968)

*ZFAKRP (K. H. Liu, E. V. Ivash)
Calculates differential cross section for (p,n) knockout reactions for non-exchange n-p interaction in the zero-range approximation and for a volume Woods-Saxon nucleon-nucleus interaction. (1969)

*ZIGURAT (W.R.Coker)
A program, with automatic search, which fits elastic scattering of strongly absorbed heavy ions using Ericson's parameterization of the S-matrix. Solves Abel integral equation to obtain Glauber-equivalent optical. See T. E. O. Eriscon, in Preludes in Theoretical Physics (North Holland, 1966) p. 321. (1971)

*ZIGZAG (H. Bledsoe, W. R. Coker, S. Sen, K. S. Low)
A general optical model program with spin-orbit coupling and automatic search on all parameters for spin 0, 1/2, and 1 projectiles incident on spin-zero targets. Has been modified explicitly for heavy-ion elastic scattering. (1970)

Computer Programs - Last Minute Additions

JJTCFP (L. B. Hubbard and David Wright)

This program calculates coefficients of fractional parentage in j-j coupling in the isospin representation(1). It has been modified and now exists in two new versions. The original program uses a recursion relation to find the n - (n + 1) c.f.p. from a table of (n - 1) -n c.f.p. and requires external sorting of output from one stage before it is used as input to the next stage.

One modified version eliminates this requirement and handles the input to successive stages automatically.

The second modified version calculates n - (n + 1) c.f.p. for maximum i-spin only and uses these values to further compute n - (n + 2) c.f.p. via a recursion relation. (1973)

(1)Hubbard, L. B., Computer Physics Communications 1, (1970) 225-231.

*MANYNUC (David Wright)

This program computes matrix elements of a velocity dependent residual interaction(1) between states consisting of two proton and two neutron orbitals simultaneously with, in principle, an arbitrary number of nucleous distributed in the orbitals. The matrix order is held to reasonable size by means of a prescription given by I. M. Band, et. al.(2) The matrix is then diagonalized and eigenvalues and eigenvectors are obtained. (1973)

(1)Green, A. M., Nucl Phy. 33, (1962) 218.
(2)Band, I. M., Kharitonov, Yu. I., and Sliv, L. A., Nucl. Phy. 54, (1964) 369-392.

*BE8EFF (W. J. Braithwaite)

This program calculates the efficiency for "detecting" Be^{8}_{gs} by a pair of adjacent silicon detectors each of which measures the energy of one of the sequentially-emitted alpha particles. The efficiency is strictly defined as the ratio of the number of coincident alpha particles to the number of Be^8 particles that would have been detected if Be^8 were bound. The integrations are performed using Monte Carlo sampling procedures which are found to converge rapidly and inexpensively to within about 1% of the exact efficiency. (1973)

V. PUBLICATIONS, ABSTRACTS, AND INVITED LECTURES

V. A. LABORATORY PAPERS IN PRINT SINCE 1972 PROGRESS REPORT

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A. Laboratory Papers in Print Since 1972 Progress Report

"The ^{107}Ag(d,p)^{108}Ag and ^{109}Ag(d,p)^{110}Ag Reactions", C. Brient, P. J. Riley, H. Seitz, and S. Sen, Phys. Rev. C 6, 1837 (1972).

"The ^{136}Xe(p,p')^{136}Xe and ^{136}Xe(p,d)^{135}Xe Reactions", S. Sen, P. J. Riley, and T. Udagawa, Phys. Rev. C 6, 2201 (1972).

"Inelastic Proton Scattering from ^{96}Mo Through Isobaric Analog Resonances", J. J. Kent, W. R. Coker, and C. Fred Moore, Phys. Rev. C 7, 388 (1973).

"A Coupled-Reaction-Channel Study of (h,t) Reactions", W. R. Coker, T. Udagawa, and H. H. Wolter, Phys. Rev. C 7, 1154 (1973).

"DWBA Analysis of ^{36,38}Ar(d,p) to Neutron Resonances in ^{37,39}Ar", W. R. Coker, Phys. Rev. C 7, 2426 (1973).

"Analysis of Stripping to Analog Resonances Using Complex Energy Eigenstates", W. R. Coker and G. W. Hoffmann, Z. Physik 263, 179 (1973).

"Coupled-Channel Born Approximation Analysis of 'Allowed' and 'Forbidden' ^{22}Ne(p,t)^{20}Ne Transitions", D. K. Olsen, T. Udagawa, T. Tamura, and R. E. Brown, Phys. Rev. C 8, 609 (1973).

"Multistep Contributions to ^{11}B(h,α)^{10}B from 8.0 to 12.0 MeV", W. R. Coker, J. Lin, J. L. Duggan, and P. D. Miller, Phys. Lett. 45B, 321 (1973).

"Exact Macroscopic Charge-Independent Analysis of Quasi-Elastic (p,n) Reactions", G. W. Hoffmann, Phys. Rev. C 8, 761 (1973).

"The ^{88}Sr(d,n$\tilde{p}$)^{88}Sr Reaction", S. A. A. Zaidi, G. W. Hoffmann and W. R. Coker, Z. Physik 260, 329 (1973).

"Multistep Contributions in ^{88}Sr(h,t)^{88}Y", W. R. Coker, T. Udagawa, and H. H. Wolter, Phys. Lett. 46B, 27 (1973).

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"In-Beam Axial β-Ray Spectrometer for the Measurement of Internal Conversion Electrons", J. Michael Picone, J. F. Fitch, J. W. Baker, G. W. Hoffmann, and C. F. Moore, Nucl. Instr. and Meth. 105, 1391 (1972).

"A New Technique for Charged-Particle Mass Identification", G. W. Hoffmann, F. Pipitone, and J. R. White, Nucl. Instr. and Meth. 109, 399 (1973).

"The Mass of ^{64}Ge and Its Role in Nucleosynthesis", C. N. Davids and D. R. Goosman, Phys. Rev. C 7, 122 (1973).

"The Decays of ^{26}Na and ^{27}Na", D. E. Alburger, D. R. Goosman, and C. N. Davids, Phys. Rev. C 8, 1011 (1973).

"Decays of ^{72}Kr and ^{73}Kr", C. N. Davids and D. R. Goosman, Phys. Rev. C 8, 1029 (1973).

"Mass and β Decay of the New Isotope ^{29}Mg: Systematics of Masses of $T_Z = 5/2$ Nuclei in the 2s - 1d Shell", D. R. Goosman, C. N. Davids, and D. E. Alburger, Phys. Rev. C 8, (1973).

"Accurate Masses and β-Decay Schemes for ^{34}P and ^{33}Si", D. R. Goosman, C. N. Davids, and D. E. Alburger, Phys. Rev. C 8, (1973).

"The Equivalence of Charge and Energy", D. P. Whitmire, Letts. Nuovo Cimento 7, 305 (1973).

"Some Effects of Urca Reactions Upon Degenerate Carbon Burning", R. G. Couch and W. D. Arnett, Astrophys. J. 180, L101 (1973).

"Associated Legendre Polynomials, Ordinary and Modified Spherical Harmonics", W. J. Braithwaite, Comput. Phys. Commun. 5, 390 (1973).

"Lyman X-rays from a Highly Stripped Nitrogen Beam", C. F. Moore, W. J. Braithwaite, and D. L. Matthews, J. Phys. B. 6, 1592 (1973).

"Lifetime Measurement of Helium-like and Lithium-like Oxygen", C. F. Moore, W. J. Braithwaite, and D. L. Matthews, Phys. Lett. 44A, 199 (1973).

"Spin Determinations with α-Heavy-Ion Angular Correlations", W. J. Braithwaite and J. C. Cramer, Phys. Rev. Lett. 31, 401 (1973).

"The Asymmetry in the $^{176}Yb(p,t)^{174}Yb$ Reaction Using Polarized Protons at 16 MeV", G. Igo, J. C. S. Chai, R. F. Casten, T. Udagawa, and T. Tamura, Nucl. Phys. A207, 289 (1973).

"Regge Description of Optical Model Scattering", H. H. Wolter and T. Tamura, Phys. Rev. C 6, 1976 (1972).

"The Reaction $^{20}Ne(^{3}He,n)^{22}Mg$ at ^{3}He Energies Below 6 MeV", R. E. Benenson, I. J. Taylor, D. L. Bernard, H. H. Wolter, and T. Tamura, Nucl. Phys. A197, 305 (1972).

"Effects of Nuclear Collectivity on the T[illegible] Neutron Cross Section", C. Y. Wong, T. Tamura, H. Marshak, and A[illegible]ord, Particle and Nuclei 4, 163 (1972).

"Optical-Model and Coupled-Channel Analysis of 60-90 MeV Deutron Scattering from ^{24}Mg and ^{89}Y", G. Hrehuss, A. Kiss, K. T. Knöpfle, C. Mayer-Böricke, M. Rogge, U. Schwimm, P. Turek, and T. Tamura, Z. Physik 260, 179 (1973).

"Gamma Cascades in ^{252}Cf Spontaneous Fission Fragments", F. F. Hopkins, J. R. White, C. F. Moore, and P. Richard, Phys. Rev. C 8, 380 (1973).

"Characteristic L X-Ray Spectra from Proton, α-Particle, and Oxygen Bombardment of Sn", D. K. Olsen, C. F. Moore, and P. Richard, Phys. Rev. A 7, 1244 (1973).

"Experimental Energy Dependence of Aluminum Multiple Inner-Shell Ionization from 3.0 to 30.0 MeV Oxygen Bombardment, D. K. Olsen, C. F. Moore, and R. L. Kauffman, Phys. Lett. 44A, 109 (1973).

"Kβ Hypersatellite Observation in Magnesium", P. Richard, D. K. Olsen, R. L. Kauffman, and C. F. Moore, Phys. Rev. A 7, 1437 (1973).

"Amomalous Low Energy Kα Lines in Al and Si from High Energy Oxygen Bombardment", P. Richard, C. F. Moore, and D. K. Olsen, Phys. Lett. 43A, 519 (1973).

"Observation of Plasmon Excitations in X-Ray Production Following Heavy Ion Bombardment", J. McWherter, J. E. Bolger, H. H. Wolter, D. K. Olsen, and C. F. Moore, Phys. Lett. 45A, 57 (1973).

"Energy Dependence of Multiple Inner-Shell of Al by Alpha-Particle Bombardment", P. Richard, R. L. Kauffman, J. H. McGuire, C. F. Moore, and D. K. Olsen, Phys. Rev. A 8, 1369 (1973).

"Sodium Satellite Structure", C. F. Moore, D. K. Olsen, B. Hodge, and P. Richard, Z. Physik 257, 288 (1972).

"K X-Ray Spectra from Si and SiO_2 after Oxygen Excitation", C. F. Moore, D. K. Olsen, J. McWherter, and P. Richard, J. Phys. Soc. Japan 34, 1020 (1973).

"Projectile and Target Dependence of the Kα Satellite Structure", R. L. Kauffman, J. H. McGuire, P. Richard, and C. F. Moore, Phys. Rev. A 8, 1233 (1973).

"Potassium and Titanium K X-Ray De-Excitation Induced by Ion Bombardment", B. Johnson, M. Senglaub, P. Richard, and C. F. Moore, Z. Physik 261, 413 (1973).

"High Resolution of K X-Ray Spectrum of 30 MeV Clorine Ion Beam", C. F. Moore, H. H. Wolter, R. L. Kauffman, J. McWherter, J. E. Bolger, and C. P. Browne, J. Phys. B 5, L262 (1972).

"Observation of Chorine Kα Satellite and Hypersatellite and Kβ Satellite Transitions", C. F. Moore and H. H. Wolter, J. Phys. B 6, L124 (1973).

"Multiply Excited States in Two and Three-Electron Oxygen Ions", D. L. Matthews, W. J. Braithwaite and C. F. Moore, Phys. Rev. A 8, 1397 (1973).

"Degenerate Carbon Burning", R.G. Couch and W.D. Arnett, Explosive Nucleosynthesis, Proc. of the Conf., Austin, April 1973, edited by D.N. Schramm and W.D. Arnett, (University of Texas Press, Austin, 1973) p. 179.

"Finite Range Coupled-Channel Born-Approximation for Heavy Ion Transfer Reactions", K.S. Low and T. Tamura, Proc. of Symposium on Heavy Ion Transfer Reactions, Argonne, March 1973 (ANL Informal Report PHY -1973B) Vol. 1, p. 655.

"Single Nucleon Transfer Reactions and Inelastic Scattering Induced by "B Ions Incident on ^{208}Pb", J.L.C. Ford, K.S. Toth, D.C. Hensley, R.M. Gaedke, P.J. Riley, and S.T. Thornton, Proc. of Symposium on Heavy Ion Transfer Reactions, Argonne, March 1973 (ANL Informal Report PHY - 1973B) Vol. 1, p. 495.

"Nuclear Moments and Related Structure of Vibrational and Transitional Nuclei", T. Tamura and T. Kishimoto, Proc. of Intern. Conf. on Nuclear Moments and Nuclear Structure, Osaka, Sept. 1972, edited by H. Horie and K. Sugimoto (J. Phys. Soc. Japan 34, supplement, 1973) p. 393.

"Collisions of Electrons with Highly Ionized Oxygen", W.J. Braithwaite, D.L. Matthews, and C.F. Moore, Proc. of Eighth Intern. Conf. on the Physics of Electronic and Atomic Collisions, Beograd, July 1973, edited by B.C. Cobic and M.V. Kurepa (Graficko Preduzece" Bucucnost, Zrenjanin, 1973) post-deadline insert.

V. B. LABORATORY PAPERS IN PRESS OR SUBMITTED

BLANK PAGE

"States in ^{85}Kr from the ^{84}Kr(d,p) Reaction", C. P. Browne, D. K. Olsen, J. Chao, and P. J. Riley, submitted to Phys. Rev. C.

"Interference Between Coulomb and Nuclear Excitation in the Inelastic Scattering of ^{11}B Ions from ^{208}Pb", J. L. C. Ford, Jr., K. S. Toth, D. C. Hensley, P. J. Riley, and S. T. Thornton, in press, Phys. Rev. C.

"Spin and β-Decay of the $T_Z = 2$ Nuclide ^{22}F", C. N. Davids, D. R. Goosman, and D. E. Alburger, in press, Phys. Rev. C.

"The Reaction ^{23}Na(α,p)^{26}Mg from E = 2.3 - 3.7 MeV and the Corresponding Stellar Reaction Rate", D. P. Whitmire and C. N. Davids, submitted to Phys. Rev. C.

"Relativistic Spaceflight and the Catalytic Nuclear Ramjet", D. P. Whitmire, submitted to Astronomica Acta.

"The Possible Equivalence of Charge, Mass, and Energy; The Creation and Annihilation of Charge", D. P. Whitmire, submitted to Nature.

"Explosive Nucleosynthesis", R. G. Couch, W. D. Arnett, and D. N. Schramm, in press, Earth and Extraterrestial Sciences.

"s-Process Nucleosynthesis in Massive Stars: Core Helium Burning", R. G. Couch, A. B. Schmiedekamp, and W. D. Arnett, submitted to Astrophys. J.

"Coupled-Channel-Born Approximation Analysis of One Nucleon Transfer Reactions to ^{25}Mg and ^{25}Al", A. K. Abdallah, T. Udagawa, and T. Tamura, in press, Phys. Rev. C.

"Note on the Forbidden (p,t) Excitation of Unnatural Parity Final States From 0^+ Targets Via Multistep Processes", T. Udagawa and D. K. Olsen, in press, Phys. Lett.

"Non-orthogonality Effects in Successive-Particle Transfer", T. Udagawa, H. H. Wolter, and W. R. Coker, in press, Phys. Rev. Lett.

BLANK PAGE

"Coupled-Channel-Born-Approximation Study of the (p,t) Reaction Leading to Two-Phonon States in Vibrational Nuclei", T. Udagawa, in press, Phys. Rev.

"Silicon and Silicon Dioxide K X-Ray Spectra from Hydrogen, Helium, and Oxygen Bombardment", J. McWhorter, D. K. Olsen, H. H. Wolter, and C. F. Moore, submitted to Phys. Rev. A.

"Excitation of Multiplet Configurations in Neon", C. P. Bhalla, D. L. Matthews, and C. F. Moore, submitted to Phys. Lett.

"High Resolution K-Auger Spectra for Multiply-Ionized Neon", D. L. Matthews, B. M. Johnson, J. J. Mackey, C. F. Moore, submitted to Phys. Rev. Lett.

"A High Resolution Study of Ar LMM Auger Electrons Produced by Ion Bombardment", B. M. Johnson, D. L. Matthews, L. E. Smith, and C. F. Moore, submitted to J. Phys. B.

"High Resolution Ne KLL Auger Spectra Produced by H^+ and He^+ Bombardment", D. L. Matthews, B. M. Johnson, J. J. Mackey, and C. F. Moore, submitted to Phys. Lett.

"Microscopic Complex Effective Interaction for (p,n) Reactions", G.W. Hoffmann and W.R. Coker, in press, Phys. Lett.

"Successive Pickup Mechanism in the $^{98}Mo(d,\alpha)^{96}Nb$ Reaction at 17 MeV", W. R. Coker, J. R. Comfort, and T. Udagawa, submitted to Phys. Rev. C.

"Exact Finite Range DWBA Calculation for $^{208}Pb(^{16}O,^{15}N)^{209}Bi$ and $^{88}Sr(^{16}O,^{15}N)^{89}Y$ Reactions", T. Tamura and K.S. Low, in press, Phys. Rev. Lett.

"Gamow-State Analysis of $^{54}Fe(d,n)$ to Proton Resonances in ^{55}Co", W. R. Coker, in press, Phys. Rev. C.

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V. C. OTHER PUBLICATIONS BY MEMBERS OF LABORATORY

BLANK PAGE

"Study of Some Two-Nucleon Pickup Reactions in the 1p Shell with 39.8-MeV Protons", C. G. Hoot, D. K. Olsen, R. E. Brown, J. R. Maxwell, and A. Scott, Nucl. Phys. A 203, 339 (1973).

"Scattering of 9.8-MeV Neutrons from Silicon and Sulfur", A. W. Obst and J. L. Weil, Phys. Rev. C 7, 1076 (1973).

"Reaction Cross Sections for ^{16}O with Fe, Ni, Ge, and Zr", A. W. Obst, D. L. McShan, M. B. Greenfield, R. Holub, and R. H. Davis, Phys. Rev. C 8, 1379 (1973).

"Isospin-Forbidden Particle Decays of T = 3/2 Levels of Mirror Nuclei", E. G. Adelberger, A. B. McDonald, C. L. Cocke, C. N. Davids, A. P. Shukla, H. B. Mak, and D. Ashery, Phys. Rev. C 7, 889 (1973).

"Production of the Light Elements Lithium, Beryllium, and Boran by Proton Induced Spallation of ^{14}N", H. Laumer, S. M. Austin, L. M. Panggabean, and C. N. Davids, Phys. Rev. C 8, 483 (1973).

"Relativistic Kinematics for Two-Body Final States", W. J. Braithwaite, Comput. Phys. Commun. 4, 227 (1972).

"Relativistic Kinematics for Three-Body Final States", W. J. Braithwaite, Comput. Phys. Commun. 4, 233 (1972).

"The ^{86,88}Sr(d,He^3)^{85,87}Rb Reaction and a Possible Z = 38 Magic Number", J. R. Comfort, J. R. Duray, and W. J. Braithwaite, Phys. Rev. C 8, 1354 (1973).

"Nucleon Transfer with Oxygen Ions and Near the Coulomb Barrier", K. G. Nair, J. S. Blair, W. Reisdorf, W. R. Wharton, W. J. Braitwaite, and M. K. Mehta, Phys. Rev. C 8, 1129 (1973).

"Projectile Coulomb Excitation of ^{20}Ne and ^{22}Ne", D. K. Olsen, A. R. Barnett, S. F. Biagi, N. H. Merrill, and W. R. Phillips, submitted to Nucl. Phys.

"The ^{19}F(^{3}He,d)^{20}Ne Reaction at 20-23 MeV", A. W. Obst and K. W. Kemper, Phys. Rev. C 8, 1682 (1973).

BLANK PAGE

"Note on the $^{19}F(\alpha,t)^{20}Ne$ Reaction at 28.5 MeV", A. W. Obst and K. W. Kemper, submitted to Phys. Rev. C.

"Anomolous Behavior of the $^{9}Be(\alpha,t)^{10}B$ and $^{13}C(\alpha,t)^{14}N$ Reactions", K. W. Kemper, S. Cotanch, G. Moore, A. W. Obst, R. Puigh, and R. L. White, submitted to Phys. Rev. C.

"Coulomb Excitation of ^{208}Pb with Heavy Ions", A. R. Barnett, S. F. Biagi, D. K. Olsen, and W. R. Phillips, Proc. of the Intern. Conf. on Nuclear Moments and Nuclear Structure, Osaka, Sept. 1972, edited by H. Horie and K. Sugimoto (J. Phys. Soc. Japan 34, supplement, 1973) p. 389.

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V. D. ABSTRACTS

BLANK PAGE

"Direct-Reaction Study of High Excitation Bound States and Neutron Resonances in the Zr Isotopes", W. R. Coker, G. W. Hoffmann, F. Pipitone, and J. R. White, Bull. Am. Phys. Soc. 18, 721 (1973).

"The ^{84}Kr(d,p)^{85}Kr Reaction", C. P. Browne, D. K. Olsen, and P. J. Riley, Bull. Am. Phys. Soc. 18, 721 (1973).

"Experimental Energy Dependence of Al Multiple Inner-Shell Ionization From 3.0 to 30.0-MeV Oxygen Bombardment", D. K. Olsen, C. F. Moore, and R. L. Kauffman, Bull. Am. Phys. Soc. 18, 559 (1973).

"Single-Neutron Transfer Reactions Induced by "B Ions Incident on ^{208}Pb", K. S. Toth, J. L. C. Ford, D. C. Hensley, R. M. Gaedke, and P. J. Riley, Bull. Am. Phys. Soc. 18, 714 (1973).

"Proton-Induced Reactions on ^{89}Y at 28 MeV", J. R. Comfort, W. J. Braithwaite, A. Nathan, and J. R. Duray, Bull. Am. Phys. Soc. 18, 721 (1973).

"Anomalous X-ray Transitions Above the Lyman-like Series Limit in $O^{7+} + e^-$", D. L. Matthews, W. J. Braithwaite, C. Camp, and C. F. Moore, Bull. Am. Phys. Soc. 18, 634 (1973).

"In Beam Conversion Electron Studies of p + Pb", L. L. Lynn, G. W. Hoffmann, J. Fitch, and C. F. Moore, Bull. Am. Phys. Soc. 18, 700 (1973).

"Decay of ^{27}Na", D. E. Alburger, D. R. Goosman, and C. N. Davids, Bull. Am. Phys. Soc. 18, 678 (1973).

"New Proton-Rich Activities Near ^{72}Kr", C. N. Davids and D. R. Goosman, Bull. Am. Phys. Soc. 18, 720 (1973).

"Coupled-Channel Calculation for the Sub-Coulomb Transfer Reaction ^{238}U(d,t)^{237}U at 8.5 MeV", J. R. Erskine and T. Tamura, Bull. Am. Phys. Soc. 18, 701 (1973).

"Boson Expansion Techniques in the Description of Nuclear Collective

BLANK PAGE

Motion", D. Braunschweig, T. Tamura, and T. Kishimoto, Bull. Am. Phys. Soc. 18, 647 (1973).

"Regge Parametrization of Optical Model Scattering", H. H. Wolter and T. Tamura, Bull. Am. Phys. Soc. 18, 624 (1973).

"Coupled-Channel-Born-Approxiamtion Analysis of (p,t) Reactions, Leading to Two-Phonon States of Even Vibrational Nuclei", T. Udagawa, T. Tamura, W. J. Braithwaite, J. R. Comfort and J. R. Duray, Bull. Am. Phys. Soc. 18, 604 (1973).

"A New Technique for High Resolution Charged-Particle Mass Identification", G. W. Hoffmann, C. F. Moore, F. Pipitone, and J. White, Bull. Am. Phys. Soc. 18, 618 (1973).

"Exact Finite Range DWBA Calculations of (^{16}O, ^{15}N), (^{12}C, ^{13}C) and (^{12}C, "B) Reactions on ^{208}Pb", T. Tamura and K. S. Low, Bull. Am. Phys. Soc. 18, 1384 (1973).

"Spin and Beta Decay of the $T_Z = 2$ Nuclide ^{22}F", C. N. Davids, D. R. Goosman, and D. E. Alburger, Bull. Am. Phys. Soc. 18, 1391 (1973).

"Complex Microscopic Effective Interaction for (p,n) Reactions", G. W. Hoffmann and W. R. Coker, Bull. Am. Phys. Soc. 18, 1392 (1973).

"Coupled-Channel-Born-Approximation Analysis of ^{20}Ne(p,t)^{18}Ne Transitions", D. K. Olsen, T. Udagawa, and R. F. Brown, Bull. Am. Phys. Soc. 18, 1400 (1973).

"Multistep Mechanism for (d,α) Reactions", W. R. Coker and T. Udagawa, Bull. Am. Phys. Soc. 18, 1401 (1973).

"Decays of ^{74}Kr and ^{75}Kr", C. N. Davids, L. A. Parks, A. Schmiedekamp, and D. P. Whitmire, Bull. Am. Phys. Soc. 18, 1408 (1973).

"Position Determination of Radiation in a Solid State Detector Using Difference in Pulse Rise Times", W. J. Braithwaite, C. R. Doss, and C. F. Moore, Bull. Am. Phys. Soc. 18, 1412 (1973).

"Possible Electron Resonances in Highly-Ionized Oxygen", C. F. Moore, W. J. Braithwaite, and D. L. Matthews, Bull. Am. Phys. Soc. 18, 1413 (1973).

"Internal Conversion Electrons from Proton Bombardment of ^{121}Sb, ^{103}Rh, and ^{93}Nb", L. L. Lynn, J. R. White, G. W. Hoffmann, and C. F. Moore, Bull. Am. Phys. Soc. 18, 1425 (1973).

"^{40}Ca(p,p') at 35 MeV", J.A. Nolen, Jr., R.J. Gleitmann, G. Hamilton, A. Moalem, and T. Udagawa, Bull. Am. Phys. Soc. 18, 1420 (1973).

"A New Method for Spin Determinations Using Heavy Ions", W.J. Braithwaite and J.G. Cramer, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.J. Mang (North-Holland, Amsterdam, 1973) Vol. 1, p. 238.

"Coupled-Channel-Born-Approximation Analysis of (p,t) Transitions to the Ground-State Rotational Band of ^{20}Ne", D.K. Olsen, T. Udagawa, T. Tamura, and R.E. Brown, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.J. Mang (North-Holland, Amsterdam, 1973) Vol. 1, p. 489.

"Study of Two-Step Reaction Mechanisms from the ^{58}Ni(p,t)^{56}Ni Reaction to Unnatural-Parity States", H.H. Wolter, T. Udagawa, and D.K. Olsen, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.T. Mang (North-Holland, Amsterdam, 1973) Vol. 1, p. 492.

"Nuclear Structure Studies with ^{84}Kr and ^{85}Kr", P.J. Riley, C.P. Browne, and D.K. Olsen, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.T. Mang (North-Holland, Amsterdam, 1973) Vol. 1, p. 218.

"Inelastic Scattering and Single-Nucleon Transfer Reactions by ^{11}B on ^{208}Pb", J.L.C. Ford, K.S. Toth, D.C. Hensley, R.M. Gaedke, P.J. Riley, and S.T. Thornton, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.T. Mang (North-Holland, Amsterdam, 1973) Vol. 1, p. 381.

"Macroscopic Charge-Independent Analysis of Quasi-Elastic (p,n) Reactions", G.W. Hoffmann and C.F. Moore, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.T. Mang (North-Holland, Amsterdam, 1973) Vol.1, p. 404.

"Systematics of Masses of $T_Z = 5/2$ Nuclei in the 2s-1d Shell", D.R. Goosman, C.N. Davids, and D.E. Alburger, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.T. Mang (North-Holland, Amsterdam, 1973) Vol. 1, p. 327.

"Decays of New Proton-Rich Nuclides ^{72}Kr and ^{73}Kr", C.N. Davids and D.R. Goosman, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.T. Mang (North-Holland, Amsterdam, 1973) Vol. 1, p. 686.

"Internal Conversion Electrons from the Proton Bombardmant of ^{206,208}Pb", C.F. Moore, L.L. Lynn, and G.W. Hoffmann, Proc. of the Intern. Conf. on Nuclear Physics, Munich, Aug. 1973, edited by J. de Boer and H.T. Mang (North-Holland, Amsterdam, 1973) Vol. 1, p. 238.

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V. E. INVITED LECTURES GIVEN BY LABORATORY MEMBERS

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"Comparative Measurements of Coulomb Mixing in the 1^+ Doublet of C^{12}", W. J. Braithwaite, University of Washington, Seattle, Washington, November 1972.

"A New Method for Spin Determinations Using Alpha-Heavy-Ion Angular Correlations", W. J. Braithwaite, Universitat zu Köln, Köln, Germany, August 1973.

"Intermediate Structure in the Scattering between Two ^{16}O", T. Tamura, Institute for Nuclear Studies, Tokyo University, Tokyo, Japan, September 1972.

"Topics in Heavy-Ion Reactions", T. Tamura, Nuclear Physics Laboratory, Kyoto University, Kyoto, Japan, September 1972.

"Boson Expansion Technique and the Nuclear Collective Motion, T. Tamura, Argonne National Laboratory, November 1972.

"Boson Expansion Technique and the Nuclear Collective Motion, T. Tamura, Ohio University, Athens, Ohio, January 1973.

"New Techniques in Distorted Wave Born Approximation Calculations", T. Tamura, Michigan State University, East Lansing, Michigan, February 1973.

"Spectroscopic Studies with the Even Krypton Isotopes", P. J. Riley, Nuclear Physics Seminar, Texas A & M University, College Station, Texas, March 1973.

"The Use of an Accelerator in Studying our Environment", P. J. Riley, Eleventh Annual Southwest Science Symposium, Dallas, Texas, March 1973.

"Two New Proton-Rich Isotopes of Interest to Nucleosynthesis - ^{64}Ge and ^{72}Kr", C. N. Davids, Nuclear Seminar, Yale University, New Haven, Connecticut, May 1973.

"Two New Proton-Rich Isotopes of Interest to Nucleosynthesis - ^{64}Ge and ^{72}Kr", C. N. Davids, Nuclear Seminar, Brookhaven National Laboratory, May 1973.

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"Coupled-Channel Born Approximation Analysis of Two-Particle Transfer Reactions in the Neon Isotopes", D. K. Olsen, University of Minnesota, Minneapolis, Minnesota, May 1973.

"Multistep Processes in Nuclear Reactions", T. Udagawa, Texas A & M University, College Station, Texas, October 1973.

"X-ray Phenomena in Heavy Ion Collisions", C. F. Moore, Physics Colloquium, Brookhaven National Laboratory, Upton, Long Island, New York, February 1973.

"Hydrogenic Oxygen", C. F. Moore, Physics Colloquium, Rutgers, The State University, New Brunswick, New Jersey, February 1973.

"Chemical Bonding Effects in X-ray Measurements", C. F. Moore, Physics Seminar, Massachusetts Institute of Technology, Cambridge, Mass., February 1973.

"The Heart of Atomic Physics", C. F. Moore, Physics Colloquium, University of Pittsburgh, Pittsburgh, Pennsylvania, February 1973.

"Atomic Physics at High Energy", C. F. Moore, Physics Colloquium, Michigan State University, East Lansing, Michigan, April 1973.

"The Few Electron Atomic System", C. F. Moore, Physics Colloquium, University of Illinois, Urbana-Champaign, Illinois, April 1973.

"X-ray Band Structure", C. F. Moore, Solid State Physics Seminar, University of Wisconsin, Madison, Wisconsin, April 1973.

"Decay of Highly Ionized Heavy Ions", C. F. Moore, Physics Colloquium, Argonne National Laboratory, Argonne, Illinois, April 1973.

"The Heart of Atomic Physics", C. F. Moore, Physics Colloquium, Universite de Montreal, Montreal, Quebec, Canada, April 1973.

"Atomic Physics", C. F. Moore, Nuclear Physics Seminar, University of Rochester, Rochester, New York, April 1973.

"The Physics of the Few Electron Atom", C. F. Moore, Physics Colloquium, Florida State University, Tallahassee, Florida, May 1973.

"X-ray Spectroscopy with High Energy Heavy Ion Beams from Nuclear Accelerators", C. F. Moore, Physics Semianr, University of Cologne, Cologne, Germany, July 1973.

"Electric Field Induced Radiative Transitions in Beam Foil X-rays", C. F. Moore, Colloque International CNRS: Aspect Moleculaires des Collisions Atomique a Moyenne et Haute Energie, GIFs/YVETTE, France, 9-11 July 1973.

"Radiation Induced Thermally Activated Depolarization Currents in Alkali Halides", C. F. Moore, Physics Seminar, University of Cologne, Cologne, West Germany, July 1973.

"Isobaric Analog States-Their Discovery and Importance in Nuclear Physics", C. F. Moore, Physics Colloquium, National Laboratory for Physics, University of Bucharest, Bucharest, Romania, July 1973.

"A New Type of Radiation Dosimeter", C. F. Moore, Physics Seminar, National Laboratory for Physics, University of Bucharest, Bucharest, Romania, July 1973.

"Atomic Spectroscopy of Heavy Ions", C. F. Moore, Physics Colloquium, National Laboratoy for Physics, University of Bucharest, Romania, July 1973.

"Atomic Spectroscopy of Heavy Ions", C. F. Moore, Physics Colloquium, Max Planck Institute fur Kernphysik, Heidelberg, Germany, August 1973.

"A New Method for Spin Determinations Using Heavy Ions", W.J. Braithwaite, contributed paper invited for oral presentation, International Conference on Nuclear Physics, Munich, Germany, August 1973.

"Macroscopic Charge-Independent Analysis of Quasi-Elastic (p,n) Reactions", G.W. Hoffmann, contributed paper invited for oral presentation, International Conference on Nuclear Physics, Munich, Germany, August, 1973.

"Atomic Physics at High Energies", C.Fred Moore, Physics Colloquium, University of Louisville, Louisville, Kentucky, November 1973.

"Macroscopic Analysis of Charge-Exchange Reactions", G.W. Hoffmann, Physics Seminar, Institut für Kernphysik, Universitat zu Köln, Germany, August, 1973.

"New Experimental Applications of Angular Correlation Techniques", W.J. Braithwaite, Colloquium, Department of Physics, Kansas State University, Manhattan, Kansas, October 1973.

"A New Look at the Atom Using Nuclear Accelerators", W.J. Braithwaite, Colloquium, Department of Physics, Ohio University, Athens, Ohio, November 1973.

"A New Method for Spin Determinations Using Alpha-Heavy-Ion Angular Correlations", W.J. Braithwaite, Nuclear Seminar, Department of Physics, Ohio University, Athens, Ohio, November 1973.

"Onward Through the Fog--- Multistep Processes in Nuclear Reactions," Colloquium, Department of Physics, University of Georgia, Athens, Georgia, November 1973: W. R. Coker.

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V. F. SEMINAR AND COLLOQUIUM SPEAKERS INVITED BY THE LABORATORY

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"Experiments with Three Nucleons", Dwight P. Saylor, Texas A&M University, College Station, Texas, Jan. 12, 1973.

"Nuclear Structure Studies of Soft Nuclei", Tom Sugihara, Texas A&M University, College Station, Texas, Jan. 12, 1973.

"Nuclear Structure with Heavy-Ion Transfer Reactions", George Morrison, Argonne National Laboratory, Argonne, Illinois, Feb. 14, 1973.

"Elastic and Inelastic Scattering of O^{16} from $Ni^{58,60,62,64}$", Leon West, Florida State University, Tallahasse, Florida, Feb. 15, 1973.

"Are the Strontium Nuclei Magic?", Joseph R. Comfort, Ohio University, Athens, Ohio, Feb. 16, 1973.

"Nuclear Deformation in the s-d Shell", Andrew Obst, Florida State University, Tallahasse, Florida, Mar. 9, 1973.

"The Light Isobars", Fay Ajzenberg-Selove, University of Pennsylvania, Philadelphia, Pennsylvania, Mar. 16, 1973.

"n + p Differential Cross Sections at 22 MeV", Chris Morris, University of Virginia, Charlottesville, Virginia, Mar. 19, 1973.

"Reaction Mechanisms and Level Density Information in Heavy-Ion Transfer Reactions", Hiromichi Kamitsubu, Institute for Research, Wakoshi, Suitama, Japan, Mar. 23, 1973.

"The Rate of the $^{12}C(\alpha,\gamma)^{16}O$ Reaction and the Death of the Giants", Peggy L. Dyer, California Institute of Technology, Pasadena, California, Mar. 30, 1973.

"Photonuclear Reactions with Heavy Ions", Peter David, University of Bonn, Bonn, Germany, Apr. 9, 1973.

"A Study of the Nuclear Spin-Isospin Forces Using $^{6}Li(^{6}Li,{}^{6}Li^{*}_{T=1})$ $^{6}Li^{*}_{T=1}$ and $^{6}Li(^{6}Li,{}^{6}He)^{6}Be$ Reactions", J. G. Cramer, University of Washington, Seattle, Washington, Apr. 30, 1973

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"Charge Independence", G. T. Garvey, Princeton University, Princeton, New Jersey, May 9, 1973.

"Lithium-Induced Nuclear Reactions", W.J. Courtney, Florida State University, Tallahasse, Florida, June 8, 1973.

"The High-Resolution Proton Spectrometer at LAMPF", Robert M. Rolfe, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, June 29, 1973.

"Shell Effects in Nuclear Fission", S. S. Kapoor, Bhabha Atomic Research Center, Bombay, India, Aug. 23, 1973.

"Non-Axial Asymmetry in High Spin Rotational States", T. Kishimoto, Texas A&M University, College Station, Texas, Oct. 5, 1973.

"Isospin Sum Rules in Transfer Reactions", R. K. Bansal, Panjab University, Panjab, India, and University of Rochester, Rochester, New York, Oct. 12, 1973.

(to be announced), C. L. Cocke, Kansas State University, Manhatten, Kansas, Nov. 21, 1973.

"In-Beam Internal-Conversion Electron Measurements", Y. Gono, Texas A&M University, College Station, Texas, Dec. 7, 1973.

"Nucleon Transfer Near the Coulomb Barrier, Using Heavy Ions", D. Gopi Nair, Texas A&M University, College Station, Texas, Dec. 14, 1973.

"Inner-Shell Vacancy Production in Heavy Ion Atom Collisions", Chander P. Bhalla, FOM - Institute for Atomic and Molecular Physics, Amsterdam, Netherlands, Oct. 3, 1973.

"Two Particle Intrinsic Excitation in Ne^{22} and Mg^{26}", George D. Craig, III, University of Darmstadt, Darmstadt, Germany, Oct. 22, 1973.

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VI. GRADUATE DEGREES AWARDED

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D. P. Whitmire, Ph.D., "The Reaction $^{23}Na(\alpha,p)^{26}Mg$ from E_α = 2.3 - 3.7 MeV, The Thermonuclear Reaction Rate, and Theoretical Investigations", Aug. 1973, Supervisor C. N. Davids.

F. Pipitone, M.S., "A New Technique for High Resolution Charged-Particle Mass Identification", May 1973, Supervisor G. W. Hoffmann.

Y. L. Tyan, Ph.D., "Calculation of Nuclear Reactions Using Projection Operator Techniques", Sept. 1973, Supervisor S. A. A. Zaidi.

R. L. Kauffman, M.S., "Projectile and Target Dependence of the Kα Satellite Structure", Jan. 1973, Supervisor P. Richard.

K. S. Low, Ph.D., "Exact Finite Range DWBA Calculations for Heavy Ion Transfer Reactions", Aug. 1973, Supervisor T. Tamura.

D. Braunschweig, Ph.D., "Boson Expansion Techniques in the Description of Nuclear Collective Motion", Aug. 1973, Supervisor T. Tamura.

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VII. PERSONNEL OF THE LABORATORY

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Faculty

W. J. Braithwaite
W. R. Coker
C. N. Davids
G. W. Hoffmann
E. Ivash
C. F. Moore
I. L. Morgan (until Jan. 15)
P. J. Riley
T. Tamura
T. Udagawa
H. H. Wolter (until Aug. 31)
S. A. A. Zaidi

Post-Doctoral Appointments

R. G. Couch
K. S. Low (after Sept. 1)
L. L. Lynn (until Aug. 31)
A. W. Obst (after Sept. 1)
D. K. Olsen
D. P. Whitmire (after Aug. 1)

Pre-Doctoral Appointments

A. Abdallah
B. Arora
S. Azima
J. Bolger (from Aug. 1)
D. Braunschweig (until Aug. 31)
C. Bjork
C. Chang (from Sept. 1)
J. Chao
S. Chou (from Feb. 1 to Sept. 10)
W. Craig
J. Fitch (until June 30)
B. Hodge
B. Johnson
C. King (from Sept. 1)
R. Kulkarni
K. Low (until Aug. 31)
M. Mahlab (from Sept. 1)
D. Matthews
R. Pardo
L. Parks
F. Pipitone (until May 15)
A. Schmiedekamp
Y. Tyan (until Sept. 31)
S. Vellas
G. Westfall (from Jan. 15)
J. White
D. Whitmire (until July 31)
D. Wright

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Engineering/Technical Staff

P. Coose (part-time)

C. Doss

H. Ellinger

R. Gilbert

R. Heald (part-time)

J. Jagger

A. Mitchell

B. Naumann

J. Peoples (until Aug. 31)

Moti Segal

Machinists

W. Davis

B. Frizzel

H. Lehnick

G. Lucas

D. Sikes

Office Staff

N. Boster (part-time from Aug. 15)

M. George

E. Riley (part-time)

S. Trad (from May 28)

S. Taylor (until Aug. 31)

B. Wolf (until May 31)

Ten Part-time Students

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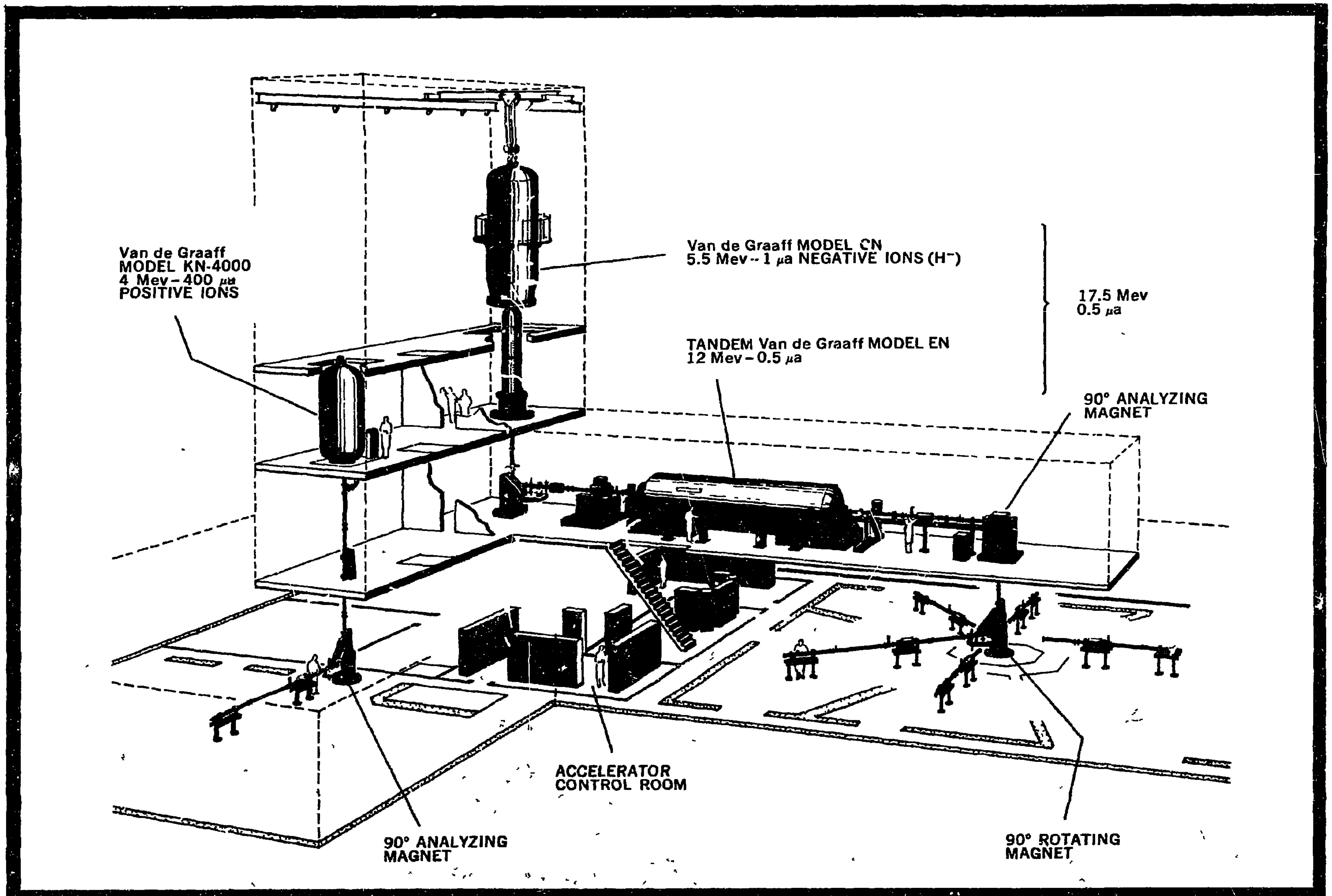
The Center for Nuclear Studies carries on an active program of research in both experimental and theoretical nuclear physics. Additional programs of research deal with problems of nuclear astrophysics, heavy ion physics, medium energy physics (in cooperation with the Los Alamos Meson Physics Facility), X-ray studies of atomic ionization and fission, and studies of atom-ion scattering. Experimental facilities on campus include two Van de Graaff accelerator systems delivering 4 to 17 MeV singly-charged particle beams to 10 completely instrumented beam stations, where are available such equipment as a 40-inch scattering chamber, a precision gas scattering chamber, various spectrometric systems, and a large solid-angle magnetic spectrograph. Two computers are available, independently or in-line, for on-line data handling and reduction; a PDP 15 with 2 disks, and a PDP 7 interfaced to the central campus CDC 6600. Experimental work is supported by a complete machine and instrument shop. An electronics shop provides equipment design, software, and maintenance.

Important theoretical work has been done at the Center on both reaction theory and nuclear structure theory. Theorists, using the very large computer facility on campus, are currently working on a wide range of problems, including the theory of resonance reactions, the theory of nuclear vibrational modes, application of Regge poles and coupled channel methods in nuclear physics, and analysis of two-nucleon transfer reactions.



University of Texas Installation