Annual Report

1972-73

Cyclotron Laboratory
Michigan State University

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ANNUAL REPORT
of the
MICHIGAN STATE UNIVERSITY
CYCLOTRON LABORATORY*
for the period
July 1, 1972 to July 1, 1973

NOTICE

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By
Project Staff

October 1973
East Lansing, Michigan

* Supported jointly by National Science Foundation, Atomic Energy Commission, Office of Naval Research and Michigan State University (see Preface for details).

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PREFACE

Our Annual Report this year continues to be a composite document, covering all programs of the MSU Cyclotron Laboratory and submitted to all of the agencies which support programs in the laboratory. Sources of current support are listed in Table I below. In addition, we call special attention to the fact that the National Science Foundation was responsible for construction of the laboratory and that therefore other agency research programs which use the facility are thus also supported substantially by the NSF. As is clear from Table I, the major operating support for the laboratory comes from the NSF. Other sources of support include the Atomic Energy Commission, which supports the Nuclear Chemistry group, and the Office of Naval Research, which has provided funds for neutron research. In Table II we list the faculty, research associates, and graduate students in the laboratory, together with the grants or contracts to which they are attached. This listing in Table II includes all persons who were at the laboratory for any part of the year 72-73. Those who have left the laboratory, either during the year or since, are identified by an entry in the present address column.

In our annual report this year we continue with the brief write-ups on "Research in Progress". These write-ups, although often incomplete, give an up-to-date presentation of current activity in the laboratory. Following the pattern of last year, we are including in this report the abstracts of papers delivered at meetings, the

abstracts of papers in press after July 1, 1973 and the title page of articles published during the year. Hopefully this first page presents sufficient information for a reader to ascertain if he is interested in that particular article, so that he can then refer to the appropriate journal or contact the authors for reprints.

The state of the laboratory at this time (October 1973) is one of busy activity in nuclear research. The years of work on improved instrumentation systems are now yielding their harvest, a flow of accurate and, we hope, significant information on nuclear phenomena. One of the major purposes of an annual report is to give others the necessary information to assess the state of our current program. If you feel inclined to make comments to us on the program we would welcome them. Finally, let me again remind all of you that we welcome collaborators from other laboratories--if you have an experiment for which our facilities would be particularly appropriate please let us know.

Henry Blosser

P.S. For the year 73-74 I will be on sabbatical leave and E. Kashy will be Director of the Laboratory.

TABLE I.--Sources of support for the MSU Cyclotron Laboratory for the fiscal year 1972-73.

Institution or Agency		Per Cent of Total
National Science Foundation	Grant GP 27483 (experimental nuclear physics)	62.4
Atomic Energy Commission	Contract AT(11-1)-1779 (nuclear chemistry)	8.4
National Science Foundation	Grant GP 31265X (theoretical nuclear physics)	5.0
Office of Naval Research	Contract N00014-68-A-0109-0008	3.3
Michigan State University		20.9

TABLE II. List of faculty, research associates, and graduate students working at the MSU Cyclotron Laboratory in the period July 1, 1972-June 30, 1973 and their principal sources of support.

Professors	supported by	present address
Sam M. Austin	NSF-exp, MSU	(On leave, LMU, Munich, Sept. 1972-Aug. '73)
Walter Benenson	NSF-exp, MSU	
George F. Bertsch	NSF-theor, MSU	
Henry G. Blosser	NSF-exp, MSU	
Aaron I. Galonsky	NSF-exp, ONR, MSU	
Morton M. Gordon	NSF-exp, NASA, MSU	(on leave CERN, 72-75)
Charles Gruhn		
Edwin Kashy	NSF-exp, MSU	
Wm. H. Kelly	NSF-exp, MSU	
Wm. C. McHarris	AEC-chem, MSU	
Hugh McManus	NSF-theor, MSU	
B. H. Wildenthal	NSF-exp, MSU	(On leave, LMU, Munich, Jan.-June '73)
<u>Associate Professors</u>		
Jerzy R. Borysowicz	NSF-theor, MSU	
Gerard M. Crawley	NSF-exp, MSU	
Sven Maripuu	NSF-exp, MSU	Univ. of North Carolina
Jerry A. Nolen, Jr.	NSF-exp, MSU	
<u>Assistant Professors</u>		
Thelma Arnette	NSF-exp, MSU	
Fred M. Bernthal	AEC-chem, MSU	
Wm. A. Lanford	NSF-exp, MSU	Yale University
R.G.H. Robertson	NSF-exp, MSU	
Ray Warner	AEC-chem, MSU	

Research Associates

	supported by	present address
John S. Boyno	NSF-exp, AEC-chem	
Stanley H. Fox	NSF-exp	U. of Cincinnati Medical Center
Greg. C. Giesler	AEC-chem, NSF-exp	Los Alamos Scientific Laboratories
Paul S. Hauge	NSF-theor	
Roger A. Hinrichs	NSF-exp	SUNY, Oswego
Teng Lek Khoo	NSF-exp, AEC-chem	
Amnon Moalem	NSF-exp	
Hermann Nann	NSF-exp, BMFT(Germany)	
Donald Patterson	ONR	
Lolo M. Panggabean	NSF-exp	Universiti Malaya
Lawrence Samuelson	NAS-NIRA	
Richard R. Todd	NAS-NIRA	Western Michigan Univ.

Graduate Students

Wm. B. Chaffee	MSU, NSF-exp	
Wilton Chung	NSF-exp	
John C. Collins	NSF-exp, ONR	SIN, Villingen, Switz.
Robert R. Doering	NSF-exp	
Carol L. Dors	NSF-exp	
Steven C. Ewald	NSF-exp	MSU, Dept. of Eng.
Richard B. Firestone	NSF-exp	
K. Gilbert		
Jean Guile	NSF-exp	
Greg Hamilton	NSF-exp	
G. Richard Hammerstein	NSF-theor	
Robert Howard (Computer Sci.)	NSF-exp	
Kenneth L. Kosanke	AEC-chem, NSF-exp	Research Assoc., MSU
Duane C. Larson	NSF-exp	Oak Ridge Natl. Lab.
Nancy Larson		Oak Ridge Natl. Lab.
Clare B. Morgan	NSF-exp	
B. Poon	NSF-theor	
Ivan D. Proctor	NSF-exp	Lawrence Livermore Laboratory
James A. Rice	NSF-exp	
David L. Show	NSF-exp	
Paul Smith	NSF-exp	
Wm. F. Steele	NSF-exp	
Wm. Wagner	NSF-exp	
Herman White	NSF-exp-APS Fellow CERN (June-Sept. 1972)	

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SECTION I
RESEARCH IN PROGRESS

I. Unnatural Parity Excitations of Nuclei (McManus)

A fair number of clearly resolved, accurately measured, unnatural parity excitations have been observed in nuclei via proton inelastic scattering by the experimental group at MSU, and more will be forth coming. For many of these shell model assignments can be made with fair certainty, so there will be a statistically significant body of data to test the components of the nuclear force, non-central as well as central, responsible for these excitations. Preliminary calculations suggest that conventional forces related in some manner or another to the bound state interaction, do not account fully for these excitations. It is possible that two step, particularly (pd)(dp), which P. D. Kunz (Kunz, Colorado preprint) has shown can be important in pn reactions, and exchange currents (though these are estimated by Erickson to give ~30% effects only) play a role. Such limited π scattering data as exists also suggests that simple excitation is not adequate to explain these and the related charge exchange excitations. In this case only exchange currents might be expected to add to the lowest order amplitudes. It seems worth while to continue with a statistical analysis of data to see whether conventional interactions are adequate or not and to establish at least the order of magnitude of effects coming from two-step and exchange currents, as π -scattering data will be becoming available, and also electron scattering testing directly the nuclear configurations involved.

II. Giant Resonances (Bertsch)

FIG. 1. Quadrupole strength in ^{208}Pb in units of $10^3/\pi \text{ fm}^4/\text{MeV}$. Dotted curve, with the free Green's function $G^{(0)}$; dashed and solid curves, for the Skyrme interactions with the diagonal G^{RPA} . Mesh spacing, 1 fm.

FIG. 2. Octupole strength in ^{208}Pb for Skyrme I interaction in units of $10^3/\pi \text{ fm}^4/\text{MeV}$. Dashed curve, with $G^{(0)}$; solid curve, with the diagonal G^{RPA} . Mesh spacing, 1 fm.

A new calculational scheme is developed for finding the nuclear response to a perturbation of arbitrary form and energy. The traditional method is to first determine the spectrum of the nucleus, and then use the eigenvectors to determine the response. Instead, we use the Green's function directly, solving by matrix inversion. To have matrices of low dimensionality, interactions and Green's functions are represented on a coarse mesh in configuration space. Skyrme-type interactions can be well described this way. Each curve (see figures) takes about 3-5 minutes of computer time to run, even though the number of configurations is typically 200. Obviously, this will be a useful tool to study core polarization, the effective particle-particle interactions, and imaginary part of the optical potential.

So far the method was applied to ^{208}Pb , and the following properties are found:

- (1) The quadrupole strength has a low state and one identifiable as the giant quadrupole;
- (2) Excitation with $L=2$ do not seem to have high energy collective parts;
- (3) The giant dipole $L=1, T=1$ is too low unless the interaction has a strong momentum dependence.

III. Nuclear Mass Formulas (Borysowicz)

(a) Alternative methods other than one used originally by Gerace are investigated to fit the Garvey-Kelson mass formula. The experimental masses are weighted accordingly to the uncertainty in their determination. One method (modified steepest descent) is working well now.

(b) A method is developed to predict nuclear masses using a neighboring region of the mass table. In general the selection of the region is based on the specific position of the considered nucleus. For example only even-even nuclei may be used to predict even-even mass. Compared to the Garvey-Kelson method:

- (1) the tedious fit to the whole mass table is avoided.
- (2) estimation of the error should be more realistic.
- (3) it can be applied to the regions which are too small to use Garvey-Kelson formula (for example $Z > N$ region).

IV. Recoil Effects in Single-Nucleon Transfer Reactions (Hauge and Bertsch)

A formalism has been developed for approximately treating the recoil of the projectile in single-nucleon transfer reactions. We begin by considering a stripping reaction of the form

$$a + A \rightarrow (b + n) + A \rightarrow (n + A) \rightarrow b + B, \quad (1)$$

where n is a nucleon that is transferred from the incident projectile a to form the final target B . The notation that we use is similar to Satchler's,¹ and the coordinates needed for specifying the interaction are shown in Fig. 1.

Following the procedure of earlier approximate recoil calculations,² we neglect the recoil of the target nucleus, translate the scattered wavefunction of the heavier projectile to a coordinate system centered about the lighter mass projectile, and make a plane-wave approximation to the translation operator. The reduced transition amplitude can then be written as:

$$T_{fi}(\theta) \sim \int d^3r \chi^-(\vec{R}_a, \vec{r}) \chi^+(\vec{R}_b, \vec{r}) \int d^3r_1 e^{i\vec{r}_1 \cdot \vec{Q}(\vec{r})} \times [\psi_{\frac{1}{2}m_2}(\vec{r}_2) V(\vec{r}_1) \psi_{\frac{1}{2}m_1}(\vec{r}_1)] \quad (2)$$

where χ^- and χ^+ are the scattered waves of the incoming and outgoing projectiles respectively, and $\vec{Q}(\vec{r})$ is proportional to the local momentum of the heavier projectile.¹

In an earlier recoil calculation,² two further approximations were made, these being (1) approximating $\exp(i\vec{Q} \cdot \vec{r}_1) = 1 + i\vec{Q} \cdot \vec{r}_1$, and (2) approximating $\psi_{\frac{1}{2}m_2}(\vec{r}_2)$ by an analytic function that is valid only for weakly bound wavefunctions. Neither of these approximations are made at present. Instead, we evaluate the inner integral of Eq. 2 exactly by using the expansion

$$\exp(i\vec{Q} \cdot \vec{r}_1) = 4\pi \sum_{\ell} i^{\ell} j_{\ell}(Qr_1) Y_{\ell m}^*(\hat{Q}) Y_{\ell m}(\hat{r}_1), \quad (3)$$

and then rotating all functions in the integrand to a coordinate system where $\vec{r}$ is along the $\hat{z}$ axis. The details are given elsewhere.³

The theory is presently being applied to light-ion projectiles, and some tentative results have been obtained for three different experimental reactions.⁴ In general, it is found that there is a noticeable change in shape between cross sections computed from the "local-energy approximation" in DWUCK and the "Recoil" theory presented here. We also find that although first-order recoil terms (i.e., terms arising from $\ell=1$

in Eq. (3) may be large, higher-order terms are comparatively much less important, and convergence is always easily obtained.

Our formalism can be generalized to multi-nucleon transfer reactions in a straight forward way, and we are presently investigating recoil effects in the three-neutron transfer reaction $^{13}\text{C}(^3\text{He}, ^6\text{He})^{10}\text{C}.$ ⁵

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Fig. 1.--Diagram showing coordinates needed for the stripping reaction $A(a,b)B$ where $a=b+n$ and $B=A+n$.

V. Nuclear Densities from the Electron Scattering. (Borysowicz together with J. Hetherington)

Following the previous work (PR **C7**, 2295(73)) an attempt is made to remove further model assumptions, while determining nuclear densities. We would like to use a complete (infinite) set of model states and to take explicitly into account the fact that the density is known to be positive defined.

VI. Cluster Model of ^{16}O and Non-Central Interactions in Nuclear Transitions. (Bertsch)

Two projects are being pursued with graduate students. B. Poon is investigating the model of ^{16}O as $\alpha + ^{12}\text{C}$, using a "realistic" α - α interaction and a model of ^{12}C as rigid triangle of α 's. We

hope to get reasonable energies and transition rates for the α -like states in ^{16}O . G. Hamilton is using the inelastic scattering code DWBA70, which includes tensor, LS, and exchange interactions, to find nuclear transitions sensitive to the noncentral parts of the interaction. We constructed a realistic interaction by fitting the G-matrix of the Reid potential, and hope to systemize the theory of transition rates induced by the noncentral parts of the interaction. Love¹ has found that LS force plays a large role in certain transitions, and Wagner of this laboratory has found that the tensor force gives most of the cross section in a particular ^{208}Pb transition.

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Reprints

1. Collective Contribution to Escape Width of Analog Resonances, N. Auerbach, and G. Bertsch.
2. Effects of Operator Renormalization on Inelastic Scattering Calculations in ^{40}Ca , H. McManus, M. Dworzecka and G. R. Hammerstein.
3. Isospin Impurities in Nuclei, George F. Bertsch and Aram Mekjian (Rutgers University).
4. Shell-Model Study of ^4He with Realistic Forces, P. P. Szydluk (State University College, Plattsburgh, New York 12901) and J. R. Borysowicz and R. F. Wagner.
5. Errors on Charge Densities Determined from Electron Scattering, J. Borysowicz and J. H. Hetherington.
6. Three-Neutron Pickup Reaction on ^{13}C , E. Kashy, W. Benenson, I. D. Proctor, P. Hauge and G. Bertsch.
7. Effects of Complex Coupling in Inelastic Cross Sections, Assymetries and Spin Flip in the DWA, R. H. Howell and G. R. Hammerstein, Nucl. Phys. A192, 651(1972).

VII. Core Polarization in Inelastic Scattering

(H. McManus, J. Borysowicz, G. Hammerstein)

Effects of core polarization on the inelastic scattering of protons on nuclei is studied in detail. Both microscopic and collective descriptions are used. In the microscopic treatment we use formalism of effective operators. The calculations of pp' scattering from Ca, Ti, Yt, Zr and Pb isotopes has been done.

Electroexcitation and (p,p') Cross-Section
to Giant Resonances--Microscopic Theory Calculations

G. R. Hammerstein, H. McManus and A. Moalem

Electromagnetic transitions rates, longitudinal (e,e') form factors and (p,p') cross-sections for the Giant Dipole Resonance (GDR) and Giant Quadrupole Resonance (GQR) in ^{40}Ca are being calculated using a microscopic description of these processes. Both the GDR and GQR have been strongly excited by electron¹ and hadron² scattering, and have been interpreted within the frame work of phenomenological collective models.³ These collective descriptions in their simplest form do not provide a link with nuclear structure. In addition another independent estimate of the cross-sections involved is important to supplement and confirm the interpretation made in previous studies.¹⁻³ The results for the GDR is summarized in the accompanying table.

Fig. 1.--S=0 transition densities for $J^\pi = 1^-$, T=1 states in ^{40}Ca .

Fig. 2.--S=1 transition densities for $J^\pi = 1^-$, T=1 states in ^{40}Ca .

The model space contains eight lp-lh excitations from the completely filled s-d shell to the f-p shell. The states which make up the resonance are admixtures of these lp-lh states and fall in the region 9.5 to 21.3 MeV; each is built primarily on one lp-lh pair (indicated in column 1

Fig. 3.--Form factors for $J^\pi = 1^-$, T=1 states in ^{40}Ca .

of the table) with the exception of the next to the highest (at 18.8 MeV) which is quite collective.

The transition densities to the two highest states are large, smooth and surface-peaked. For the 18.8 MeV state the S=0 density is three times stronger than the S=1, while for the 21.3 MeV state the reverse is true (see Figs. 1-2). The other states are rather weak and uninteresting for the present study except for the 16.5 MeV, whose S=0 density oscillates; a weak, surface-peaked first maximum goes over to a moderately strong second maximum located well inside the surface.

These features imply the following:

1) The 18.8 MeV state has about 90% of the electromagnetic transition strength and dominates the low momentum transfer electron scattering. The predicted value of the form factor agrees very well with the experimental values extracted for small momentum transfer.¹

2) At higher momentum the main resonance peak should shift to lower energy and decrease in magnitude due to the fall off of the 18.8 MeV state form factor and increasing sampling of the 16.5 MeV state form factor. (See Fig. 3). However a peak at higher excitation should appear much more strongly, corresponding to transverse excitation of the 21.3 MeV state. Some indications of this can be found in Ref. 4.

3) Inelastic proton scattering is dominated by the 21.3 MeV and 18.8 MeV states. Unlike low momentum transfer (e,e') scattering, the S=1 transition density yields an appreciable contribution to the (p,p') cross-section. Thus the resonance peak taken with protons should be

TABLE I.--Columns 1 and 2 list the main lp-lh configuration and excitation energy of each state. The B(E1) (in single particle units), and the square of form factors at two values of momentum transfer are given respectively in columns 3, 4, and 5. Columns 6 and 7 list the relative (p,p') cross-sections with RPA and TDA vectors provided by Kuo.⁵

	E	B(E1)	$ F(q=.51\text{fm}^{-1}) ^2$	$ F(q=1.03\text{fm}^{-1}) ^2$	$\sigma_i/\sigma_{\text{Eot.}}$	
	(MeV)	S:P:U		$\times 10^{-4}$	RPA	TDA
$d_{5/2}^{-1} f_{5/2}$	21.3	1.76	0.312×10^{-3}	.215	36	20
$d_{5/2}^{-1} f_{7/2}$	18.8	19.10	3.130×10^{-3}	.958	41	44
$d_{5/2}^{-1} p_{3/2}$	16.5	.005	0.047×10^{-3}	2.22	4	4
$s_{1/2}^{-1} p_{1/2}$	14.9	.003	0.077×10^{-5}	.053	6	5
$d_{3/2}^{-1} f_{5/2}$	14.1	.132	0.013×10^{-3}	.053	3	2
$s_{1/2}^{-1} p_{3/2}$	13.0	.076	0.028×10^{-3}	.049	2	2
$d_{3/2}^{-1} p_{1/2}$	12.1	.137	$.014 \times 10^{-3}$	.642	3	19
$d_{5/2}^{-1} p_{3/2}$	9.5	.005	$.003 \times 10^{-3}$	.041	5	4

somewhat higher in excitation energy than that observed in (e,e') scattering at low momentum transfer.

4) The calculated total cross-section with RPA or TDA vectors are the same. However, the relative strength of the various components are different.

5) The total integrated cross-section with RPA vectors is .6 mb. This value is to be compared with .3.3 mb obtained for the Jensen-Steinwedel model.³ Similar calculations for the GQR are in progress.

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Calculation of Elastic π^- - ^4He Scattering

in the Energy Region 50-300 MeV

K. E. Gilbert and J. H. Hetherington

The Los Alamos Meson Physics Facility (LAMPF) will soon make stable high flux pion beams available to nuclear physicists on a routine basis. Consequently, there has been considerable interest in recent years in the π -nucleus interaction. Attempts to calculate elastic π -nucleus scattering using the usual impulse approximation have had moderate success.^{1,2,3} However, there still exist serious discrepancies between the theoretical elastic cross sections and existing data. As a result, many workers have questioned the validity of the simple impulse approximation, but so far there has been no systematic theoretical study of effects such as fermi motion, nuclear binding and the proper transformation of the π -nucleon scattering amplitude from the π -nucleon c.m. frame to the π -nucleus c.m. frame.

We have calculated elastic scattering of negatively charged pions from ^4He in the energy region 50-300 MeV. We treat the problems of fermi motion, nuclear binding and the π -nucleon scattering amplitude transformation exactly in a simple independent particle model. We have found that nuclear binding effects are very small except in the region of the (3,3) resonance where the elastic amplitude is reduced by 15%. A simple approximation has been developed that adequately describes the binding effects in the resonance region. Fermi motion and the π -nucleon scattering amplitude transformation are treated using techniques borrowed from 3-body theory. Preliminary results indicate that a proper treatment of these two effects considerably improves agreement with experiment.

We are also investigating the sensitivity of elastic π -nucleus scattering to different off-shell parameterizations of the π -nucleon scattering amplitude. In the simple impulse approximation, the effective on-shell π -nucleon force is independent of the off-shell parameterization. However, if fermi motion is taken into account, different off-shell parameterizations give different on-shell π -nucleon effective forces. This can be an important factor since elastic π -nucleus scattering is very sensitive to the on-shell part of the effective force.

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L. E. Samuelson,^{**} R. R. Todd,^{***} W. H. Kelly, Wm. C. McHarris and F. M. Bernthal

We have been revising the 1961 Nuclear Data Sheets for the mass chains A=101, 102 and 104.

The revision for A=101 has been completed and now appears as Nuclear Data Sheets 10, 47 (1973). The abstract of this compilation appears elsewhere in this report.

The A=102 compilation, nearing completion, contains information from approximately 60 publications. There are seven known nuclei for A=102. Only the ground state is known for ^{102}Cd , while the levels in ^{102}Mo are known only from a study of the $^{100}\text{Mo}(t,p)^{102}\text{Mo}$ reaction.

The relative positions of the ground and isomeric states of ^{102}Tc are unknown. No γ -rays have been observed from the decay of 5.38-s ^{102}Tc . The situation in ^{102}Rh is somewhat better. The decays of both the 207-d and 2.9-y activities have been extensively studied; however the relative positions of the ground and isomeric states are not known.

The levels of ^{102}Ru have received extensive study via β -decay, γ -decay, Coulomb excitation and the $(\alpha,2n\gamma)$ reaction. The levels of ^{102}Pd are known primarily from decay scheme studies of the 7.7-m ^{102}Ag isomer and the 12.9-m ^{102}Ag ground state. The placement of the ^{102}Ag isomer is uncertain and depends on indirect evidence.

Our revision of the 1961 Nuclear Data Sheets for A=104 is nearing completion with a projected finishing date of November, 1973. Information is included on eleven members of the A=104 mass-chain extending from ^{104}Zr to ^{104}Tc .

A variety of experiments, in addition to those associated with β -decay, have been performed on the A=104 nuclei. The members of the neutron excess wing, extending from ^{104}Zr to ^{104}Tc , have been studied in fission-fragment experiments, while neutron deficient ^{104}Sn has been studied sparingly with (HI,xn) reactions. Coulomb excitation experiments have been performed on the two stable isobars, ^{104}Ru and ^{104}Pd . In addition, (d,t) and (p,α) reaction experiments and a (p,p') experiment have been done on ^{104}Pd . The former yielded nuclear structure information while the latter yielded energy level placement to complement ^{104}Ag β -decay studies. The odd-odd nucleus ^{104}Rh has been studied extensively using a variety of methods that are associated with neutron capture by ^{103}Rh . A (d,p) experiment has determined some energy levels of ^{104}Rh .

The low-lying levels in the even-even members of the A=104 mass chain seem best described using a vibrational theory. Both ^{104}Ru and ^{104}Pd exhibit E2-enhanced $\Delta J=1$ γ -transitions between 2-phonon and 1-phonon vibrational states. The

^{104}Rh nucleus exhibits a quite complex level structure with a myriad of low-lying states (at least 44 levels with $J \leq 3$ exist below 1 MeV of excitation). Because the A=104 nuclei can have many active valence nucleons and have several energetically accessible shell-model orbitals, the odd-odd members are expected to exhibit complex level structure.

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Calculations of the Matrix Elements Connecting Quasiparticle

States in Even-Even and Odd-Odd Deformed Nuclei

T. L. Khoo and G. F. Bertsch

Unexpectedly large matrix elements between proton and neutron two quasiparticle states have recently been observed in $^{176,178}\text{Hf}$.^{1,2} We are currently performing calculations to account for these non-zero off-diagonal matrix elements. The single-particle Nilsson wave functions are expanded in a harmonic oscillation basis and the matrix elements between two particle states are then evaluated in terms of two-body matrix elements.³ There are provisions in the computer program for using any two-body force, including tensor forces, which can be expressed in terms of matrix elements in the relative coordinates of the particles.

We have so far performed calculations for the $K=6^+$ states in ^{176}Hf using:

(a) a δ -interaction $H(\delta) = 4\pi g \left(\frac{V}{2\pi}\right)^{3/2} (1 - \alpha + \alpha \frac{V}{2\pi} \cdot \frac{g}{g_2})$, with the force strengths $4\pi g \left(\frac{V}{2\pi}\right)^{3/2} = 5.82 \text{ MeV}$ and $\alpha = 0.146$ selected to reproduce the binding energy and the splitting of the Gallagher-Moskowsky pairs in the neighboring odd-odd nuclei $^{174,176}\text{Lu}$;

and (b) interaction matrix elements derived from a realistic (Reid) two-body force, including tensor components, in the Bruekner theory.³

The calculated off-diagonal matrix elements for the $K=6^+$ states in ^{176}Hf are shown in Table 1. The agreement with experiment is fair. Results for two neighboring odd-odd nuclei are given in Table 2. Calculations on other odd-odd cases are being performed to ascertain the suitability of the realistic interaction presently employed and to determine an appropriate effective interaction. Other even-even cases will also be investigated.

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TABLE 1.--Off-diagonal matrix elements for $K=6^+$ states in ^{176}Hf .

Matrix Element ^{a)}	δ -intrn	Realistic Intrn	Expt.
$\langle \frac{7}{2}^+ \frac{5}{2}^- V_{np} \frac{5}{2}^+ \frac{7}{2}^- \rangle_{1-}$	388	163	
$\langle \frac{5}{2}^+ \frac{5}{2}^- V_{np} \frac{7}{2}^+ \frac{7}{2}^- \rangle_{0-}$	-268	-92	
$ \langle p_1 p_2 V n_1 n_2 \rangle_{K=6^+} $	299	115	209

a) $|\langle p_1 p_2 | V | R_1 n_2 \rangle| = |(U_{n_1} V_{n_2} V_{p_1} U_{p_2} + V_{n_1} U_{n_2} U_{p_1} V_{p_2})$
 $\times \langle n_1 \bar{p}_1 | V_{np} | \bar{n}_2 p_2 \rangle - (U_{n_1} V_{n_2} U_{p_1} V_{p_2} + V_{n_1} U_{n_2} V_{p_1} U_{p_2})$
 $\times \langle n_1 \bar{p}_2 | V_{np} | \bar{n}_2 p_1 \rangle|$ (Ref. 4). The U's and V's are the usual BCS amplitudes; the bar over a subscript denotes the time-reversed orbital.

TABLE 2a.--Splittings of Gallagher-Moszkowski pairs.

Nucleus	Configuration		K^π		δ	Splitting	
	Proton	Neutron	$\Sigma=0$	$\Sigma=1$		Realistic	Expt.
^{174}Lu	7/2(404)+	3/2(521)+	5 ⁻	2 ⁻	72	41	90
		1/2(521)+	3 ⁻	4 ⁻	77	121	80
		3/2(512)+	6 ⁻	1 ⁻	99	35	110
^{176}Lu	7/2(404)+	7/2(514)+	0 ⁻	7 ⁻	-395	147	-240
		1/2(510)+	4 ⁻	3 ⁻	89	117	118

TABLE 2b.--Contributions of n-p residual interaction to the binding energy.

Nucleus	ground state spin	n-p interaction		
		δ	Realistic	Expt.
^{174}Lu	1 ⁻	-432	-309	-421
^{176}Lu	3 ⁻	-367	-305	-473

The present calculations employ the Sussex matrix elements¹ to derive an effective interaction in the sd-shell model space. The relative harmonic oscillator matrix elements given in Ref. 1 are transformed from LS- to jj- coupling. The Brody-Mosinsky transformation has been performed for $b=1.7$ fm, presumably the appropriate oscillator length parameter for the (sd)-shell. The two-body matrix elements thus obtained are considered to correspond to the "bare" reaction matrix elements. In order to be used in a small model space they have to be corrected for space truncation effects. We have used perturbation theory up to second order to calculate 3p-1h, $2\hbar\omega$ and 4p-2h corrections. Energy denominators up to $2\hbar\omega$ excitations have been included. The energy denominators have the same oscillator size parameter as the one used in the calculation of the unperturbed matrix elements. We have taken the single-particle energies or one-body interactions from the experimental spectrum of ^{17}O . This approach has also been used by Kuo and Brown.² The calculation is thus performed without free parameters.

The two-body matrix elements obtained with the above described method are summarized in Table I. The different columns of Table I show the unperturbed interaction, V , the different perturbative corrections, V_{3p-1h} , V_{4p-2h} , V_{2p} , and the effective interaction, V_{eff} , respectively. The effective interaction, V_{eff} , is taken as the sum of the unperturbed interaction and the different corrections.

Excitation energies in $A=18-22$ nuclei have been calculated in full 0s-1d model space by using the present two-body matrix elements (and the experimental ^{17}O single particle binding energies). The construction of many-body Hamiltonians and diagonalization of the energy matrices has been performed with the codes described by French, Halbert, McGrory and Wong.³

The spectra of ^{18}F and ^{18}O are shown in Figs. 1 and 2. The energy scales used in Figs. 1 and 2 indicate binding energy with respect to ^{16}O . The agreement between experiment and theory is good except for the $J^{\pi}T=1^{+}0$ ground state of ^{18}F which is predicted somewhat too high. The calculated and experimental spectra for $A=19-22$ nuclei (not shown) are all well predicted. The calculated spectra are very similar to those obtained with the Kuo-Brown interaction although a different procedure has been followed. (A detailed comparison has been left out since the Kuo-Brown matrix elements contained some small errors⁴).

In Fig. 3 we have plotted the ground state binding energies for $A=19-22$ nuclei. For each mass number we have normalized the spectrum to the binding energy of the ground state with lowest isospin. Included are also some levels close to the experimental (or predicted) ground states. It can be concluded from Fig. 4 that for most cases the predicted isospin splitting is somewhat smaller than the observed one. Larger discrepancies are found for the binding energies of ^{21}O and ^{22}O .⁵ In general, we also found that the absolute ground state binding energies turned out to be somewhat too large (interaction too attractive), indicating that better agreement would have been obtained with a somewhat smaller oscillator constant. However, it is not clear whether a physically reasonable size parameter will accomplish such an agreement. Furthermore, we find that the inclusion of the 4p-2h corrections greatly improves the isospin splitting. Higher order corrections might remove the remaining discrepancies provided the present model space is reasonable.

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TABLE 1.--The two-body matrix elements $\langle ab; JT|V|cd; JT \rangle$, for the (1s0d)-shell together with the perturbative corrections. The numbers abcd represent $2J_a$, $2J_b$, $2J_c$ and $2J_d$, respectively. All matrix elements are calculated for the oscillator length parameter $b=1.7$ fm and are expressed in MeV.

a	b	c	d	J	T	V	V _{3plh}	V _{4p-2h}	V _{2p}	V _{eff}
5	5	5	5	1	0	-0.113	-0.314	-0.134	-0.645	-1.206
				3	0	-0.769	+0.097	-0.033	-0.187	-0.892
				5	0	-2.990	-0.149	0	-0.388	-3.527
				0	1	-1.390	-0.587	-0.301	-0.298	-2.576
				2	1	-1.147	+0.099	-0.055	-0.123	-1.226
				4	1	-0.529	+0.336	0	-0.058	-0.251
1	1	1	1	1	0	-2.883	+0.159	-0.075	-0.440	-3.239
				0	1	-2.386	+0.244	-0.006	-0.160	-2.308
3	3	3	3	1	0	-0.043	-0.147	-0.047	-0.549	-0.786
				3	0	-1.861	+0.041	-0.108	-0.360	-2.288
				0	1	-0.034	-0.219	-0.228	-0.302	-0.783
				2	1	-0.297	+0.374	-0.039	-0.063	-0.025
5	1	5	1	2	0	-0.369	+0.060	-0.001	-0.400	-0.710
				3	0	-2.879	-0.285	-0.035	-0.500	-3.699
				2	3	-1.280	-0.027	-0.012	-0.098	-1.417
				3	1	-0.429	+0.455	0	-0.026	-0.000
5	3	5	3	1	0	-3.505	+0.109	-0.849	-0.529	-4.774
				2	0	-3.210	+0.064	-0.542	-0.429	-4.117
				3	0	-1.005	+0.241	-0.120	-0.239	-1.123
				4	0	-3.771	+0.199	0	-0.761	-4.333
				1	1	-0.551	+0.209	-0.003	-0.077	-0.422
				2	1	-0.465	+0.217	-0.025	-0.110	-0.383
				3	1	-0.555	+0.483	0	-0.026	-0.098
				4	1	-2.143	+0.433	0	-0.169	-1.879
1	3	1	3	1	0	-2.126	+0.045	-0.172	-0.386	-2.639
				2	0	-1.345	+0.212	-0.001	-0.522	-1.656
				1	1	-0.452	+0.528	-0.000	-0.015	+0.061
				2	1	-0.655	+0.369	-0.010	-0.125	-0.421
1	1	5	5	1	0	-0.246	-0.169	-0.014	-0.177	-0.606
				0	1	-0.768	-0.207	-0.038	-0.081	-1.904
3	3	5	5	1	0	+2.259	-0.558	-0.068	+0.180	+1.813
				3	0	+0.286	+0.177	-0.059	+0.050	+0.454
				0	1	-3.323	-0.409	-0.179	+0.010	-3.901
				2	1	-0.644	-0.196	-0.032	-0.023	-0.895
5	1	5	5	3	0	-1.005	-0.201	-0.034	-0.226	-1.466
				2	1	-0.601	-0.204	-0.025	-0.070	-0.900
5	3	5	5	1	0	+2.531	+0.004	+0.230	+0.215	+2.980
				3	0	+1.475	+0.220	+0.062	+0.097	+1.854
				2	1	-0.386	+0.049	-0.035	+0.017	-0.355
				4	1	-1.076	-0.252	0	-0.072	-1.400
1	3	5	5	1	0	-0.034	-0.299	+0.088	-0.200	-0.445
				2	1	-0.566	-0.242	-0.013	-0.054	-0.875
3	3	1	1	1	0	-0.408	+0.149	-0.022	+0.119	-0.162
				0	1	-0.627	-0.119	-0.032	-0.065	-0.843
5	3	1	1	1	0	+1.515	-0.191	+0.085	+0.213	+1.622
1	3	1	1	1	0	-0.653	+0.301	+0.090	-0.198	-0.460
5	1	3	3	3	0	+0.105	-0.066	-0.062	-0.110	+0.133
				2	1	-0.804	+0.078	-0.011	-0.037	-0.774
5	3	3	3	1	0	-0.253	+0.203	+0.065	-0.208	-0.193
				3	0	+1.477	+0.292	+0.114	+0.113	+1.996
				2	1	-0.834	-0.153	-0.026	-0.035	-1.048
1	3	3	3	1	0	+0.453	-0.071	+0.043	+0.250	+0.675
				2	1	-0.010	-0.094	-0.020	-0.060	-0.184
5	3	5	1	2	0	-1.243	+0.017	-0.018	-0.281	-1.525
				3	0	+0.809	+0.007	+0.065	+0.098	+0.979
				2	1	-0.161	+0.059	-0.016	-0.065	-0.183
				3	1	-0.047	-0.002	0	-0.011	-0.060
1	3	5	1	2	0	-2.392	+0.159	-0.001	-0.296	-2.530
				2	1	-1.531	-0.010	-0.005	-0.073	-1.619
1	3	5	3	1	0	-0.872	-0.012	-0.321	-0.005	-1.210
				2	0	-1.522	+0.303	-0.022	-0.345	-1.586
				1	1	-0.131	+0.040	+0.000	-0.003	-0.094
				2	1	-0.724	-0.050	-0.012	-0.014	-0.800

Shell Model Predictions for the Decay Schemes of

"Exotic" Oxygen and Fluorine Isotopes

W. A. Lanford and B. H. Wildenthal

There is presently great interest in so called "exotic" light nuclei, that is nuclei far from the line of β -stability. It is now well established that the shell model calculations properly predict most of the features of light (s-d) shell nuclei.¹ In particular, the model predicts spin, parities and excitation energies very well. Recent work² has shown that the β -decay schemes can also be successfully predicted. It now seems appropriate to extend the established calculations to nuclei far from the line of β -stability and predict the spectra and β -decay schemes of these nuclei. It is already clear from the experience of the past year that if reasonably good predictions can be made for half-lives and β -decay branching ratios the experimentalist looking for new isotopes can tune their experimental equipment to take advantage of these predictions.

We have calculated wave functions for the oxygen and fluorine isotopes A=18-24. The β -decay half-lives and log (ft)-values have been predicted for the oxygen isotopes. At present we do not have calculations for the heavy Ne isotopes, so predictions of the β -decays of the fluorine isotopes cannot be made.

The calculations assume these nuclides can be described by A-16 nucleons distributed over the $d_{5/2}$, $s_{1/2}$ and $d_{3/2}$ shell model orbital. These nucleons can occupy all the Pauli allowed configurations in this shell. The interaction between these nucleons is the same one which was used to describe the nuclei near β -stability with A=18-22.

The predicted excitation energies and β -decay schemes for this nuclei are shown in Fig. 1. The A=19 and 20 decay schemes are included here to show the quality of agreement between the calculation and experiment for cases where experimental information exists. Notice that the predicted excitation energies and β -decay log (ft) values are in excellent agreement.

Of the decay schemes for which there is no present experimental information, perhaps the most interesting are those for A=22 and A=24. Notice that for both these cases there is predicted to be a large gap between the ground state (0^+) and the first excited state (2^+). ^{22}O corresponds to closing the $d_{5/2}$ shell for neutrons; ^{24}O corresponds to closing the $s_{1/2}$ shell. The mass of ^{22}O has been recently reported by a group at Dubna³ using the $^{232}\text{Th}(^{22}\text{Ne}, ^{22}\text{O})$ reaction. To measure the mass of ^{22}O it is necessary to extrapolate the continuous spectrum of ^{22}O particles down many MeV to the max energy of the spectrum. However if the first excited state of ^{22}O is at 3.22 MeV, the mass they deduced may be the mass

as measured to the region of the spectrum where the density of states is reasonably high, i.e. several MeV above the ground state.

By using the calculated log (ft) values, half-lives for this isotope can be predicted. These half-life predictions are given in Table I along with the measured value where available.

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TABLE I.--Predicted and Experimental Half-Lives of the Oxygen and Fluorine Isotopes.

Isotope	Calc. $t_{1/2}$	expt. $t_{1/2}$
F^{17}	56s	66s
F^{18}	70m	110m
O^{19}	32s	29s
O^{20}	19s	14s
F^{20}	9.1s	11.s
O^{21}	1.2s	--
F^{21}	4.5s	4.5s
O^{22}	.15s	--
F^{22}	3.2s	4.0s
O^{23}	.11s	
O^{24}	.046s

FIGURE CAPTION.--The calculated level schemes and β -decay transition rates for the oxygen and fluorine isotopes. The even nuclei have levels labeled by their spins (J); the odd nuclei have levels indicated by $2J$.

Many successful shell model calculations exist up to date. Most of them, however, have been performed within one particular major shell. It seems to be less rewarding to perform calculations for nuclei in mass regions where the nucleon-nucleon interaction crosses a major shell. The phenomenological interactions are less known; the deduction of realistic interactions becomes more difficult due to ambiguities in determining the proper energy denominators. In addition there is the problem of spurious states.

The present investigation has been performed in order to try to study the interaction between nucleons in the upper part of the (sd)-shell and the lower part of the (fp)-shell. The calculations have been performed for K and Ar nuclei in different configuration spaces and with different two-body Hamiltonians.

For most spectra the configuration space includes up to two holes in $d_{5/2}$, $s_{1/2}$ and $d_{3/2}$ orbits, and no more than two particles in the $p_{3/2}$ shell. In some spectra we have also included 4-hole configurations.

Three different Hamiltonians have been used:

1. A realistic interaction, deduced from the Sussex matrix elements and corrected for space truncation effects. Perturbative corrections up to $2\hbar\omega$ have been included in 3p-1h, 4p-2h and 2p diagrams.

2. The modified surface delta interaction (MSDI).

3. The above mentioned realistic interaction modified such that the $d_{3/2}$ - $f_{7/2}$ diagonal two-body matrix elements are treated as free parameters. There are altogether 258 of those two-body matrix elements. Eight of them have been fitted to 48 energy levels in A=38-47 nuclei.

We have calculated energy levels, spectroscopic factor for one-nucleon transfer reactions, magnetic moments, M1 transition strengths and log ft values for β -decay for A=38-47 nuclei. Most observables are in reasonably good agreement with predicted values. Some of the results are displayed in Figs. 1-3. In Fig. 1 the experimental spectrum of ^{42}K is compared with the predicted values from the three different two-body interactions. The same quantities for ^{46}K are shown in Fig. 2. The calculated spectroscopic factors for some (d,p)-reactions are compared with experimental results in Fig. 3.

Generally, the realistic interaction and the df-free parameter interaction are in better agreement than the MSDI. The MSDI seems to have trouble when a somewhat larger range of nuclei has to be covered with the same set of parameters.

Many results are as yet preliminary.

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Fig. 1.--The experimental spectrum of ^{42}K as compared with three different predictions (see text).

Fig. 2.--The experimental spectrum of ^{46}K as compared with three different predictions (see text).

Fig. 3.--Spectroscopic factors for the $^{38}\text{Ar}(d,p)^{39}\text{Ar}$ ($\ell=1$ and $\ell=3$), $^{40}\text{Ar}(d,p)^{41}\text{Ar}$ ($\ell=3$) and $^{41}\text{K}(p,d)^{42}\text{K}$ ($\ell=3$) reactions. All predictions have been made with the realistic interaction.

Calculations are presently underway to find an effective interaction and basis space for nuclei in the A=52-55 mass region. Limitations in the computer code MULTISHELL¹ allow us to have at most four particles (or holes) in the $f_{7/2}$ shell, and we are therefore forced to carry out all of our calculations in hole formalism.

Several truncated spaces have been considered, and in each case we have determined the effective two-body matrix elements (2BME's) by performing a least-squares fitting to 61 experimental levels in the region. Originally, we included all basis configurations of up to four holes in the $f_{7/2}$ shell and all possible particle excitations to the $p_{3/2}$ orbit. However it was found that the number of basis states for such a truncated space was very small for the A=52 nuclei (5 or less for each JT pair), and increased rapidly with increasing A, being usually greater than 100 for each JT pair in the A=55 nuclei. Therefore, we imposed a further restriction on the active space by allowing not more than one particle in the $p_{3/2}$ shell. Table I displays the optimum 2BME's that were obtained from a six-parameter MSDI interaction (four potential parameters plus two single-hole energies), and a 21-parameter fitting where we allowed all relevant 2BME's to vary. The 2BME's that are left blank in the second fitting were not determined because of the limitation of only one particle in the $p_{3/2}$ shell. The r.m.s. deviation between experimental and theoretical levels was 0.55 MeV for the MSDI interaction, and this number was reduced to 0.33 MeV for the 21-parameter case.

In order to see how good our results were, we performed a third calculation on the same nuclei using only the $f_{7/2}$ shell configurations in our active space. It was found that several of the experimental levels well-described in our expanded $f_{7/2}$ - $p_{3/2}$ space could not be described as simple $(f_{7/2})^n$ configurations. The r.m.s. deviation was also much higher. On the other hand, we have also found that a few of the experimental levels have definite $p_{1/2}$ or $f_{5/2}$ character, and so we are presently expanding our fitting procedure to allow at least one-particle excitation into both of these shells as well.

TABLE I.--Effective 2BME's for the $f_{7/2}$ - $p_{3/2}$ basis. The quantum numbers for the 2BME's are given in the first column, and the numbers abcd refer to $2J_a$, $2J_b$, $2J_c$ and $2J_d$ respectively. The numerical values of the 2BME's are then displayed in the second and third columns for the two fittings discussed in the text. The two single-hole energies, which were also treated as parameters, are given at the end of the table.

2BME's abcd-JT	6 PARAM MSDI	21 PARAM
7777-01	-2.561	-3.202
10	-2.944	-2.590
21	-0.853	-1.933
30	-2.459	-2.073
41	-0.584	-0.881
50	-2.437	-2.311
61	-0.449	-0.403
70	-2.739	-3.515
7773-21	-0.784	-0.68
30	-0.533	-1.05
41	-0.302	+0.07
50	-0.686	-1.02
7733-01	-1.585	-
10	-0.682	-
21	-0.347	-
30	-0.454	-
7333-20	-2.625	-1.813
21	-1.474	-2.391
30	-2.690	-1.994
31	-0.321	-1.527
40	-2.083	-2.096
41	-0.673	-0.592
50	-3.193	-2.421
51	-0.321	+0.012
7333-21	-0.510	-
30	-0.581	-
3333-01	-1.441	-
10	-2.551	-
21	-0.545	-
30	-2.551	-
S.H.E. ϵ_7	26.390	27.907
ϵ_3	24.070	23.907

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Recent electron and proton inelastic scattering studies^{1,2} have given evidence of a localization of the E2 strength in many nuclei at an excitation comparable to the giant dipole resonance (GDR) region. If the E2 strength is localized in a small region of excitation it should show up in inelastic ^3He scattering since this process favors collective states. However, the existing ^3He inelastic scattering data is very sparse and conflicting. One study³ showed an enhanced region near the GDR on two heavy nuclei, the other⁴ showed no enhancement in light and medium weight nuclei.

We undertook the study of inelastic ^3He scattering with the idea of checking very carefully whether the continuum region is in fact enhanced and if so whether the excitation can be proven to be E2. We used 70 MeV ^3He -particles and detected them in both the spectrograph (using a wire counter) and in a scattering chamber with silicon detectors. We studied 12 targets ranging throughout the periodic table from ^{16}O to ^{209}Bi . In every case we observed the enhancement of the continuum expected for the giant quadrupole resonance. Figure 1 shows some of the spectra obtained at 22° . We were unable to prove positively the E2 nature of the excitation. Angular distributions at this energy appear to be forward peaked and independent of L-transfer. Some results have been published.⁵ The main conclusions can be stated as follows: (1) All spectra exhibit qualitatively the same characteristics as were observed in (e,e') and (p,p'). The width of the observed structure is considerably broader than the GDR and the main strength lies 2-3 MeV below it. (2) For lighter nuclei $A \leq 58$ the spectra exhibit a considerable amount of fine structure. For heavier nuclei the enhancement consists of a smooth single asymmetric bump. (3) The energy centroid of the structure appears to follow the rule predicted by the hydrodynamic model ($E \sim 60A^{-1/3}$) for an E2 state. (4) The cross section is A dependent increasing with increasing A. For heavier elements the magnitude exhausts the E2 sum rule limit. For light elements it is not possible to estimate the magnitude properly since the yield is spread out over so much of the continuum.

The fine structure of the giant resonance region in light nuclei is particularly interesting, and it is now the subject of further studies. The details of the structure can be compared with results from a variety of photo-nuclear and electro-excitation studies. ^{16}O is a very good example of this. The E2 strength observed in $^{12}\text{C}(\alpha, \gamma)$ shows up as strong peaks in the data as can be seen in Fig. 2. Many of the E1 states show up as well but with less

strength. It remains now to reproduce the structure with a calculation that takes into account both the GQR and the GDR.

Experimentally, we plan to study a similar excitation energy region in some of the same nuclei with 50 MeV α -particles to examine the isospin of the enhanced regions. If the proposed new state is of an isoscalar type it should be excited more strongly relative to the isovector GDR. An experiment investigating proton decays of the GQR in ^{40}Ca is already in progress.

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Fig. 1.

FIGURE 1.--Spectra from the $(^3\text{He}, ^3\text{He}')$ reaction on ^{27}Al , ^{40}Ca , ^{58}Ni , ^{90}Zr , ^{122}Sn , ^{208}Pb , and ^{209}Bi at 20° . The arrow indicates the position of the GDR as determined from photonuclear experiments. The broad peak near channel 1000 is due to elastic scattering from hydrogen.

Fig. 2.

FIGURE 2.--Spectra from the $^{16}\text{O}(^3\text{He}, ^3\text{He}')^{16}\text{O}$ reaction. The position of known $J^\pi=1^-, 2^+$ states in the GDR region are also indicated.

The $^{40}\text{Ca}(p,p')^{40}\text{Ca}$ Reaction at 35 MeV

J. Nolen, A. Moalem, T. Udagawa,* R. Gleitsmann, G. Hamilton, and H. McManus

A high resolution study of the $^{40}\text{Ca}(p,p')^{40}\text{Ca}$ reaction is in progress. This process was studied previously in this laboratory by Gruhn, *et al.*¹ but was limited to a resolution of 30 keV and several pairs of levels could not be resolved. These unresolved levels are the origin of our interest in this matter, and our objective is to obtain a reasonably complete picture of their nuclear structure. Also we attempt to solve some of the discrepancies noted in Ref. 1 between microscopic theory analyses and experiment. The new data, being recorded on nuclear emulsions in the split-pole magnetic spectrograph, are now in preliminary stages of analysis. A sample spectrum obtained at a scattering angle of 15° is shown in the figure. The experimental resolution is 4-4.5 keV, FWHM, which is adequate to resolve most of the states of interest up to about 10 MeV excitation energy.

The primary interest in the previous (p,p') calculation was in the states which were primarily of the $f_{7/2}$ -particle, $d_{3/2}$ -hole configuration. These states have spins 2^- , 3^- , 4^- , 5^- and isospin 0 and 1. The largest discrepancy in this analysis, which was in the 4^- T=0 and T=1 states is now seen to be at least partially due to contributions from previously unresolved nearby levels. The remaining discrepancy of about a factor of five in the 4^- T=0 and a factor of two in the 4^- T=1 level can possibly be removed by a modification of the tensor component of the nucleon-nucleon force used in the calculation.²

The role of multiple excitation is also being investigated for the 0_2^+ (3.35 MeV), 1_1^- (5.90 MeV), 2_1^- (6.03 MeV), 3_2^- (6.29 MeV) and 4_1^- (5.62 MeV) states. Simple coupling schemes which include the first excited 2_1^+ state and first octupole 3_1^- states are considered, i.e.,

$$0_1^+ \xrightarrow{0.1} 2_1^+ \xrightarrow{0.3} 0_2^+$$

and

$$0_1^+ \xrightarrow[0.3]{0.1} 2_1^+ \xrightarrow[0.1]{0.3} 3_1^- \xrightarrow{0.3} I^- \quad (I=1,2,3,4)$$

The deformation parameters which characterize the transition strengths are indicated and have been taken from Ref. 3. Preliminary results show that multiple excitation is important for inelastic excitation of the 0_2^+ and 1_1^- levels (about 50% and 100% of the experimental cross-sections respectively). The calculations are being performed with the computer code JUPITOR.⁴

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With the recent experimental improvements in energy resolution, many new and interesting levels can now be studied which were previously inaccessible at intermediate energies. Using ultra-high resolution proton inelastic scattering we are currently investigating the nuclei ^{207}Pb , ^{208}Pb , and ^{209}Bi . This study should allow extensive testing and possibly extension of the considerable theoretical work already carried out in this mass region.

Data has been taken on nuclear emulsions with a resolution of 5 to 8 keV (FWHM) at 35 MeV. The Michigan State University spectrometer-cyclotron high resolution system and an on-line resolution monitoring technique¹ were used. Angular distributions were taken from 10 to 100 degrees. Numerous levels were observed up to an excitation energy of 8 MeV and discrete states were seen up to about 7.5 MeV excitation. A typical spectrum is shown in Fig. 1. Data of 45 to 80 keV (FWHM) resolution was taken with a position sensitive proportional counter in the spectrometer to study the collective states with improved statistics and to normalize the plate data. Because of the necessity to scan in fine steps the plate scanning has proven to be a severe time limitation and thus far only the ^{208}Pb data is near completion.

Every spectrum recorded is dominated by the highly excited octupole level at 2.615 MeV of excitation as well as the first excited 2^+ , 4^+ , 5^- , and 6^+ levels. The preliminary results of the plate data analysis is shown in Fig. 2 for some of these states. The cross section in mb/sr is plotted against the center-of-momentum scattering angle. The solid line is a collective model fit to the data using the Becchetti-Greenlees optical model parameters.² The reduced transition probabilities obtained from these fits are in good agreement with values previously measured in low energy experiments but are consistently larger than the values determined in a 61 MeV (p,p') experiment.³ This discrepancy is probably not due to exchange phenomena since the optical model parameters used in the collective model implicitly account for some exchange effects.

Microscopic model predictions for inelastic cross sections can be obtained without knowledge of the wave functions provided the nuclear transition density is known. The wealth of (e,e') data for ^{208}Pb provides this information for a number of different multipolarity transitions. Thus, without ambiguities in the nuclear motion a critical study of the nucleon-nucleon interaction can be made.

The dashed curves shown in Fig. 2 present microscopic model calculations using the Random Phase Approximation wave functions of Gillet, *et al.*⁴ Both central and non-central forces were used and exchange was treated exactly in the calculations using the code DWBA70 of Schaeffer and Raynal. For each state these predictions underestimate the data. This is consistent with the anomalously small electromagnetic transition rates obtained with these wave functions. However, in the microscopic model poor agreement between the experimental and theoretical electromagnetic properties does not imply that the measured and predicted cross sections will be in poor agreement. The converse is also true. Hence, one "unique" aspect of the many wave functions for ^{208}Pb can be examined.

The third figure illustrates cross sections for some of the non-normal parity states which were observed. Spin and parity assignments were adopted from published results. The calculations were performed with the wave functions of True, *et al.*⁵ and with central (dashed curves) and with central plus non-central forces (solid curves). For each case, the curves labeled D or D+E correspond to the direct or the direct-plus-exchange calculations, respectively. For the normal parity transitions the introduction of non-central forces provided little enhancement of the pure central result, perhaps 10 to 20 per cent. For the non-normal parity states the non-central forces are apparently the primary mediators of the excitations. The two 4^- states are interesting since each wave function is believed to be well known and is probably either a proton or a neutron configuration. Different portions of the non-central effective interaction can thus be probed. In each case the data is underestimated and the tensor force makes a much greater contribution to the cross section than the $L \cdot S$ force. Some knowledge of the small $T=0$ portion of the tensor interaction may be gained by this study. Coupled Channels calculations indicate that the two step processes via the highly excited 3^- or 2^+ levels is not important.

With this study of ^{208}Pb as a basis the ^{207}Pb and ^{209}Bi data should allow extension of the weak coupling and core polarization models to unstudied regions of excitation energy and multipolarity in the mass region.

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Figure 1

$d\sigma/d\Omega \text{ (mb/sr)}$

Figure 2

Figure 3

Collective States of Actinide Nuclei

from Inelastic Proton Scattering*

J. S. Boyno, J. A. Nolen and Wm. C. McHarris

We have initiated a program to study the collective states of actinide nuclei via inelastic proton scattering. Previous work in this field,^{1,2} done with 18 MeV deuterons, has shown that ground rotational bands, β - and γ -vibrations, and octupole vibrational states are all strongly excited in inelastic scattering, and that meaningful information about level energies, spins and parities can be extracted from such measurements. In addition, it has been shown^{1,2} that $B(E\lambda)$ for the excitation of strong states can be obtained from cross section measurements.

Using the dispersion matched magnetic spectrograph system with the "resolution meter"³ system, we should be able to produce very high resolution spectra with good peak intensities.

The first run in this program was performed with a thin ($<100 \mu\text{g}/\text{cm}^2$) ^{238}U target bombarded with 35 MeV protons from the MSU cyclotron. The resolution obtained was poor, ~ 25 keV FWHM. This was due to several experimental problems which developed in the use of the "resolution meter". We believe we have corrected these problems and we expect to greatly improve the resolution of these reactions in subsequent runs.

* Supported by USAEC and NSF.

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A Search for $T=T_z+2$ Resonances in Heavy Nuclei

P. A. Smith, G. M. Crawley, T. L. Khoo and P. S. Miller

Prior to August, 1971, when Hoffmann, et al.¹ reported the observation of the $T=23$ state in ^{210}Po , double analog states, i.e. states with $T=T_z+2$, had not been seen except in light nuclei. To date no other double analog states have been found in heavy nuclei.

In light nuclei states with $T=T_z+2$ can be excited by direct reactions such as (p,t) . However, the ratio of the cross sections for $T=T_z+2$ states to $T=T_z$ states in the same nucleus goes approximately as T^{-2} .² Thus in heavy nuclei, these direct reactions are greatly inhibited. It is more profitable to look for these states where T is large by isospin forbidden reactions such as $p+^{209}\text{Bi}$, where the statistical factors are more favorable. This reaction is made possible by isospin mixing with the high density of nearby $T=T_z+1$ states.

Hoffman, et al., recognized that the double analog state will preferentially decay in an allowed manner by the emission of two protons, as shown in the figure for ^{208}Bi . This suggests that one should look for enhancement in the summed coincidence spectrum as the bombarding energy is moved across the resonant energy.

In the previous experiment two E-veto telescopes were set up opposing each other and perpendicular to the beam. Enhancement in the summed coincidence spectrum was observed in the $E_1+E_2=24$ MeV energy region.

The reaction $p+^{209}\text{Bi}$ to the $T=23$ state in ^{210}Po may not be the most favorable case because of the spin statistical factor. The reaction $p+^{207}\text{Pb}$ to the double analog of ^{208}Tl in ^{208}Bi might be more favorable since the ground state spin of ^{207}Pb is $1/2$ as compared to $9/2$ for ^{209}Bi . The reactions $^3\text{He} + ^{205}\text{Tl}$ and $^3\text{He} + ^{207}\text{Pb}$ to these same states might be even easier to observe since the ratio of true proton coincidences to chance coincidences should be larger.

We have studied the reaction $^{207}\text{Pb}(p,2p)$ by looking for coincident protons in two ΔE -E-veto telescopes. This arrangement allows us to identify the protons, which was not done previously, and to eliminate the elastic protons from the chance spectrum. The number of elastically scattered protons is also kept to a minimum by placing each telescope 105° from the beam. The chances with this arrangement come primarily from the (p,np) reaction.

To check that the system is working correctly p - p scattering is observed using a Kapton³ target. Time resolution of 3 ns. has been obtained.

No enhancement has been observed as yet. We set an upper limit on the cross section of $2\mu\text{b}/\text{sr}$.² This upper limit is approximately 10 times

larger than the cross section found by Hoffman, et al. Since the spin statistics are approximately forty times more favorable in our case, it is puzzling that we have not observed the resonance. More sensitivity is needed.

The telescope requirement prevents us from obtaining larger solid angles with solid state detectors. To overcome this difficulty we are building and testing two scintillator telescopes.

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A. Equipment Improvements

During the past year we have rearranged our neutron time-of-flight apparatus in order to cover a larger angular range with a longer flight path. At present we can go from 10° to 160° with a 5 meter flight path. Longer flight paths are available over a restricted angular range. A separate target station, followed by a 20° bending magnet, enables us to observe neutrons at 0° .

While doubling the neutron flight path improves our energy resolution by about a factor of two, it also reduces the solid angle by a factor of four. In order to compensate for this loss of overall efficiency, we have assembled a new neutron detector which has $4\frac{1}{2}$ times as much liquid scintillator as the old detector. The new detector consists of a 3 inch diameter by $1\frac{1}{2}$ inch thick glass encapsulated NE213 liquid scintillator coupled to a RCA 8575 photomultiplier tube via a short lucite light pipe. In tests with ^{60}Co gamma-rays, we deduced a time resolution of 0.3 nsec FWHM, for the new detector. The time resolution of the system while taking data is usually between 0.4 and 0.5 nsec, as measured by the width of the target gamma-ray peak.

A major improvement in operating efficiency has been obtained by motorizing the detector assembly so that the neutron detection angle may be controlled from the data room. The detector is housed inside a steel naval gun barrel which is surrounded by boxes full of water. The entire detector assembly sits on a motorized air pad so that it may be floated and moved easily about the experimental area. The assembly is constrained to move in a fixed-radius arc about the target position by a 5 inch diameter aluminum pipe that pivots above the target. The signal and power cables for the detector are run through the pipe in order to avoid having cables on the floor that might impede the movement of the detector assembly. The gun barrel is constrained to point at the target by a pair of steel guy wires that also pivot above the target. The target angle and gun barrel orientation is monitored by TV cameras mounted on the aluminum pipe and the gun barrel, respectively. The scattering angle may be measured to better than 0.1° .

In the past, a major source of background has been due to small angle scattered beam striking the beam pipe after the target. This background has been reduced by about a factor of ten by placing a quadrupole triplet immediately after the target box in order to refocus the beam into a well shielded beam dump 8 meters from the target. In addition, the beam pipe between the target and beam dump has been electrically isolated so that the beam which does not reach the beam dump can

be integrated. Thus the total integrated charge can be measured to an accuracy of better than a few per cent, independent of the target thickness.

B. (p,n) Isobaric Analog State Data

We have embarked on a program to measure differential cross sections of (p,n) reactions exciting the isobaric analog state of the target ground state. The objectives of the program are to determine the isospin dependent part of the nucleon-nucleon effective interaction, V_T , and to determine the isospin-dependent part of the nucleon-nucleus optical potential. The targets chosen for this program are ^{48}Ca , ^{90}Zr , ^{120}Sn , and ^{208}Pb . These targets were chosen for their large neutron excess, their simple ground state shell model configurations, and because they span a large mass range. In order to study the energy dependence of the isospin-dependent interaction, data have been taken at proton bombarding energies of 25, 35, and 45 MeV. Figures 1 and 2 show typical neutron time-of-flight spectra obtained at 10° and 130° . The neutron energy resolution of the analog peaks vary from about 400 keV for ^{48}Ca to about 250 keV for ^{120}Sn . Low energy neutrons from previous beam bursts were eliminated by setting a sufficiently high energy threshold on the photomultiplier light output signal. The unlabeled arrows in the figures indicate the position of the target gamma-rays, which appear in the neutron spectra even though they are reduced by about a factor of 200 by our neutron-gamma pulse shape discriminator system. Figures 3 and 4 show the 25 and 35 MeV data. The 45 MeV data are not yet complete. The error bars indicated in the figures represent the uncertainties in the relative cross sections only. The uncertainty in the absolute cross sections is estimated to be about 10 to 20 per cent. Note that all of the data have a reasonable amount of structure, especially at back angles.

C. Macroscopic Analysis of the Data

We are in the process of trying to fit our 25 and 35 MeV data with Lane-model-consistent¹ DWBA macroscopic calculations. In the Lane model, the nucleon-nucleus optical potential may be written as

$$U(r) = -U_0(r) + 4(\vec{\tau} \cdot \vec{T})/A U_1(r) + (\frac{1}{2} - t_3) U_C(r)$$

where U_0 , U_1 , and U_C are the isospin-independent, isospin-dependent, and Coulomb potentials, respectively; $\vec{\tau}$ and $\vec{T}$ are the isospin of the projectile and target, respectively; and A is the atomic number of the target nucleus. If the isospin of the target ground state has its minimum allowed value, then $T = T_z = \frac{1}{2}(N-Z)$ and the potentials for proton, neutron, and quasielastic

Fig. 1.--Neutron time-of-flight spectra obtained at 10° with $E_p = 25$ MeV.

Fig. 2.--Neutron time-of-flight spectra obtained at 130° with $E_p = 25$ MeV.

(p,n) scattering are

$$U_{pp}(r) = -U_0(r) - \frac{(N-Z)}{A} * U_1(r) + U_c(r)$$

$$U_{nn}(r) = -U_0(r) + \frac{(N-Z)}{A} * U_1(r)$$

$$U_{pn}(r) = 2 \frac{\sqrt{N-Z}}{A} * U_1(r)$$

We have assumed that the Becchetti-Greenlees proton optical potentials² provide a reasonable parameterization of U_0 if the potential strength terms proportional to $(N-Z)/A$ are omitted. U_1 has been parameterized similar to U_0 , that is with a linear energy dependence. A non-linear least-square search program has been written, using a subroutine version of the DWBA program DWUCK³, to optimize the parameters of U_1 . We are currently in the process of doing global searches on all of our 25 and 35 MeV data. As an indication of the kind of agreement that can be obtained without searching, the dashed curves in figures 3 and 4 show the results of macroscopic DWBA calculations using the Becchetti-Greenlees best-fit proton and best-fit neutron parameters. The (p,n) form factor was obtained by summing the isospin-dependent strengths and averaging the geometry parameters of the proton and neutron potentials. It should be noted that these are not Lane model consistent calculations. The calculations do agree with our data surprisingly well, but there is still considerable room for improvement.

D. Microscopic Analysis of the Data

In the microscopic DWBA neglecting exchange, the transition amplitude for a reaction $A(a,b)B$ may be written

$$T_{ba} = \int \chi_b^{(-)} \langle \psi_f | V_{eff} | \psi_i \rangle \chi_a^{(+)} d^3r$$

where the χ 's are distorted waves generated in an appropriate optical potential, the ψ 's are the wave functions of the states involved, and V_{eff} is the nucleon-nucleon effective interaction which induces the transition from the initial to the final state. We have chosen our targets for their simple ground state shell model configurations, so that the nuclear wave functions should not contribute much to the uncertainty of the calculations. In addition, the good overlap of the initial and final states in reactions exciting the isobaric analog of the target ground state tends to make the calculations insensitive to the fine details of the wave functions. Our macroscopic analysis of the data should provide us with good optical model parameters, so the distorted waves should not be much of a source of uncertainty either. Thus, the microscopic analysis of the data should provide a sensitive way to investigate V_{eff} . For central forces, V_{eff} may be written

$$V_{eff} = \sum_i (V_0(r) + V_\sigma(r) \sigma_i \cdot \sigma_p + V_\tau(r) \tau_i \cdot \tau_p + V_{\sigma\tau}(r) \sigma_i \cdot \sigma_p \tau_i \cdot \tau_p)$$

where the sum is over the valence nucleons. For the isobaric-analog-state transition, only the V_τ term contributes to the direct transition amplitude. Thus, our measurements should provide reasonably unambiguous information about the isospin part of the effective interaction. The solid curves in figures 3 and 4 were obtained from microscopic calculations using the DWBA program DWUCK. The Becchetti-Greenlees best-fit proton and best-fit neutron optical parameters were used to calculate the distorted waves. The nuclear wave functions were assumed to be $(f_{7/2})^8$ for ^{48}Ca and $(g_{9/2})^{10}$ for ^{90}Zr . $V_\tau(r)$ was assumed to have a Yukawan radial dependence with a range of 1.0F. The strength of V used in the calculations is 20 MeV for the 25 MeV calculations and 18 MeV for the 35 MeV calculations.

E. $^{40}\text{Ar}(p,n)$ to the Anti-Analog State

When the valence nucleons of a target are in more than one shell-model orbital, the isobaric analog state (IAS) is a linear combination of these orbitals. Then there is an orthogonal linear combination of the same orbitals called the anti-analog state (AAS). The (p,n) transition to the AAS is expected to be small and sensitive to the details of the wave functions and reaction mechanism because of the poor overlap between the target ground state and the AAS wave functions.

In $^{3}\text{He}, t$ reactions to AAS in several nuclei, it was found that the angular distributions could not be fitted by the usual DWBA macroscopic analysis.⁴ Microscopic computations⁵ for $^{40}\text{Ar}(^3\text{He}, t)^{40}\text{K}(\text{AAS})$ produced both an incorrect shape and a magnitude less than one-tenth that observed. It was then shown⁶ that a reasonable fit could be obtained if the 2-step process $(^3\text{He}, \alpha) - (\alpha, t)$ was included. Perhaps the composite nature of ^3He and t and the strength of $(^3\text{He}, \alpha)$ cross sections make the 2-step process more important in $(^3\text{He}, t)$ reactions than in (p,n) reactions between the same states.

To test this possibility, we have measured the $^{40}\text{Ar}(p,n)^{40}\text{K}(\text{AAS})$ differential cross section with 24 MeV protons. Figure 5 shows the time-of-flight spectrum obtained at 15° with a 11.5 meter flight path. Due to difficulties in determining the target thickness, we extracted the ratio of the AAS to the IAS cross sections. We then used the experimental values⁶ obtained at the University of Colorado for the IAS with 22.8 MeV protons to normalize our AAS to IAS ratio. The results are shown in Figure 6. The curves in Figure 6 are the results of one-step microscopic calculations, including exchange,

Fig. 3.--(p,n) angular distributions of the isobaric analog state for 25 MeV incident protons. The solid and dashed curves are the results of microscopic and macroscopic DWBA calculations, respectively, as described in the text.

Fig. 4.--(p,n) angular distributions of the isobaric analog state for 35 MeV incident protons. The solid and dashed curves are the results of microscopic and macroscopic DWBA calculations, respectively, as described in the text.

that were done using the program DWBA-70 of Raynal and Schaeffer. We used the Becchetti-Greenlees best-fit optical parameters² for the distorted waves, a $(d_{3/2}^2 f_{7/2}^2)$ target wave function, and Yukawan effective interaction with a range of 1.0F and strengths as follows⁷: $V_0 = -30$ MeV, $V = 6$ MeV, $V = 20$ MeV, and $V = 15$ MeV.

Our conclusion is that there is no compelling need to include a 2-step reaction in order to obtain agreement with the data.

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Fig. 5.--Neutron time-of-flight spectrum obtained at 15° for $^{40}\text{Ar}(p,n)^{40}\text{K}$ with $E_p = 24$ MeV. The neutron flight path was 11.5 meters.

Fig. 6.-- $^{40}\text{Ar}(p,n)^{40}\text{K}$ angular distributions of the isobaric analog state and the anti-analog state. The IAS data are from the University of Colorado and the AAS data are from MSU. The curves are the results of one-step microscopic DWBA calculations, including exchange, as described in the text.

The structure of ^{13}C was investigated by the pickup reaction $^{14}\text{C}(p,d)^{13}\text{C}$ at a proton bombarding energy of 35 MeV. While the levels in this nucleus have been studied by neutron stripping from ^{12}C practically no pickup information is presently available.

The target contained about $14 \mu\text{g}/\text{cm}^2$ of ^{14}C and also impurities of ^{12}C , ^{16}O and ^{14}N . The deuterons were detected in a resistive-wire proportional counter placed in the focal plane of the magnetic spectrograph. The proportional counter was backed by a plastic scintillator which was used to identify the deuterons by a time of flight measurement. Since the counter was only 10 inches long, three separate runs were taken at each angle to study the spectrum of ^{13}C up to an excitation energy of 18 MeV. A proton monitor counter at 90° checked the condition of the target and checked the accuracy of the charge collection from run to run. The monitor counts were used to obtain angular distributions from 7° to 70° .

Angular distributions for eight states in ^{13}C are shown in Fig. 1 including the angular distribution for the isobaric analogue state ($J^\pi=3/2^-$, $T=3/2$) at 15.1 MeV. The angular distributions for the ground state ($J^\pi=1/2^-$) and 3.68 MeV ($J^\pi=3/2^-$) states are generally similar as expected since both are reached by a $\ell=1$ transfer but have slight differences especially forward of 20° . The angular distribution for the 3.09 MeV ($J^\pi=1/2^+$) is very strongly forward peaked, characteristic of $\ell=0$ transfer.

Distorted wave calculations were carried out using the code DWUCK72. Becchetti-Greenlees¹ proton optical parameters were used. Two sets of deuteron parameters were tried, the adiabatic model set² and parameters obtained by the Argonne group.³ Some comparison of theoretical fits to the data are also shown in Fig. 1. Spectroscopic factors were extracted by comparing the fits from the adiabatic model with the experimental curves at the position of the forward maximum in the angular distribution. These spectroscopic factors normalized to the value 2.0 for the ground state are shown in the table together with values calculated by Cohen and Kurath⁴ and by Maripuu and Hauge⁵ and by True.⁶

The S-factors for the negative parity states of ^{13}C are in good agreement with shell-model predictions. The experimental C^2S value for the $E_x=3.09$ MeV $J^\pi=1/2^+$ state is considerably larger than the value predicted by True,⁶ indicating the existence of a larger amount of S $1/2^2$ configuration in the ^{14}C ground state wave function than predicted by this model.

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TABLE I.--

Ex (MeV)	Experiment			Ex (MeV)	Theory		
	J	T	C^2S		Cohen & Kurath	Hauge & Maripuu	True
					C^2S	C^2S	C^2S
0.0	$1/2^-$	$1/2$	2.0	0.0	1.73	1.79	--
3.09	$1/2^+$	$1/2$	0.12	--	--	--	0.025
3.68	$3/2^-$	$1/2$	1.70	3.58	2.04	2.28	--
3.85	$5/2^+$	$1/2$	0.20	--	--	--	0.14
6.86	$5/2^-$	$1/2$	0.12	--	--	--	--
9.50	(3^-)	$1/2$	0.20	10.4	0.33	0.20	--
15.1	3^-	$3/2$	1.86	14.8	1.58	--	--

Fig. 1.--Angular distributions observed in the $^{14}\text{C}(p,d)^{13}\text{C}$ reaction at $E_p=35$ MeV. The solid curves are DWBA calculations.

Study of Sulfur Isotopes Via the (p,d) Reaction

A. Moalem, H. B. Wildenthal and D. Show

The (p,d) reaction on ^{32}S , ^{33}S and ^{34}S has been conducted as part of a systematic study of this reaction on nuclei in the sd shell region. Our objective in the present work is to obtain a reasonably complete understanding of the nuclear structure of levels in the Sulfur nuclei, including the region of the analog states, so as to allow more critical evaluation of recent shell model predictions.

The experiment was performed with a 35 MeV proton beam from the MSU sector focused cyclotron. Angular distributions were measured independently with a position sensitive wire proportional counter and nuclear emulsions in the focal plane of Engeström type spectrograph. We obtained a resolution of about 8 keV, FWHM, for the emulsion spectra. The data from the counter were limited to 50 keV resolution and were used to confirm the results obtained from the nuclear emulsions.

To this end data analysis for the $^{32,33}\text{S}(p,d)$ reaction is at very preliminary stages. For data for the $^{34}\text{S}(p,d)$ ^{33}S reaction is near completion and the results are summarized in the accompanying table. A total number of thirty-seven levels have been resolved up through 7.5 MeV, essentially all of them known from previous studies. The excitation energy values obtained in the present work usually agree within the quoted errors with those obtained in Ge(Li) γ -ray studies of levels in ^{33}S . The spectroscopic factors appear to agree with those obtained in large space shell model calculations, for most of the strongly excited levels.

TABLE I.

E _x (keV)	ℓ	100xC ² _{S²,j}	
		Experiment	FPSDI
0	2	187	187
840	0	80	85
1966	2	5	17
2313	2	17	25
2867	2	127	158
2935	3	2	
2969	(4)	1	
3220	1	0.2	
3832	2	59	0
3935	2	2.5	13
4048	(4)	(0.8,0.4)	
4053*	0	0.3	10
4096			
4147±3.5	4143 ±3.	(3,4)	
4211	4212 ±2.	---	
4380±6.	4377 ±5.	0	15
4425	4426 ±5.		
4733	4732 ±6.		
4747	4747 ±6.		
	4869 ±6.		
	4920 ±2.		
4947	4941 ±6.	3	5
5182	5177 ±6	3	4
	5210 ±6		
5273	5272 ±6		
5288±3.2	5287 ±6	flat	
5347	5340 ±6	2	3
	5351 ±6		
5403	5399 ±6	flat	
5485	5475.4±1.4	0	46
	5599 ±5		
5619	5613 ±6	0	10
5718±3.1	5715 ±6	flat	
5728±3.		4	(1.2,1.3)
	5854 ±6		
5890			
5918*	5915 ±6	0	8.2
	5982 ±6		
6364	6360 ±6	2	21
6423±3.3	6428 ±2		
	6689 ±6		
	6892 ±6		
6907±6		2	35
6968	6965 ±6		18
7194	7193 ±2		
7341	7344 ±12	2	41
	7420 ±2		40
8100			

The $^{206}\text{Pb}(p,d)^{205}\text{Pb}$ Reaction

W. A. Lanford

There have recently become available shell model calculations of $^{206,205,204}\text{Pb}$ based on 2, 3 and 4 neutron holes in the lead ^{208}Pb core. These calculations have been very successful in predicting the spins, parities and excitation energies. Spectroscopic factors from the $^{207}\text{Pb}(p,d)^{206}\text{Pb}$ reaction² are also in excellent agreement. These calculations are based on the assumptions that (1) the six strong states excited in the $^{208}\text{Pb}(p,d)^{207}\text{Pb}$ reaction are single neutron hole states and (2) the low lying states in $^{206,205,204}\text{Pb}$ can be described as 2, 3 and 4 neutron holes distributed over these six neutron orbits. In order to make the analysis of the $^{206}\text{Pb}(p,d)^{205}\text{Pb}$ correspond to these assumptions, we have measured spectroscopic factors for transitions to states in ^{205}Pb relative to the strengths experimentally determined for the $^{208}\text{Pb}(p,d)^{207}\text{Pb}$ reaction. To distinguish these relative spectroscopic factors from absolute spectroscopic factors, we will denote them as C^2S . This use of relative C^2S is appropriate not only because they are the quantities predicted by most theories, but also because they can be evaluated to a few percent accuracy. That is by measuring the cross-sections for $^{206}\text{Pb}(p,d)$ relative to the cross-sections measured in $^{208}\text{Pb}(p,d)$ (not relative to DWBA as is usually done), one can avoid most for the uncertainties present in a DWBA analysis.

There is one simple test of these ideas which can be easily applied. The angular distributions measured on ^{206}Pb and ^{208}Pb targets must be the same, or clearly the procedure suggested above is inappropriate. Shown in Fig. 1 are $f_{7/2}$ angular distributions as measured on all four of the stable lead isotopes. Note that the curve is the same in all four cases and is simply an interpolation between the $^{208}\text{Pb}(p,d)$ data points. Clearly for all practical purposes, the angular distributions are the same. Similar plots for the other l -values could also be shown.

These (p,d) reactions have been studied at 35 MeV using a combination of data taken with nuclear emulsions and with a position sensitive proportional counter in the focal plane of a spectrometer. Shown in Fig. 2 is a spectrum obtained using nuclear emulsions. The data taken with emulsions had resolution of about 15 keV (FWHM) while the data taken with the counter had about 45 keV resolution. The proportional counter data was used for states for which 45 keV resolution was sufficient and the plate data was used for other states. The proportional counter data has the advantages of better statistics and not having the uncertainty introduced by human scanners. On the other hand, the plate data has both better resolution and an accurately known

calibration. Shown in Table I are the excitation energies and l -values observed in the $^{206}\text{Pb}(p,d)^{205}\text{Pb}$ reaction along with information on ^{205}Pb from the literature.

Preliminary analysis of the data gives the spectroscopic factors given in Table II. Also shown are the predicted excitation energies and spectroscopic factors of McGrory, et al.¹ Note that there is generally good agreement.

1. J. B. McGrory, et al., Bull. Am. Phys. Soc. 17, 579(1972) and private communication.
2. W. A. Lanford and G. M. Crawley, submitted to Phys. Rev. C.
3. J. H. Hamilton, et al., Vanderbilt University, preprint.

TABLE I.--Comparison of the Excitation Energies from the $^{206}\text{Pb}(p,d)^{205}\text{Pb}$ Reaction with Results in the Literature.

Excitation Energy	l -value	Nucl. Data Sheet Plus Hamilton, <u>et al.</u> ³	J^π assumed for this analysis
.0006	1+3	$5/2^-$ 0.0	$5/2^-$
.262	1	$1/2^-$.0022	$1/2^-$
.577	1	$3/2^-$.2628	$3/2^-$
.762	3	$7/2^-$.5761	$7/2^-$
.802	(1)	$5/2^-$.7034	$5/2^-$
.997	(1)	$1/2^-$.7615	$1/2^-$ ($3/2^-$)
1.011	6	$9/2^-$.803	$9/2^-$
1.042	3	$3/2^-$.9876	$3/2^-$ ($1/2^-$)
1.373	1	$13/2^+$ 1.0137	$13/2^+$
1.583	3	$7/2^-$ 1.044	$7/2^-$
1.615	3	$5/2^-$ 1.2647	$5/2^-$
1.758	3	$9/2^-$ 1.4991	$9/2^-$
2.352	1	($9/2^-$, $7/2^-$) 1.5753	$5/2^-$ ($7/2^-$)
(2.521)	3	$9/2^+$ 1.5936	$9/2^+$
2.562	5	$7/2^-$ 1.6144	$7/2^-$
2.692	5	($11/2^-$, $9/2^-$) 1.7050	$7/2^-$
2.795	0	$1/2^+$ 1.7564	$1/2^+$
2.903	5	$9/2^+$ 1.7585	$9/2^+$
3.933		$7/2^-$ 1.7643	$7/2^-$
3933		$7/2^-$ 1.7758	$7/2^-$
3999			
4013			
4050			
4.984			
5.095			
5.145			
5.174			
		$9/2^-$, $7/2^-$ 2.5214	
		$9/2^+$ 2.5651	

TABLE II.--Spectroscopic Factors for the $^{206}\text{Pb}(p,d)^{205}\text{Pb}$ Reactions Relative to the $^{208}\text{Pb}(p,d)^{207}\text{Pb}$ Reaction to the Single Neutron Hole States in ^{207}Pb . Also shown are the shell model predictions of McGrory, et al.

J^π	Excitation		C^2S	
	Expt.	Calc.	expt.	Calc.
$5/2^-$	0.0	.07	4.73	5.34
$1/2^-$	.002	0.0	.65	.94
$3/2^-$	.262	.21	3.00	3.36
$3/2^-$	.577	.75	.084	.04
$7/2^-$	.703	.91	0.0	0.0
$5/2^-$	.762	.88	.08	.19
$1/2(3/2)$	.803	.80	(.02)	.01
$9/2^-$	.988	1.06	0.0	0.0
$3/2^-(1/2^-)$	.997	1.02	.16	.23
$13/2^-$	1.011		11.52	
$7/2^-$	1.044	1.13	.54	.36
$5/2^-$	1.265	1.01	0.0	.01
$3/2(1/2)$	1.373	1.35	.008	.02
$9/2^-$	1.499	1.54	0.0	0.0
$(9/2^-, 7/2^-)$	1.575		0.0	
			$C^2S(f_{1/2})=.06$	
$5/2^-(7/2^-)$	1.583	1.37		0.0
$9/2^+$	1.594		0.0	
$7/2^-$	1.615	1.58	1.04	.96
$11/2^-(9/2^-)$	1.705		0.0	
$7/2^-$	1.756	1.76	6.08	6.32

Fig. 1.--The $f_{1/2}$ angular distributions as measured on all four stable isotopes of lead. Note that the curve is the same in all four cases. The curve is simply the results of interpolating between the data points from the $^{208}\text{Pb}(p,d)^{207}\text{Pb}$ reaction.

Fig. 2.--A spectrum of the $^{206}\text{Pb}(p,d)^{205}\text{Pb}$ reaction. The peaks are labeled with excitation energies in keV. The cross-hatched peaks are from impurities in the target. The peaks labeled with asterisks were too intense to scan and would go off the top of the scale.

H. Nann, W. Benenson, and W. A. Lanford

The simultaneous investigation of the $(p, {}^3\text{He})$ and (p, t) reactions on target nuclei with isospin $T=1/2$ has two purposes. On one hand effects of a spin-isospin dependent interaction potential in the DWBA analysis of the two-nucleon transfer reactions can be studied. On the other hand, since the $(p, {}^3\text{He})$ reaction permits an $S=0$, $T=1$ and an $S=1$, $T=0$ spin-isospin transfer of a proton neutron pair, whereas the (p, t) reaction allows only an $S=0$, $T=1$ transfer of two neutrons, it is possible to test different parts of the wave functions of the target and the final nuclei.

We have begun the comparative measurements of these reactions on ${}^{29}\text{Si}$ and, till now to a lesser extent, on ${}^{31}\text{P}$ using the 40 MeV proton beam of the MSU Cyclotron. The reaction products were detected in a position sensitive proportional counter backed by a plastic scintillation counter on the focal plane of the split-pole magnetic spectrograph. The scintillation counter provides an energy signal and a time signal, both of which are used for particle identification. An overall energy resolution of about 30 keV was obtained.

We have measured angular distributions between 6° and 55° for mirror transitions to states up to 5 MeV excitation energy in the final nuclei. The transitions show nearly equally strength except the ground state transitions, the strengths of which are about one order of magnitude larger. We have tried to reproduce the experimental differential cross sections with microscopic DWBA calculations which employ spectroscopic amplitudes extracted from shell model wave functions of Wildenthal and McGrory.¹ In Fig. 1 we show as an example measured and calculated angular distributions of the (p, t) and $(p, {}^3\text{He})$ reactions on ${}^{29}\text{Si}$ for transitions to the first five states in the final nuclei. In all DWBA calculations the same sets of optical model parameters are used. The agreement between experiment and calculation for the shape of the angular distributions is generally quite satisfactory. The discrepancies in the ${}^{29}\text{Si}(p, t){}^{27}\text{Si}$ angular distributions may point to some contributions from two step processes and not to inadequacies of the shell model wave functions used in the analysis. Each calculated angular distribution is independently normalized to the experimental data. Using the values $|D(S=0)|^2=0.72$ and $|D(S=1)|^2=0.30$ for the spin-isospin exchange terms in the stripping interaction² and a common normalization, corresponding to $D_0^2=18 \cdot 10^4 \text{ MeV}^2 \text{ fm}^3$, one obtains the ratios $\sigma_{\text{exp}}/\sigma_{\text{th}}$ which are given in Table 1. These relative magnitudes of the angular distributions produced in the $(p, {}^3\text{He})$ and the (p, t) reactions are affected not only by the details of the wave functions but also by the chosen values of $D(S)$.

Our data indicate that the ratio $|D(S=1)|^2/|D(S=0)|^2$ used in the present analysis is too high in agreement with the results of Fleming, et al.³ The detailed test of the shell model wave functions is still in progress.

1. B. H. Wildenthal and J. B. McGrory, Phys. Rev. C7, 714(1973).
2. J. C. Hardy and I. S. Towner, Phys. Lett. 25B, 98(1967).
3. D. G. Fleming, J. Cerny and N. K. Glendenning Phys. Rev. 165, 1153(1968).

TABLE 1.--Comparison of experimental and theoretical cross sections.

J^π	$E_x({}^{27}\text{Al})$ (MeV)	$E_x({}^{27}\text{Si})$ (MeV)	$\sigma_{\text{exp}}/\sigma_{\text{th}}$ ($p, {}^3\text{He}$)	$\sigma_{\text{exp}}/\sigma_{\text{th}}$ (p, t)
$5/2^+$	0.00	0.00	0.64	1.39
$1/2^+$	0.84	0.78	1.17	0.84
$3/2^+$	1.01	0.96	1.33	0.84
$7/2^+$	2.21	2.16	0.89	0.67
$5/2^+$	2.73	2.65	0.72	4.6

Fig. 1.--Angular distributions for the $^{29}\text{Si}(p,t)^{27}\text{Si}$ and $^{29}\text{Si}(p,^3\text{He})^{27}\text{Al}$ reactions at $E_p=40.1 \text{ MeV}$ bombarding energy. For the $^{29}\text{Si}(p,^3\text{He})^{27}\text{Al}$ reaction, displayed in the lower half, the contributions of the $S=0, T=1$ transfer (dotted curve) and the $S=1, T=0$ transfer (dashed-dotted curve) to the total differential cross section (full curve) are shown.

The purpose of this investigation is to resolve some discrepancies in the energy levels and spin assignments of ^{56}Ni which occur in comparing results of previous studies of the $^{54}\text{Fe}(^3\text{He},n)^{56}\text{Ni}$ reaction^{1,2,3} and the $^{58}\text{Ni}(p,t)^{56}\text{Ni}$ reaction.^{4,5} All these studies suffered from a lack of good energy resolution. As an example, in all ($^3\text{He},n$) experiments a spin-parity of $J^\pi=0^+$ is uniquely assigned to the level at 3.95 MeV while a value of 4^+ is found in the (p,t) reaction. Schneider, *et al.*³ found a doublet at that energy and made spin assignments for the two levels.

We have measured angular distributions of the $^{58}\text{Ni}(p,t)^{56}\text{Ni}$ reaction at a bombarding energy of 40.3 MeV for the transitions to states up to 12 MeV excitation energy in ^{56}Ni . The triton spectra were recorded using either a position sensitive Si semiconductor detector or a position sensitive proportional counter in the focal plane of the split-pole magnetic spectrograph. An energy resolution of 8 and 25 keV, respectively, was obtained. Fig. 1 shows a triton spectrum taken with the proportional counter.

Besides the doublet at 3.95 MeV we found three other new doublets at 5.00, 5.33 and 5.99 MeV. The triton angular distributions for the transitions to the doublets at 3.95 and 5.00 MeV are displayed in Fig. 2. The angular distributions of the transitions to the 3.952 and 5.007 MeV states both exhibit a clear $L=0$ pattern; therefore these states have unambiguously the spin assignments $J^\pi=0^+$, the first assignment being in contradiction with that given by Schneider, *et al.*³ From the $L=4$ pattern of the angular distribution of the 3.923 MeV transition a spin-parity of $J^\pi=4^+$ can be deduced. The 4.937 MeV state is probably an unnatural parity state with $J^\pi=3^+$. These assignments were deduced by comparing the shapes of the present angular distributions to those observed in the $^{56}\text{Fe}(p,t)^{55}\text{Fe}$ reaction for transitions to known 4^+ and 3^+ states, respectively.

Particular interest was directed to the transitions to $J^\pi=0^+$ states in ^{56}Ni , especially to $T=2$ states⁶ around 10 MeV excitation energy. The analysis of this part is still in progress.

We presume from the strange shapes of some angular distributions that there are many unresolved levels in ^{56}Ni . Therefore further high resolution experiments on this reaction are being carried out using nuclear emulsions.

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 2. D. Evers, *et al.*, Nucl. Phys. **A198**, 268(1972).

Fig. 1.--Spectrum of the $^{58}\text{Ni}(p,t)^{56}\text{Ni}$ reaction observed with a position sensitive proportional counter in the focal plane of the magnetic spectrograph.

Fig. 2.--Angular distributions of the $^{58}\text{Ni}(p,t)^{56}\text{Ni}$ reaction to the states at 3.923, 3.952, 4.937 and 5.007 MeV in ^{56}Ni .

The study of odd-A rare-earth nuclei by the (p,t) reaction is continuing. The bulk of previous results dealt with levels in odd-Z nuclei.¹ Preliminary results of the $^{163,161}\text{Dy}(p,t)$ reactions which involve odd-N nuclei were also presented last year.¹ An effort was made to improve the spectra obtained from the $^{163}\text{Dy}(p,t)$ reaction, and although the resolution in the spectra shown in Fig. 1 is still not good enough to allow detailed analysis, certain features of the ^{161}Dy level scheme are now under investigation.

Angular distribution data, taken using a $\sim 200 \mu\text{gcm}^{-2}$ target and a beam of 33 MeV protons from the MSU cyclotron, indicates tentatively that the very strong peak near channel 740 is an $\ell=0$ transition. One expects that the strongest $\ell=0$ transfer in this reaction would be the transition involving the $K^\pi=5/2^-$ ground state in ^{163}Dy with the $K^\pi=5/2^-$ excited state at 26 keV in ^{161}Dy . The absence, or extreme weakness, of the ground to ground transition, $5/2^- \rightarrow 5/2^+$ is not surprising as this involves a parity change with consequent change in structure.

With the high level density in both the target and final nucleus, the addition of coupled channel programs to the cyclotron software library is welcomed. The many possibilities for direct and indirect population of the states in ^{161}Dy may require coupled channel analysis for explanation.

Work continues on this project with the fabrication of very thin ($\sim 100 \mu\text{gcm}^{-2}$) targets using the Th reduction method.² With the high resolution proton beam available from the MSU cyclotron, the thinner targets, in conjunction with the use of photographic plates, will enable us to obtain the 5-10 keV FWHM resolution necessary to separate the closely spaced ^{161}Dy levels.

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2. L. Westgaard and S. Bjornholm, Nucl. Inst. and Meth. 42, 77(1966).

FIGURE 1.-- $^{163}\text{Dy}(p,t)$ spectra taken at $\theta_1=10^\circ, 20^\circ$. These spectra were recorded using a wire counter in the focal plane of the spectrograph.

W. Benenson, E. Kashy, A. Moalem and H. Nann

In the past years the ($^3\text{He}, ^6\text{He}$) reaction has been used for the study of exotic nuclei ranging from $A=9$ to $A=55$. Most of the solid targets which can be used for this type of investigation have now been bombarded. The last in this series was a study of ^{11}N using the $^{14}\text{N}(^3\text{He}, ^6\text{He})$ reaction. Our attention has therefore turned to three topics closely related to the previous ($^3\text{He}, ^6\text{He}$) work. These are; (a) ($^3\text{He}, ^6\text{He}$) on gas targets, (b) ($^3\text{He}, ^6\text{He}$) on solid targets leading to non-exotic or "garden variety" nuclei, and (c) the ($p, ^6\text{He}$) reaction. The general method diagrammed in Fig. 1 is applicable to all three topics.

Gas targets have properties which are not well matched to the spectrograph's capabilities. The main difficulties stem from the extended source defined by the collimator system. This difficulty was recently shown to be surmountable in a mass measurement of ^{34}Ar (J. C. Hardy, H. Schmeing, W. Benenson, G. M. Crawley, E. Kashy and H. Nann, to be published) performed in this laboratory and reported in this volume. In this experiment a gas cell with a narrow slit exit window was used. Focusing the optics of the spectrograph on this slit permitted an energy resolution of about 40 keV. This same technique is being applied to mass measurements of ^{33}Ar and ^{17}Ne and a remeasurement of the mass ^{29}S . A broad peak (1.5 MeV wide) corresponding to the ^{11}N ground state was observed with a solid melamine target. This experiment will be repeated with a ^{14}N gas target.

The ($^3\text{He}, ^6\text{He}$) reaction is one of the very few reactions which have been used to study $T_Z = -1$ nuclei. It can reveal different features of the final nucleus than does the more commonly used (p, n) and ($^3\text{He}, t$) reactions. The new levels in ^{10}C near 10 MeV shown in Fig. 2 below are examples of this. On the other hand $^{27}\text{Al}(^3\text{He}, ^6\text{He})$ and $^9\text{Be}(^3\text{He}, ^6\text{He})$ revealed no new features of ^{27}Al and ^9Be which have not been observed in $^{24}\text{Mg}(^3\text{He}, t)$ and $^6\text{Li}(^3\text{He}, t)$ reactions.

Fig. 1.--The apparatus for time of flight particle identification in the spectrograph.

The first runs on the ($p, ^6\text{He}$) reaction took place recently. The reactions studied lead to well known non-exotic final nuclei. An example, $^{50}\text{Ti}(p, ^6\text{He})$, is shown in the Fig. 3. The cross section for this reaction was surprisingly large, approximately 50 nb/sr. This cross section is large enough to permit thin target experiments and therefore accurate mass measurements. The first nuclei to be studied will be ^{53}Co , ^{49}Mn and ^{45}V . These will be done at 45 MeV beam energy. Most of the other exotic nuclei which can be reached by ($p, ^6\text{He}$) have Q -values so large and negative that special techniques will have to be used to detect the ^6He 's even if the highest available beam energies (48-50 MeV) are used.

Fig. 2.--Spectrum from the $^{13}\text{C}(^3\text{He}, ^6\text{He})^{10}\text{C}$ reaction at 70 MeV.

Fig. 3.--The first spectrum of the ($p, ^6\text{He}$) reaction obtained in this laboratory.

The lifetime of the nucleus ^{44}Ar has been reported^{1,2} but until now its mass and energy levels were unknown. During the past year, using the $^{48}\text{Ca}(^3\text{He}, ^7\text{Be})^{44}\text{Ar}$ reaction at 70 MeV ^3He bombarding energy, we have measured the mass of ^{44}Ar and the excitation energies of several of its excited states.

The ^3He beam was produced by the MSU variable energy sector focused cyclotron. The reaction products were analyzed by an Enge split-pole magnetic spectrograph.³ Detection of ions in the focal plane of the spectrometer was accomplished by means of a system composed of a plastic scintillator photomultiplier unit behind a 25 cm single wire charge division gas proportional counter.⁴ The counter measures both position along the focal plane and differential energy loss of an ion, while the scintillator is used to measure time-of-flight in the spectrograph.

^7Be spectra are complicated by those outgoing ^7Be ions which are in the .432 MeV particle stable first excited state. Thus each level in the residual nucleus produces in the ^7Be spectrum two peaks which are separated by about .4 MeV, the exact amount depending on the kinematical parameters. The experimental resolution (FWHM), due primarily to target thickness, of the spectrum measured at 7° laboratory angle (Fig. 1) is about 120 keV, which allows discernment of peak pairs, particularly those of impurities. Peak pairs corresponding to levels in ^{44}Ar occur as well.

Table I summarizes the mass excesses and excitation energies of levels identified as belonging to ^{44}Ar . Both the primary (^7Be .000) and secondary (^7Be .432) peaks corresponding to a given level have been used in calculating its entry. While levels above 4 MeV are observed, contaminant peaks make the assignment of excitation energies very difficult. The ground state mass excess differs from the Garvey-Kelson⁵ prediction by about +500 keV which is about 10 times the average deviation found in their table. A new calculation by Borysowicz,⁶ also listed in Table I, which uses more recent masses and which includes a weighting for the actual errors in the 1972 mass table,⁷ is closer to our measured value for ^{44}Ar but still differs by about 350 keV.

Because of the ^{40}Ca impurity in the target, a comparison of the $^{40}\text{Ca}(^3\text{He}, ^7\text{Be})^{36}\text{Ar}$ and $^{48}\text{Ca}(^3\text{He}, ^7\text{Be})^{44}\text{Ar}$ reactions is possible. Unfortunately the ^{36}Ar ground state transition occurs in only a few spectra so the ratio of $^{36}\text{Ar}(0.0)/^{44}\text{Ar}(0.0)$ of approximately 10 is not well determined. The first excited state transition is measureable in more of our spectra and in this case the ratio $^{36}\text{Ar}(1.977)/^{44}\text{Ar}(.700)$ is roughly 16.

The ground state transition ratio is qualitatively in agreement with a shell model prediction. If one uses the shell model wave-functions of Maripuu and Ewvaraye⁸ for the $J^\pi=0^+$ ground states of ^{36}Ar , ^{40}Ca , ^{44}Ar , and ^{48}Ca and assumes the ($^3\text{He}, ^7\text{Be}$) reaction to proceed via α -particle pickup,⁹ one obtains a ratio of 15 for the squared ratio of wave-function overlaps between the partitions $^{40}\text{Ca}+^{36}\text{Ar} + \alpha$ and $^{48}\text{Ca}+^{44}\text{Ar} + \alpha$. For a more sophisticated calculation one must take into account the transformation coefficients describing the internal motion of the particles in the α -cluster as well as four-particle transfer fractional parentage coefficients. Such a calculation, however, would not at present be justified considering the large experimental cross-section uncertainty. The shell model⁸ places the ^{44}Ar first excited state at 1.26 MeV. The measured value of .700 MeV is lower than not only the shell model value, but also lower than the excitation energies of the first excited states of all other known even-even argon isotopes.

In addition to using the ($^3\text{He}, ^7\text{Be}$) reaction for mass measurements, the reaction mechanism itself is being studied.¹⁰ To this end, detailed angular distributions are being measured. Displayed in the accompanying figure are angular distributions for the $^{24}\text{Mg}(^3\text{He}, ^7\text{Be})^{20}\text{Ne}$ reaction to the lowest 0^+ , 2^+ , and 4^+ states in ^{20}Ne . Their shapes appear to be distinctive: the 0^+ rises at forward angles while the 2^+ declines and the 4^+ has a broad forward hump falling off at extreme forward angles. All distributions have distinct diffraction structure and fall off sharply with increasing angle.

Future work on the ($^3\text{He}, ^7\text{Be}$) reaction will include measuring cross sections for targets of mass greater than 90. It has been suggested¹¹ that while cross sections for ($^3\text{He}, ^7\text{Be}$) reactions drop with increasing mass number, at some point they may reach a minimum and begin to rise. Also to be studied are the differences between the primary and secondary angular distributions for a given level, the shapes of which show qualitative rather than quantitative agreement.¹²

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TABLE I.--Energy levels of ^{44}Ar

Level	Mass Excess (MeV)	Excitation Energy in ^{44}Ar (MeV)
1	$-32.27 \pm .04^+$	0.00
2	$-31.55 \pm .04$	0.70
3	$-30.71 \pm .09$	1.55
4	$-28.91 \pm .18$	3.34
5*	$-27.56 \pm .16$	4.69

*Garvey-Kelson prediction for ground state mass excess -32.76 MeV

Borysowicz prediction for ground state mass excess -32.60 MeV

*The fifth level is included only tentatively.

J. S. Boyno, W. Benenson, T. L. Khoo, Wm. C. McHarris and R. A. Warner

The investigation of the properties of the $(\alpha, ^6\text{He})$ reaction has begun here at MSU with the $^{154}\text{Sm}(\alpha, ^6\text{He})^{152}\text{Sm}$ reaction, chosen for the relatively large level spacing of ^{152}Sm states, and for the fact that these states have been investigated and identified in (p, t) reactions.¹

The reaction was performed with 50 MeV α -particles obtained from the MSU cyclotron. A single-wire gas filled proportional counter was used and a plastic scintillator was placed behind the counter to give timing information. Time of flight information was used to separate all reaction products from the tritons and ^6He produced by the (α, t) and $(\alpha, ^6\text{He})$ reactions, respectively. The use of $\Delta E/E$ identification then separated the abundant tritons from the relatively rare ^6He particles. Resolution obtained was c. 40-50 keV FWHM which is quite good when one considers the energy width of the α -beam, the severe target loss problem and the poor dispersion of the ^6He ions.

Despite the large negative Q-value for this reaction ($Q=-13.0$ MeV), the momentum match of the α - and ^6He -particles is better than in (p, t) . For this reason we are quite interested in obtaining complete angular distributions to see the features of the angular distribution for each l -value.

Some of the results we have obtained are presented in Table 1. The presented cross sections for the $(\alpha, ^6\text{He})$ reaction are based on an estimate of the target thickness and should be taken only to within $\pm 50\%$.

One is immediately struck by the near equality of the $I^\pi=0^+$ and 2^+ cross sections in the $(\alpha, ^6\text{He})$ reaction. In contrast the $I^\pi=0^+$ states in the (p, t) are much stronger than the corresponding $I^\pi=2^+$ states. At $\theta=20^\circ$ in the $(\alpha, ^6\text{He})$ reaction (not shown), the $I^\pi=2^+$ at 122 keV appears to be 1 1/2 times as strong as the ground state 0^+ .

The absolute cross sections for the $(\alpha, ^6\text{He})$ reaction seem to be quite small and it will take some time before we have accumulated full angular distributions with sufficient statistics at each angle to perform a detailed analysis. These first experiments, however, appear quite different from (p, t) reaction results, and this difference may be useful in extracting spectroscopic data from two nucleon transfer reactions.

*Supported by USAEC and NSF.

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TABLE I.--Comparative Cross sections in ^{152}Sm

Level E (keV) ^{a)}	$(d\sigma/d\Omega)_{22.5^\circ}^{(p, t)} (\mu\text{b})$	$(d\sigma/d\Omega)_{8^\circ}^{(\alpha, ^6\text{He})} (\mu\text{b})$	$(d\sigma/d\Omega)_{14^\circ}^{(\alpha, ^6\text{He})} (\mu\text{b})$	Identity ^{a)}
0	510	50	15	0^+
122 $\pm$ 10	34	35	16	2^+
370 $\pm$ 10	37	6	3	4^+
694 $\pm$ 10	100	14	5	0^+
819 $\pm$ 10	40	17	3	2^+
1779 $\pm$ 10	125	25	7	$(3, 4^-)$

^{a)}Taken from Ref. 1.

Mass and Energy Levels of ^{64}Ga

R.G.H. Robertson and W. Benenson

The mass of ^{64}Ge is of astrophysical interest, and has been measured¹ by determining the β^+ end point in coincidence with 427 keV γ -rays from an excited state in the daughter ^{64}Ga . Interpretation of the data rests on knowledge of the mass and level scheme of ^{64}Ga . Although ^{64}Ga has been extensively investigated by the (p,n γ) reaction, seemingly conflicting evidence has come from the threshold studies of Davids, *et al.*,² and from the n- γ and γ - γ coincidence studies of King³ and Hansen, *et al.*⁴

In hopes of resolving the discrepancies and at the same time measuring the ground state mass of ^{64}Ga , the $^{64}\text{Zn}(^3\text{He},t)^{64}\text{Ga}$ reaction has been examined at 37.6 MeV with the Enge spectrograph. Initial inspection of the spectra did not clarify the level scheme because the energy resolution was ~ 35 keV, the level density was high and it was not certain that the ground state was populated. Very recently, however, Hansen and her collaborators have obtained a high-resolution neutron time-of-flight spectrum of $^{64}\text{Zn}(p,n)^{64}\text{Ga}$, and have settled most of the uncertainties in the ^{64}Ga spectrum. Careful fitting of the ($^3\text{He},t$) peaks with the program SAMPO has shown that a 9°

and 12° the ground state is very weak compared to the 41-keV state, and that there is in fact excellent correspondence with the spectrum seen by Hansen. The level scheme has been extended to beyond the I.A.S. and a precise value for the mass of ^{64}Ga has been determined.

The spectrum of $\theta_{\text{lab}} = 9^\circ$ is shown in the figure, with energies in keV. Since the ground state is scarcely resolvable, the Q-value of the 323 keV level has been determined by comparison with the $^{27}\text{Al}(^3\text{He},t)^{27}\text{Si}$ reaction. The 2646.8 keV level in ^{27}Si provides a calibration peak very close to the 323 keV state in ^{64}Ga . Mass measurements for ^{64}Ga are summarized below:

Mass Excess(MeV)	Error	Ref.
-58.934	0.030	5
-58.836	0.006	1
-58.819	0.008	Present

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R.G.H. Robertson and S. M. Austin

^{65}Ge is a very neutron-deficient isotope first identified in 1958 by Porile¹ by chemical separation of germanium from ^{64}Zn after α -particle bombardment. He measured a half-life of 1.5 min and observed 2 weak γ -rays of 0.67 and 1.72 MeV, but concluded that >95% of the decay went to the ground state of ^{65}Ga . No observation of ^{65}Ge , has been reported since. We recently carried out a search for the isotope ^{64}Ge ,² and a byproduct of that work has been extensive new information on the decay of ^{65}Ge . Independent measurements of the ^{65}Ge decay have also been in progress in Amsterdam,³ and the results are in excellent agreement with ours, and in disagreement with the early work of Porile.

The Ge activities were produced by the $^{64}\text{Zn}(^3\text{He}, xn)$ reactions on enriched ^{64}Zn targets at 50 MeV. Following a fast chemical separation of Ge from other activities by vacuum distillation of the tetrachloride, the γ -rays were observed with a Ge(Li) detector and multiscaled into 8 4K bins at 50 sec intervals.

The decay of the strongest line, 650 keV, is shown in Fig. 1. The good energy fit with levels seen⁴ in $^{64}\text{Zn}(^3\text{He}, d)^{65}\text{Ga}$ and the rapid growth of the ^{65}Ga activity leads us to associate this and 8 other γ -rays with the decay of ^{65}Ge , although the measured half-life, 30.0 ± 1.2 sec, is a factor of 3 shorter than Porile's result.¹

Figure 2 shows the decay scheme from our work compared with the $^{64}\text{Zn}(^3\text{He}, d)^{65}\text{Ga}$ results. Absolute γ -ray intensities have been obtained by normalizing to the measured growth of daughter activity. In contrast to Porile, we find very little direct feed to the ground state, although normalization uncertainties would allow up to 25%. Nevertheless, allowed transitions to $1/2^-$ and $5/2^-$ states suggest $J^\pi = 3/2^-$ for ^{65}Ge .

These results are in excellent agreement with the subsequently published work of Jongsma, et al.,³ except that they observed a large number of weaker γ -rays which were unable to see, but not the 1230 keV line which is concealed in their spectra by a ^{65}Ga contaminant. There is also an unexplained discrepancy in the intensity of the 1880 keV transition.

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R.G.H. Robertson, W. Benenson,
D. Mueller and E. Kashy

We have spent about four days in the search for this 5-neutron pickup reaction with goals of (a) making a more precise measurement of the ^8He mass and (b) using this reaction for reaching further into the proton rich nuclear region. The detection system is essentially the same as is currently used in the $(^3\text{He}, ^6\text{He})$ research¹ with the exception that a two-wire position sensitive proportional detector is used instead of a single wire detector. This has resulted in a background rate of less than 1nb/MeV-sr. Results so far indicate a cross section for the $^{26}\text{Mg}(^3\text{He}, ^8\text{He})^{21}\text{Mg}$ of less than 2nb/sr. Present plans include the search for the $^{13}\text{C}(^3\text{He}, ^8\text{He})^8\text{C}$ reaction which is expected to have a larger cross section and to also yield information on the yet unobserved ^8C nucleus.

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Search for New Isotopes in the $N=Z=50$ Region*M. Edmiston, K. Kosanek, F. M. Bernthal,
and Wm. C. McHarris

A search has been undertaken to find ^{90}Tc by use of the $^{92}\text{Mo}(p, 3n)^{90}\text{Tc}$ reaction. The Q-value for this reaction is -35 MeV and that for the $(p, 4n)$ reaction is -44 MeV. Thus we are required to use the MSU cyclotron near its high energy limit for protons: the γ -ray spectra are obtained by using the Helium-Jet-Transport System to carry activity from an in-beam target to a Ge(Li) detector. A novel target is being employed which is made by adhering ^{92}Mo powder to a 2-mil aluminum backing with "Zip-grip" brand adhesive. "Zip-grip" has a relatively featureless γ -ray spectrum and apparently forms a thin enough coating over the powder to allow the recoils to escape through the back of the target.

So far, data for an excitation function have been collected and are being analyzed. A half-life determination for lines tentatively attributed to ^{90}Tc decay is in progress.

Further experiments are planned to utilize both the ^3He and proton beams available to search for additional new isotopes far from β -stability in the $Z=N=50$ region.

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J. C. Hardy,* H. Schmeing,* W. Benenson, G. M. Crawley, E. Kashy and H. Nann

The object of this experiment was to measure the masses of several $T_z = -1$ nuclei in the sd shell which are crucial to beta decay theory. The energy of the decay and hence the mass of the initial state enter directly into ft value determination. The mass of ^{34}Ar was particularly important since in the A=34 nuclei a large mirror asymmetry between ft values has been observed.¹

The experiment was performed in the spectrograph with a ^{36}Ar gas target. The rigidity of tritons from the $^{36}\text{Ar}(p,t)^{34}\text{Ar}$ reaction at 22.50 was compared to that of tritons from the (p,t) reaction on other gasses mixed with the ^{36}Ar . The particles were detected on plates and also in a

current division wire counter backed by a plastic scintillator. The results for ^{34}Ar are given in the table below. Although the results are in agreement with all preceding measurements, they differ from the 1971 mass table value by 16 keV. The mirror asymmetry is thus reduced from $-4.6 \pm 1.7\%$ to $0.0 \pm 0.6\%$. The masses of ^{22}Mg , ^{26}Si , ^{30}S , ^{31}S and ^{35}Ar were measured as well. In every case the agreement with the most recent and accurate experiments is excellent as can be seen in the second table below.

*Visitors from Chalk River National Laboratory.

1. J. C. Hardy, H. Schmeing, J. S. Geiger, R. L. Graham and I. S. Towner, Phys. Rev. Lett. 29, 1027(1972).

TABLE I.--The mass excess of ^{34}Ar .

Experiment	Measured mass excess (keV)	Reference
$^{32}\text{S}(^3\text{He},n)^{34}\text{Ar}$	$-18394 \pm 30^a)$	W. R. McMurray, et al., Nucl. Phys. <u>A92</u> , 401(1967).
	$-18395 \pm 15^a)$	R. G. Miller and R. W. Kavanagh, Nucl. Phys. <u>A94</u> , 261(1967).
	$-18394 \pm 30^a)$	M. Hagen, et al., Phys. Lett. <u>26B</u> , 432(1968).
$^{36}\text{Ar}(p,t)^{34}\text{Ar}$	-18370 ± 11	R. A. Paddock, Phys. Rev. <u>C5</u> , 485(1972).
	-18379 ± 3	this experiment.

a) Values used in obtaining the mass excess quoted in the 1971 mass tables: viz. -18395 ± 12 keV.

TABLE II.--Measured Mass Excesses.

Nucleus	This Experiment		Previous most accurate value
^{22}Mg	-399 ± 3	-394 ± 2	J. Nolen, et al., Nuc. Inst. and Meth. (in press)
^{26}Si	-7143 ± 3	-7147 ± 8	1971 Mass Table
^{30}S	-14062 ± 3	-14065 ± 10	"
^{31}S	-12818 ± 3	-12817.8 ± 3	A. Moalem and H. B. Wildenthal (to be published)
^{35}Ar	-13028 ± 3		1971 Mass Table

Anomalous ϵ/β^+ Branching Ratios in Allowed Transitions*

R. B. Firestone, Wm. C. McHarris, W. H. Kelly, and R. A. Warner

We have measured a number of anomalous ϵ/β^+ branching ratios for transitions that are known to be allowed. Most of these involve odd-mass nuclei in the region below $N=82$. A rule of thumb statement seems to be that in a hindered allowed transition, one that involves a nuclear rearrangement in addition to the "simple" conversion of a proton into a neutron plus leptons, the β^+ branch is much worse than the ϵ branch. At the very least, this implies that the nuclear matrix elements for β^+ and ϵ decay are not the same. Explanations range from interference effects from second-forbidden decay to hints that weak interaction theory itself may be incorrect. One of the most clear cut examples is the decay of ^{145}Gd , which we illustrate below.

Relative β^+ feedings to levels in ^{145}Eu were measured in the $\gamma^+-\gamma$ coincidence experiments where coincidences between two 511-keV γ^+ pulses tagged a β^+ event and a third γ -ray labeled the β -fed level. Corresponding ϵ feedings were obtained from X- γ coincidence experiments. These two sets of intensities were normalized to each other by assuming the theoretical value of the $\epsilon(\text{tot})/\beta^+$ branching ratio to the 1757.8-keV level in ^{145}Eu . Additional, straightforward, corrections for K/L, K/M, etc., capture ratios were also made. The $\epsilon(\text{tot})/\beta^+$ branching ratios thus arrived at are presented in Table I.

The feedings to the 1757.8-, 1880.6-, 2494.8-, and 2642.2-keV levels appear quite well predicted by theory. The β -transitions to the 1757.8- and 1880.6-keV levels are well understood. Simplistically, they involve the transition of an $h_{11/2}$ proton from a proton pair to the $h_{9/2}$ neutron orbit, forming the three-quasiparticle states $(\pi h_{11/2})(\nu h_{9/2})(\nu s_{1/2})^{-1}$. Presumably the transitions to the 2494.8- and 2642.2-keV levels involve similar modes, but this is uncertain at this time. The branching ratio to the 1041.9-keV level shows signs of anomalous feedings, and that to the 808.5-keV level differs considerably from theory. These transitions are to simple single-particle levels but their modes are quite complicated. [The single-particle nature of the final state is demonstrated quite well from stripping experiments, E. Newman, *et al.*, Phys. Rev. C **1**, 1118 (1970).] They presumably involve the breaking of a $d_{5/2}$ proton pair, formation of an $s_{1/2}$ neutron pair, and promotion of the odd proton to an $s_{1/2}$ or $d_{3/2}$ level. The slowness of such transitions is evident from the log ft values.

Current β -decay theory assumes a constant force in all forms of decay but this work suggests that certain hindered transitions involve different

matrix elements for ϵ vs. β^+ decay. The possibility of such a complex beta force leads to conclusions such as interference effects from second-order decay or even implications for weak interaction theory and such aspects are currently under investigation.

TABLE I.--Measured $\epsilon(\text{tot})/\beta^+$ Branching Ratios for Decay of ^{145}Gd to States in ^{145}Eu .

Energy (keV)	% β (Total) ^a	$[\epsilon(\text{tot})/\beta^+]^b$ Theoretical	$[\epsilon(\text{tot})/\beta^+]$ Experimental	log ft ^a
808.5	5.1	0.45	8.02	6.9
1041.9	8.7	0.60	0.71	6.5
1757.8	35.7	1.17	1.17	5.6
1880.6	36.3	1.37	1.33	5.6
2494.8	1.3	3.39	3.02	6.7
2642.2	2.0	4.41	4.68	6.4

^aValues from R. E. Eppley, Wm. C. McHarris, and W. H. Kelly, Phys. Rev. C **3**, 282 (1971).

^bValues calculated in Nuclear Data A10, 205(1971).

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M. Slaughter, K. Kosanke, M. Edmiston, R. A. Warner

R. Firestone, Wm. C. McHarris and W. H. Kelly

A search for ^{141}Eu has been conducted with the 45 MeV proton beam of the MSU cyclotron and the helium jet recoil transport system. γ -ray singles spectra were taken with a Ge(Li) detector having a photopeak efficiency of 10.4% of 1333 keV (relative to a 3x3 NaI(Tl) detector). The optimum resolution of the system is 2.1 keV FWHM at the same energy. Targets were originally made by fixing ^{144}Sm oxide to an aluminum foil backing with an adhesive, but later we dispensed with the adhesive and relied on a pressure of approximately 20 tons per square inch to press the ^{144}Sm onto the backing.

Initially a very crude half-life determination was attempted by varying the speed of the paper tape upon which the activity was collected. The tape speed was varied between experiments so that the activity was counted for periods of 5 min, 1 min, 20 sec, and 10 sec following collection. A few γ -ray peaks of unknown origin were observed and their half-life was estimated as ~15 sec. A second, more extensive half-life determination was made using the data-taking program T00TSIE to accumulate 10 successive spectra with each counted for 9.4 sec. A cadmium-beryllium absorber was placed between the tape and the detector to reduce the bremsstrahlung background. Only two transitions were observed with half-lives comparable to that expected of ^{141}Eu based on our previous study of the growth of ^{144}Sm activity following the retrieval with a pneumatic rabbit of activity prepared by the $^{144}\text{Sm}(p,4n)^{141}\text{Eu}$ reaction; and on the work of L. Westgaard, et al.¹ who report a half-life of 37 ± 3 sec. These peaks are at 584.5 and 1611.4 keV and have a half-life of 45 ± 10 sec. In addition to half-life experiments, γ -ray singles spectra were collected for bombardment energies of 45 MeV, 41 MeV, and 39 MeV. The 584.5- and 1611.4-keV peaks were most intense at 45 MeV as would be expected if our assignment is correct.

Fig. 1.--Spectrum of γ -rays from activity deposited by the HeJRT system on moving paper tape. Recoils were obtained from an oxide target enriched in ^{144}Sm , bombarded with 45-MeV protons.

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L. E. Samuelson, W. H. Kelly, R. A. Warner, and Wm. C. McHarris

As a continuation of our study of the excited states of ^{48}V (see Ref. 1 and summary in Table I) two additional experiments have been performed. In the first, the $^{48}\text{Ti}(p, n\gamma)^{48}\text{V}$ reaction with $E_p = 7.20$ MeV was used to determine half-lives in the nano-second region. The ^{48}V γ rays were counted with a high-resolution planar Ge(Li) spectrometer. A beam sweeping system which removed every other cyclotron beam burst allowed counting in several 5.177-nsec time bands between the on-target beam pulses. The time bands were defined using the MSU cyclotron on-line Σ -7 computer data-acquisition program TOOTSIE.² A TAC measured the time intervals between start signals from events in the Ge(Li) detector (determined by constant-fraction timing discrimination) and stop signals derived from the cyclotron r.f. The cyclotron r.f. provided the time calibration.

The γ -ray spectra obtained from this experiment are shown in Fig. 1. As can be seen ^{48}V γ rays of 98.0-, 112.5-, 210.4-, and 308.3-keV are delayed. Since the half-life lower limit for this experiment is approximately 1 nsec, no other ^{48}V states below 1.7 MeV of excitation have half-lives greater than 1 nsec. The decay curves of the four delayed γ rays are plotted in Fig. 2. The decay curve of the 112.5-keV γ follows closely those of the 98.0- and 210.4-keV γ 's, thus this delay must be caused by γ -feeding and the half-life of the 420.8-keV state itself must

be much shorter than 1 nsec. Weighted least-squares fits (the straight lines of Fig. 2) to the data yield half-lives of 7.12 ± 0.04 and 2.72 ± 0.06 nsec for the 308.3- and 518.8-keV states, respectively. The measured half-life of the 308.3-keV state is compared with previous measurements using the ϵ -decay of ^{48}Cr in Table II. The excellent agreement lends confidence to our experimental techniques and data analyses.

The 7.12-nsec half-life of the 308.3-keV state is expected because of the energy and E2 multipolarity of its only possible γ decay. However, the 2.72-nsec half-life of the J=1 518.8-keV state is unusually large. If this low-lying state were to have positive parity, one would expect it to have particle configurations similar to the ground and first three excited states, thus facilitating rapid M1 decay. On the other hand a negative parity with particle configurations of $(\pi d_{3/2})^{-1}(\pi f_{7/2})^4(\nu f_{7/2})^5$ or $(\pi s_{1/2})^{-1}(\pi f_{7/2})^4(\nu f_{7/2})^5$ would yield j-forbidden E1 decays. Assuming E1 transitions, we obtain B(E1)'s of 6.39×10^{-5} and $1.05 \times 10^{-5} e^2 \text{fm}^2$ for the 98.0- and 210.4-keV γ 's, respectively. These are retardations of 1.3×10^4 and 9.1×10^4 over the single-particle estimates. Retardations by factors of 10^4 - 10^5 over single-particle estimates are commonly observed for E1 transitions of this sort.

In the second experiment we used the $^{46}\text{Ti}(\alpha, p n\gamma)^{48}\text{V}$ reaction with $E_\alpha = 24$ and 30 MeV

Table I: Energies and Spins of ^{48}V States and Energies, Branching Ratios, and Multipole Mixing Ratios of ^{48}V γ -rays from the $^{48}\text{Ti}(p, n\gamma)$ Reaction

Initial State (keV)	$J_i \pi_i$	$J_f \pi_f$	γ -Out (keV)	γ -Branching (%)	Mixing Ratio $\leq \delta \leq$
308.3 $\pm$ 0.1	2 +	4 +	308.3 $\pm$ 0.1	100	E2
420.8 $\pm$ 0.1	1 +	2 +	112.5 $\pm$ 0.1	100	-0.14 -0.02
427.9 $\pm$ 0.1	5(+)	4 +	427.9 $\pm$ 0.1	100	-0.15 -0.12
518.8 $\pm$ 0.1	1(-)	1 +	98.0 $\pm$ 0.1	38 $\pm$ 2	-0.08 +0.37
		2 +	210.4 $\pm$ 0.1	62 $\pm$ 2	+0.01 +0.07
613.4 $\pm$ 0.1	4(+)	5(+)	185.5 $\pm$ 0.1	11 $\pm$ 2	-0.02 +0.07
		4 +	613.4 $\pm$ 0.1	89 $\pm$ 2	-0.21 -0.17
627.3 $\pm$ 0.2	6(+)	5(+)	199.3 $\pm$ 0.2	37 $\pm$ 5	-0.23 +0.03
		4 +	627.3 $\pm$ 0.2	63 $\pm$ 5	(E2)
745.1 $\pm$ 0.1	2(-)	1(-)	226.3 $\pm$ 0.1	92 $\pm$ 1	-0.08 -0.06
		1 +	324.2 $\pm$ 0.1	3.1 $\pm$ 0.3	-0.21 +0.16
		2 +	436.8 $\pm$ 0.1	4.9 $\pm$ 0.4	-0.21 +0.14
765.0 $\pm$ 0.1	3(+)	4(+)	151.7 $\pm$ 0.2	2.2 $\pm$ 0.3	----
		2 +	456.7 $\pm$ 0.1	55 $\pm$ 2	-0.03 -0.01
		4 +	764.9 $\pm$ 0.1	43 $\pm$ 2	-0.05 +0.00
1055.9 $\pm$ 0.2	3(-)	2(-)	310.8 $\pm$ 0.1	92 $\pm$ 3	----
		1(-)	537.2 $\pm$ 0.2	8 $\pm$ 3	(E2)
1099.3 $\pm$ 0.2	4	4 +	1099.3 $\pm$ 0.2	100	-0.21 +0.22
1264.6 $\pm$ 0.2	5(+)	6(+)	637.3 $\pm$ 0.2	25 $\pm$ 4	----
		4(+)	651.2 $\pm$ 0.2	75 $\pm$ 4	-0.26 -0.03
1521.5 $\pm$ 0.2	2(+)	3(+)	756.4 $\pm$ 0.1	20 $\pm$ 2	-0.02 +0.13
		1 +	1101.0 $\pm$ 0.2	35 $\pm$ 4	-0.05 +0.03
		2 +	1212.9 $\pm$ 0.2	45 $\pm$ 4	+0.14 +0.28
1557.6 $\pm$ 0.2	4(-)	3(-)	501.8 $\pm$ 0.1	78 $\pm$ 4	-0.11 -0.06
		2(-)	812.2 $\pm$ 0.3	22 $\pm$ 4	(E2)
1685.6 $\pm$ 0.3	(5)	4	586.3 $\pm$ 0.2	100	----
1781.0 $\pm$ 0.2	3(+)	4(+)	1167.8 $\pm$ 0.2	42 $\pm$ 5	-0.20 +0.07
		2 +	1472.5 $\pm$ 0.2	43 $\pm$ 5	-0.12 +0.07
		4 +	1780.9 $\pm$ 0.3	15 $\pm$ 3	----
1998.6 $\pm$ 0.2	(3)-	4	899.4 $\pm$ 0.2	----	----
		2(-)	1253.3 $\pm$ 0.2	----	----

to measure γ - γ coincidences with a Ge(Li)-Ge(Li) coincidence spectrometer. The primary objective of this investigation is to look for high spin states which were weakly excited at best, in the (p,n γ) work. Preliminary results show that a very strong 627.3-keV line is a narrow multiplet (in coincidence with itself) with the number of components uncertain. The 199.3- and 427.9-keV γ 's and a new 395.2-keV γ appear to be in coincidence with the entire multiplet, making the placement of the multiplet components and the 395.2-keV γ uncertain. A 504.7-keV γ is found in coincidence with the 226.3-, 310.8-, and 501.8-keV γ cascade suggesting a new state at 2062.3 keV.

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Fig. 1.-- γ -ray spectra from ^{48}V half-life determination experiment.

Fig. 2.--Decay curves of four ^{48}V γ rays. Where not shown error bars are smaller than the data point symbol.

TABLE II.--Half-life measurements of the 308.3-keV state of ^{48}V .

$t_{1/2}$ (nsec)	Reference
7.12 ± 0.04	Present Work
7.21 ± 0.21	3
7.07 ± 0.14	4
7.09 ± 0.07	5
7.55 ± 0.28	6

Fig. 2

Fig. 1

L. E. Samuelson, C. B. Morgan, W. H. Kelly and Wm. C. McHarris

The radioactive decay of ^{56}Co has been studied quite extensively.¹ However, no γ-γ coincidences obtained with a Ge(Li)-Ge(Li) spectrometer have been reported.² In the present work, a 4.5%-efficient Ge(Li) detector and a 7%-efficient Ge(Li) detector were arranged in 150° geometry with a graded (Pb-Sn-Cu) absorber placed between them to suppress coincident Compton scattering from one detector into the other. A typical two-parameter fast-slow coincidence arrangement with constant fraction timing discrimination in the fast timing network was used. A resolving time $2\tau \approx 40$ nsec. was obtained. Addresses corresponding to the energies of coincident γ rays were listed in pairs on magnetic tape. This listing yielded a 4096x4096-channel array of prompt coincidence events which were later sorted off-line in gated slices. Each gated slice included careful subtraction of background coincidences which were determined from the adjacent continuum. The commercially obtained ^{56}Co source³ was positioned such that counting rates of approximately 15000 cps were obtained in each detector. A total of 15.8 million coincidence events were recorded in approximately 22h (coincidence rate 200 cps). The estimated chance coincidence rate ($2\tau N_1 N_2 \approx 9$ cps) was approximately 4.5% of the total coincidence rate. Both integral spectra and representative gated spectra are shown in Fig. 1. The size of the 846.78-keV peak appearing in its own gate is indicative of the importance of the chance coincidence rate. The coincidence results are summarized in Table I.

The γ-γ coincidence results (excluding those γ's too weak to be seen) are consistent with the decay scheme of Ref. 1. The only exception (possibly because of poor peak statistics) is the 733.70 keV γ which is not observed to be in coincidence with the 1037.83 keV γ. In the 733.70 keV gated spectrum the 1037.83 keV peak should be as strong as the 846.78 and 1238.28 keV peaks which stand out nicely above the background. An alternative placement of the 733.70 keV γ cannot be made without the introduction of a new energy level, possibly at 2818.76 keV. More detailed analyses of the data are underway.

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TABLE I.--Results of two parameter γ-γ coincidence experiment from ^{56}Co decay. All coincidences indicated by an X are definite. The γ-ray energies are from Ref. 4. γ-ray photo-peaks not listed were too weak to be observed.

E_{Gate} (keV.)	E_{γ} (keV)	511.00	733.70	846.78	977.46	1037.83	1175.13	1238.28	1360.22	1771.49	1963.94	2015.36	2034.92	2113.80	2213.10	2598.58	3010.20	3202.30	3253.60	3273.25	3451.55	3548.05
511.00		X		X		X		X								X						
733.70			X					X														
846.78		X			X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X
977.46				X		X		X														
1037.83		X	X	X		X	X															
1175.13				X		X		X														
1238.28		X	X	X	X	X			X	X	X	X	X		X							
1360.22				X				X														
1771.49				X				X														
2015.36				X				X														
2034.92				X				X														
2598.58		X	X																			
3202.30			X																			
3253.60			X																			
3273.25			X																			
3451.55			X

Fig. 1.--Integral and representative gated γ - γ coincidence spectra from ^{56}Co decay. Coincidence displays of the 7% detector were gated on the 4.5% detector. γ -ray energies are those of Ref. 4. The notations SE and DE stand for single and double escape, respectively. Note that the energy scales of the two integral spectra are slightly different.

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W. H. Kelly, Wm. C. McHarris, E. M. Bernstein*, and R. Shamu*

Introduction

The residual n-p interaction is still one of the most important problems facing the nuclear spectroscopist. Some fundamental understanding of its manifestations can be obtained from the study of odd-odd spherical nuclei. Unfortunately, these nuclei are very rich in states, making such investigations difficult. Some simplifications are possible near closed shells. A series of investigations of odd-odd nuclei, along with the on-going studies of the adjacent odd mass nuclei, have been initiated near the Z=50 and N=82 closed shells. Here one has a comparatively large number of stable isotopes that can be conveniently used as targets to investigate, for example, the systematic effects as one adds pairs of neutrons for the similar cases of Z=51 or pairs of protons for the N=81.

Because of the complexity of the excited nuclear states, it is necessary to use as many different experimental techniques as possible to study them. We are using those of in-beam gamma ray spectroscopy via the (p,xn γ) and (α ,xn γ) reactions [where x=1,2,3], beta decay, and the high resolution scattering reactions, such as the (p,d), (^3He ,t), (α ,d).

The next sections briefly describe the work in progress on ^{116}Sb and ^{118}Sb and a following section describes that on ^{140}Pr .

The Odd-Odd Nucleus $^{116}_{51}\text{Sb}_{65}$

We have performed a series of in-beam gamma-ray experiments using the (p,n γ) reaction. These consist of excitation function data, gamma-gamma coincidence, and lifetime measurements. In addition, some preliminary work has been done using the (α ,3n γ) and (p,3n γ) reactions which transfer larger amounts of angular momentum.

The (p,n γ) excitation data were taken with thick targets ($\approx 5 \text{ mg/cm}^2$) in 100 keV steps from 5.68 to 7.48 MeV. Approximately 90 gamma-rays have been identified in this 1.8 MeV interval. Analysis of these data gives growth curves for the transitions and branching ratios for level depopulation.

Coincidence data have been taken at 6.54, 7.28, 7.99, 8.40, and 11.75 MeV. Only 44 of the transitions appear in the coincidence data. Most of the remaining gammas are too weak to appear.

The energy level diagram below 1.6 MeV that is consistent with the excitation data and the coincidence data is given in Fig. 1.

Lifetime measurements using the beam sweeping system indicate that only the 93.7 keV transition is delayed more than two nanoseconds.

This lifetime is larger than 0.5 μ sec, which is the maximum time duration between successive swept cyclotron beam bursts with our current system.

The electron capture decay of $2.5 \text{ h } 0^+$ ground state of ^{116}Te has also been investigated briefly. Only three gamma rays were definitely identified with this activity. The intensities of the 103.0 and 628.7 keV gamma transitions are approximately the same while that of the 93.7 keV transition is about 5 times stronger. This supports our placement of these three transitions using the (p,n γ) data, shown in Fig. 1. The electron capture feedings to the 757.1 and 93.7 keV levels have log ft. values of 4.8 and 5.3, respectively (assuming no unobserved feedings to other states).

Gamma ray angular distribution measurements are in process to determine the levels spins and parities. (^3He ,t), (α ,t) and (α ,d) experiments are planned for the near future.

The First 1.2 MeV of $^{118}_{51}\text{Sb}_{67}$

The in beam gamma-ray experiments were performed using the $^{118}\text{Sn}(p,n\gamma)^{118}\text{Sb}$ reaction. The early, preliminary results of the excitation function data and the gamma-gamma coincidence data, the preliminary results of the comparatively low resolution $^{118}\text{Sn}(^3\text{He},t)^{118}\text{Sb}$, $^{117}\text{Sn}(^3\text{He},d)^{118}\text{Sb}$, and $^{117}\text{Sn}(^4\text{He},t)^{118}\text{Sb}$ scattering experiments were reported on in our last annual report.¹ Since then high precision energy calibration experiments and lifetime measurement experiments have increased the refinement of the suggested energy level diagram.

At present 118 gammas have been identified as very probably belonging to the de-excitation of the levels of ^{118}Sb up to about 1.2 MeV. Of these 56 gammas are intense enough to have been identified as being in coincidence with one or more other transitions.

The energy level diagram for levels up to 1.2 MeV incorporating the best present experimental information is shown in Fig. 2.

The lifetime measurements show that three of the gamma rays (238.46 keV, 187.72 keV, and 103.67 keV) that decay from the 269.6 keV state decay with a half-life of 13.3 n sec. The 115.40 keV gamma shows both a prompt ($\approx 2 \text{ n sec.}$) and a delayed component with a half-life of 13.2 n sec.

Gamma ray angular distribution measurements are planned for the near future to facilitate the assignment of spins to the states. The level density in this nucleus is so high that the charged particle scattering experiments have

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1553.8
1535.9
1507.9
1463.6
1424.6
1418.2
1332.1
1317.2
1291.8
1259.1
1249.5
1242.7
1234.9
1225.6
1222.9
1152.7
1112.8
1070.6
1046.2
1022.8
998.5
973.4
907.4
866.5
846.0
840.5
757.1
694.4
679.4
660.3
638.0
599.9
528.5
517.9
491.4
480.6
436.3
122.4
93.7
25.4
0.00

874.4
1055.3
889.9
784.2
806.6
937.6
814.2
637.8
612.4
778.5
1121.8 (45)
762.1 (35)
538.0 (23)
546.1 (21)
1129.1 (39)
1128.0 (36)
395.5
621.4
590.1 (29)
432.6 (80)
952.5 (41)
917.8 (33)
694.4
480.6 (32)
948.4 (24)
532.1 (21)
291.0 (67)
471.1
338.0
288.0
712.1 (70)
161.1 (30)
628.6
550.9
223.9
637.3
574.4 (32)
108.4 (61)
92.1 (23)
517.1 (23)
491.4 (11)
480.6 (8)
460.6 (3)
432.1 (3)
410.9 (8)
387.7 (13)
102.9
93.7
25.4
0.00

3⁺

116Sb65

53

Fig. 2.--Tentative and partial energy level diagram of $^{118}_{51}\text{Sb}$.

Using the $^{140}\text{Ce}(p,n\gamma)$, $^{141}\text{Pr}(p,d)$, $^{139}\text{La}(\alpha,3n\gamma)$ and $^{142}\text{Ce}(p,3n\gamma)$
to Study the Odd-Odd Nucleus ^{140}Pr

Jean Guile, C. B. Morgan, R. A. Warner, R. W. Goles, Wm. C. McHarris
W. H. Kelly, E. M. Bernstein*, and R. Shamu*

A series of investigations of the N=81 odd-odd nuclei are underway to study the residual p-n interaction near the N=82 closed shell and to see if shape isomerism exists in these "spherical" nuclei. The high density of the states of odd-odd nuclei require the use of high resolution spectroscopies using a variety of nuclear reactions and experimental techniques in complementary ways. Last year we reported¹ the results of some initial work using the (p,n γ) and (p,d) reactions for the investigations of $^{140}\text{Pr}_{81}$. This is a continuation of that study.

Figure 1 is the energy level diagram obtained involving only those states below 1200 keV that are excited in the (p,n γ) reaction. This is based upon the (p,d) reaction data, excitation function measurements with the (p,n γ) reaction and extensive coincidence measurements with the (p,n $\gamma\gamma$) reaction. This energy level diagram represents a refinement of that reported last year, with substantial additions.

In order to clarify certain discrepancies that appeared between the present (p,n γ) data, the earlier $^{141}\text{Pr}(\gamma,n\gamma)^{140}\text{Pr}$ work of Krehbiel¹ and the (p,d) data, we have also performed some additional gamma ray experiments using the $^{139}\text{La}(\alpha,3n\gamma)$ and $^{142}\text{Ce}(p,3n\gamma)$ reactions both in beam and pulsed beam. These discrepancies have been removed with the placement of a delayed state ($t_{1/2}=3.0\mu\text{sec}$) at 763.2 keV (not shown in Fig. 1). This is depopulated by a 635.7-keV gamma transition to the 0.5 μsec 127.5 keV state. The 763.2 keV state is populated via a $\ell=5$ transition in the (p,d) reaction and is not populated significantly in the (p,n γ) reaction. Apparently this inhibition is due to the low angular momentum transfer of the low energy (p,n γ) reaction.

The gamma ray spectra from the $^{142}\text{Ce}(p,3n\gamma)$ and the $^{139}\text{La}(\alpha,3n\gamma)$ reactions are considerably more complex than those of the (p,n γ) reaction for approximately the same energy of excitation in the residual nucleus. This indicates that the energy level diagram is considerably more complex than that indicated in Fig. 1 or by the (p,d) data. Presumably, the additional states are higher spin states which would be excited more strongly with the higher average angular momentum transfer of the ($\alpha,3n\gamma$) and (p,3n γ) reactions.

Considerable coincidence data have been obtained with the (p,3n γ) reaction and these are presently undergoing analysis. We are planning some gamma ray angular distribution measurements

in the near future. Those, coupled with the results of our (p,d) studies, should aid in the assignment of the spins and parities of the states and the determination of the multipolarities of the gamma transitions. Comparisons of these results with limited shell model calculations should aid in the understandings of the natures of the states.

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Fig. 1.--The energy level diagram of $^{140}_{59}\text{Pr}_{81}$ below 1200 keV obtained from the (p, γ) data.

R. B. Firestone, Wm. C. McHarris, and W. H. Kelly

Our work is essentially completed on the ϵ/β^+ decays of 2.61-min ^{143}Eu and 8.9-min ^{143}Sm .¹ These isotopes were prepared by the reaction, $^{144}\text{Sm}(p,2n)^{143}\text{Eu}$, using 28-MeV protons. Extensive γ - γ coincidence measurements have been made, including two-parameter "megachannel" coincidence experiments in which the events were listed on magnetic tape to be recovered later. Also, the ϵ/β^+ ratios were measured, using an 8"x8" NaI(Tl) split annulus as a pair spectrometer and using x-ray vs γ -ray coincidence experiments to confirm the results. Some of these ratios are listed in Table I along with theoretical predictions.² It can be seen that there are some major discrepancies, although not quite so blatant as for ^{145}Gd decay.³

These nuclei are important both for their own sakes and also for the way they fit into our overall studies of odd-mass nuclei below $N=82$, where we have been able to trace proton-pair occupation numbers via β decay and have found ϵ/β^+ decay to three-quasiparticle multiplets.⁴ The two decay schemes are presented in Fig. 1. Although it is not too obvious from the ^{143}Sm decay scheme alone, comparing its decay with that of ^{145}Gd and ^{141}Nd indicates that here again we have decay into a three-quasiparticle multiplet including the $3/2^+$ states at 1402.5 and 1514.5 keV (possibly even some of the 1056.2- and 1173.0-keV states, although these are primarily $d_{3/2}$ and $s_{1/2}$ states). We interpret this as the $h_{11/2}$ proton orbitals' receiving some occupation by pairs (not so much as in ^{145}Gd) and the $h_{11/2}$ neutron orbitals' having some small amount of vacancy, so the decay can be stylized as $wh_{11/2}^+ \rightarrow v_{h_{11/2}}$. Only the high-multiplicity of this decay causes it to be even as fast as it is.

Similarly, the decay of ^{143}Eu to states like those at 1536.69 and 1912.60 keV present some problems of interpretation and they may involve some sort of three-quasiparticle configuration. It is more difficult to pin this down at this point, however, and we plan to explore it further in a forthcoming paper.

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TABLE I.--Experimental and theoretical $\epsilon(\text{tot})/\beta^+$ branching ratios for ^{143}Eu and ^{143}Sm decays.

	State Energy in Daughter (keV.)	$\epsilon(\text{tot})/\beta^+$	
		Exp.	Theor.
^{143}Sm	1056.58	≈ 9.7	9.7
	1173.18	52 ± 13	13
	1403.06	35 ± 9	29
	1514.98	48 ± 12	49
^{143}Eu	1107.15	≈ 0.72	0.72
	1536.69	1.3 ± 0.2	1.17
	1565.85	0	1.21
	1715.14	1.7 ± 0.3	1.48
	1912.60	1.5 ± 0.4	1.95

* Supported by the U.S. Atomic Energy Commission and U.S. National Science Foundation.

Figure 1.--Decay scheme of ^{143}Eu . $Q = 5 \text{ MeV}$, $t_{1/2} = 2.3 \text{ min.}$

Figure 2.--Decay scheme of ^{143}Sm . $Q = 3.32 \text{ MeV}$, $t_{1/2} = 8.9 \text{ min.}$

The $\text{EC-}\beta^+$ decay of ^{177}Ta has been under study in hopes that low lying positive parity states associated with the $i_{13/2}$ family of Nilsson single particle orbits might be seen in levels of ^{177}Hf .¹ Study of this decay has been based on γ -ray singles and γ - γ coincidence spectroscopy as described in Ref. 1, and energies and intensities of γ -rays produced by the decay are given in Table 1.

The decay scheme for ^{177}Ta is shown in Fig. 1, and represents some modification of the decay scheme proposed by West, *et al.*² Figure 2 consists of representative coincidence spectra which brought about these modifications. Figure 2a is a spectrum of γ -rays in coincidence with the 420.8-keV transitions. It can be seen that γ -rays of 313.8, 177.0, and 105.3 keV are present, corresponding to a level at 426.7 keV which is well known from $^{177\text{m}}\text{Lu}$ decay. This indicates that the 420.8-keV γ -ray is a transition out of the level at 847.4 keV, and represents a substantial change in the decay scheme, as West had thought this γ -ray to be a transition to the ground state from a $3/2^+$ level at 421 keV.

Figure 2b is a spectrum resulting from a gate set on the 805.7-keV γ -ray. This transition is in coincidence with γ -rays of 197.1 and 142.4 keV, and is evidence for the newly assigned levels at 805.7, 948.0, and 1002.8 keV. The level at 873.0 keV is based primarily on energy sums and differences. However, this level and the level at 805.7 keV are in agreement with the (d,p)-(d,t) reaction work of Rickey and Sheline,³ in which $3/2^-$ and $5/2^-$ states are observed at 804 and 878 keV, respectively.

The conversion coefficients of γ -rays produced in ^{177}Ta decay are included in Table 1, and were calculated using the conversion electron data of West, *et al.* These data were normalized to the 249.7-keV γ -ray, known from $^{177\text{m}}\text{Lu}$ decay to be E2. Multipolarities listed in Table 1 were determined from the conversion coefficients using the theoretical values of Hager and Seltzer.⁴

In calculating β -decay feeding, the 78% branching to the ground state of ^{177}Hf , and the value $Q_{\text{ec}} = 1.166$ MeV proposed by West, *et al.* were assumed correct. Branching ratios for the decay were then determined using the measured relative γ -ray intensities, and $\log (ft)$ values were calculated using the tables of Love and Martin.⁵

The main point of interest in this level scheme is the even parity state at 1002.8 keV. The choice of even parity for this state is based on the K conversion coefficient of the

256.9-keV γ -ray, and is considered tentative due to the large error in this measurement. If the assignment is correct, the level could be the $5/2^+[642]$ state, associated with the $i_{13/2}$ family of Nilsson orbits. Additional evidence for this assignment is the similarity of $\log (ft)$'s of the state at 1002.8 keV, and the $9/2^+[624]$ and $7/2^+[633]$ band heads. The $\log (ft)$'s are quite high for "allowed" β -decay, consistent with the nucleon transition over two major oscillator shells required by the $7/2^+[404] \rightarrow 5/2^+[642]$, $7/2^+[633]$, and $9/2^+[624]$ β -decay transformations. It is expected that new conversion electron data will become available shortly, hopefully allowing a more definite assignment for the parity of the 1002.8-keV level.

* Supported by the USAEC and the NSF.

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FIGURE 1.--Decay of ^{177}Ta to levels of ^{177}Hf .

(a)

(b)

FIGURE 2.--Gated coincidence spectra for ^{177}Ta decay.

γ -Ray Transitions Seen In Decay of ^{177}Ta

γ -Ray Energy (keV)	γ -Ray Relative Intensity	α_K	α_L	Multipolarity
96.3	13. $\pm$ 2.		1.2 $\pm$.3	
105.3	8.9 $\pm$.9			M1 + E2 ^{e)}
112.9	10000. $\pm$ 1000.	0.63 $\pm$.1	1.1 $\pm$.2	E2 + M1 ^{e)}
129.9	1.5 $\pm$.2			
136.7	11. $\pm$ 1.	0.42 $\pm$.04	0.39 $\pm$.03	E2
142.4 $\pm$.2	0.75 $\pm$.12			
177.0	2.8 $\pm$.3			
197.1	4.0 $\pm$.3			
208.4	1300. $\pm$ 100.	0.043 $\pm$.004	0.0070 $\pm$.0006	E1
249.7	43. $\pm$ 3.	[0.090]	0.035 $\pm$.003	E2
256.9	1.2 $\pm$.1	0.6 $\pm$.4		(M1)
268.6	0.18 $\pm$.05			
283.2	0.76 $\pm$.08			
297.7	1.8 $\pm$.2	0.10 $\pm$.02		E2 + $\approx$ 40% M1
311.9 $\pm$.2	0.67 $\pm$.07			
313.8 $\pm$.2	0.98 $\pm$.11	<0.3	<0.1	
321.3	30. $\pm$ 3.	0.078 $\pm$.007	0.017 $\pm$.002	E1
354.9	2.5 $\pm$.2	0.06 $\pm$.02	0.03 $\pm$.02	(M1 + E2)
365.1	0.22 $\pm$.05			
395.2	7.3 $\pm$.58	0.036 $\pm$.005		E2 + $\approx$ 20% M1
398.3 $\pm$.2	0.78 $\pm$.11			
420.8	43. $\pm$ 3.	0.051 $\pm$.009	0.011 $\pm$.003	M1 + (E2)
424.6	150. $\pm$ 12.	0.058 $\pm$.006	0.010 $\pm$.002	M1
439.9 $\pm$.2	0.48 $\pm$.10			
453.2	3.1 $\pm$.3	0.047 $\pm$.007		(M1)
491.5	43. $\pm$ 3.	0.042 $\pm$.004	0.0064 $\pm$.0007	M1
494.7	5.9 $\pm$.6			
508.1	97. $\pm$ 8.	0.031 $\pm$.003	0.0050 $\pm$.0005	M1 + $\approx$ 35% E2
526.1	23. $\pm$ 2.	0.027 $\pm$.002	0.0046 $\pm$.0008	M1 + $\approx$ 40% E2
549.6	8.3 $\pm$.7	0.030 $\pm$.003		M1
597.7	13. $\pm$ 1.	0.005 $\pm$.003		
604.4	30. $\pm$ 2.	0.0092 $\pm$.0010	<0.002	E2 + (M1)
632.9	40. $\pm$ 3.	0.0033 $\pm$.0004	<0.0008	E1
681.5	1.1 $\pm$.2			
734.4	54. $\pm$ 4.	<0.0037 ^{d)}		E1
736.4	22. $\pm$ 2.	<0.0093 ^{d)}		E1
745.9	290. $\pm$ 20.	0.0023 $\pm$.0003		E1
760.0	0.91 $\pm$.09			
805.7	3.8 $\pm$.3			
847.4	37. $\pm$ 3.	0.0015 $\pm$.0002	0.0009 $\pm$.0007	E1
873.0	1.2 $\pm$.1			
944.8	76. $\pm$ 6.	0.0079 $\pm$.0008	0.0016 $\pm$.0002	M1
1002.8	1.4 $\pm$.1			
1057.8	400. $\pm$ 30.	0.0057 $\pm$.0005	0.0010 $\pm$.0001	M1 + ($\approx$ 20% E2)

- a) Unless otherwise indicated, errors may be taken as ± 0.1 keV.
b) Normalized to 112.9 keV γ -ray.
c) Conversion electron data taken from West et al. (Ref 2) normalized to 249.7 keV line.
d) Doublet not resolved in conversion electron spectra. The values of α_K represent in both cases the total electron intensity produced by the doublet.
e) Known from ^{177}Lu decay.

Decay of ^{199}Tl to Levels in ^{199}Hg *

G. Matthews and F. M. Bernthal

The region just below the ^{208}Pb doubly closed shell has been the subject of considerable interest and some speculation in recent months for several reasons, among them: (1) the apparent rotational-like structure of odd-A Hg isotopes at very high spins; (2) the discovery by the CERN group of sharp isotope-shift anomalies near ^{186}Hg ; (3) the prediction of a possible "bubble" structure in ^{200}Hg . For these reasons, among others, we have begun a study of the decays of Tl isotopes into their Hg daughters. Such studies are often of great significance to the correct interpretation of the in-beam γ -ray data.

The lower-spin level scheme of ^{199}Hg is of interest in its own right, ^{199}Hg being traditionally assigned the role of a "typical" deShalit¹ core excitation nucleus. Later and more precise data have indicated that this simple picture may require modification to explain experiment. The work on ^{199}Tl decay now in its final stages in our laboratory indicates that indeed the ^{199}Hg level is not well-described by the simple core-excitation picture. The difficulties present with even the more refined treatment of Kalish and Gal² persist. Our decay data are consistent with the recent (d,p) and (d,t) transfer data of Moyer³ and support the idea that the shell-model single-particle strength is in many cases fragmented among the various low-lying states in ^{199}Hg . This is especially true of the $3p_{3/2}$ shell model state; at least 4 low-lying $I^\pi = 3/2^-$ states are identified below 750 keV in ^{199}Hg , and none of them appears to be predominantly single-particle $p_{3/2}$, or particle-phonon ($p_{1/2}^{-2+}$) or ($p_{1/2}^{-2+}$) in character.

The ^{199}Tl decay scheme is largely unchanged from that proposed earlier,⁴ and so is not reproduced here again; one problem remains to be resolved, i.e. the possible doublet character of the 455.5-keV ($1/2^- \rightarrow 1/2^-$) γ -ray, the most intense line in the ^{199}Tl γ -ray spectrum.

Details of the ^{199}Tl decay investigation will be described in a forthcoming publication.

* Supported by the U.S. Atomic Energy Commission and the National Science Foundation.

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M. W. Johnson, R. A. Warner, Wm. C. McHarris, and W. H. Kelly

Previous work at this facility¹ reported many new levels in ^{199}Tl populated by the decay of the 90-minute ground-state ^{199}Pb . A total of 89 transitions among 29 levels were identified with this decay. In addition, the neutron-deficient lead isotopes have relatively long-lived metastable states based on the low-lying $i_{13/2}$ neutron level. For $^{199\text{m}}\text{Pb}$, a $t_{1/2}$ of 12.7 minutes has been reported²; the only known γ -ray emission is the 425-keV isomeric transition. Here we report several new levels and transitions from this activity.

The ^{199}Pb isotope can be produced through a variety of reactions on thallium and mercury. Most satisfactory for our purposes was the ($^3\text{He}, 4n$) reaction on ^{200}Hg . This was accomplished by bombardment of a target of separated (88%) isotope ^{200}HgO with 70-MeV ^3He ions from the MSU cyclotron, degraded to 35 MeV with aluminum. Although this energy is slightly above the threshold for formation of ^{198}Pb , we observed the latter only in negligible amounts. The targets were then counted with Ge(Li) detectors in both singles and coincidence modes. A typical singles spectrum (Figure 1) contained approximately 125 peaks ranging in energy from x-rays through a 2751-keV transition.

Most of the peaks observed are known from the earlier work as belonging to the decay of $^{199\text{g}}\text{Pb}$, but there are several new peaks as well. The most prominent addition is the 382-keV transition from the metastable state (9/2-) in the daughter nucleus ^{199}Tl to the known 366.9-keV first excited state (3/2+). Although this peak has little independent significance as it is known from other work, it is indicative of formation of high-spin $^{199\text{m}}\text{Pb}$, as the ground-state decay does not populate such a high-spin state to any appreciable extent. As the $t_{1/2}$ of $^{199\text{m}}\text{Tl}$ is short (28 msec) compared to that of $^{199\text{m}}\text{Pb}$, it is possible to use the relative intensity of this and the 425-keV isomeric transition as a function of time to determine those peaks to which the metastable decay contributes heavily. A list of such peaks appears in Table 1.

As coincidence data for this decay are currently lacking, it is not possible to say with certainty what, if any, new levels are observed from the metastable decay. However, there seems to be fairly good evidence for a new level at 2612 keV, as well as several levels proposed by Doebler but not included in his final scheme for $^{199\text{g}}\text{Pb}$. The evidence is strongest for a level at 2019 keV and another at 1647 keV; however, other levels at 1602 keV, 2399.2 keV, and possible 2751.9 keV are also suggested. The latter energy must be viewed with suspicion as it

is very close to that found in the decay of 15.0-h ^{24}Na , which is known to exist as a contaminant based on neutron capture. However, the peak demonstrates a time dependence consistent with a half-life on the order of 50 min, so one may suspect a component from the decay being studied. In addition, it appears that the known 1695-keV level is much more strongly populated by metastable decay than ground-state decay.

Our future plans include gamma-gamma coincidence studies and more exacting examinations of variation of intensities with time. In addition, we plan to continue examination of light lead nuclei by looking at the next odd-mass nucleus, ^{197}Pb .

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TABLE 1.--New transitions (energies in keV).

145.1 $\pm$ 0.15	1223.2 $\pm$ 0.15
323.4 $\pm$ 0.4	1602.2 $\pm$ 0.2
387.1 $\pm$ 0.1	1891.0 $\pm$ 0.5
416.5 $\pm$ 0.4	2399.2 $\pm$ 0.4
896.1 $\pm$ 0.4	2612.9 $\pm$ 0.4
947.3 $\pm$ 0.17	2751.9 $\pm$ 0.4

Figure 1.--Single γ -ray spectrum for ^{199m}Pb decay taken with a 10.4% Ge(Li) detector.

An Experimental Demonstration of Backbending
from a Band-Crossing in ^{154}Gd

T. L. Khoo, F. M. Bernthal, J. S. Boyno and R. A. Warner

At high spins the rotational bands of a number of nuclei exhibit a phenomenon commonly referred to as back-bending--a name derived from the characteristic S-shaped plots of the moment of inertia, $2\mathcal{I}/\hbar^2$, vs the square of the nuclear rotational frequency, $(\hbar\omega)^2$.¹⁻³ This anomalous behavior has been attributed to the Mottelson-Valatin⁴ effect, which is a phase transition from the normal superfluid state to one in which the nucleon pairs have been coherently broken by the Coriolis force. It is also possible to explain the back-bending effect in terms of a band which intersects the ground band to become the yrast band.^{5,6} The question then reduces to one of the intrinsic character of the band. This intersecting band might be the Mottelson-Valatin⁴ type unpaired band, the decoupled band of Stephens and Simon,⁵ or perhaps even a quasiparticle or vibrational band. However, until now there has been no experimental evidence that explicitly demonstrates the band-crossing feature. We shall show here a case in which back-bending in the yrast band can be directly attributed to band-crossing.

The levels of ^{154}Gd have been studied by means of the $^{154}\text{Sm}(\alpha, n)^{154}\text{Gd}$ reaction using α -beams from the Michigan State University sector-focused cyclotron. Both γ -singles and γ - γ coincidence measurements were performed with Ge(Li) detectors of 4.5 and 8% efficiency (at 1.3 MeV). Measurements of the angular distributions of the γ -rays as well as the γ - γ coincidence experiments were performed with 48 MeV α -beams, while excitation function measurements were made with beams of 41, 45, 48 and 50 MeV. Supplementary singles data from the $^{152}\text{Sm}(\alpha, 2n)^{154}\text{Gd}$ reaction with 24 MeV α 's were also accumulated.

Members of two rotational bands--ostensibly the ground and β -bands--have been identified and these are shown in Fig. 1. There is an ambiguity regarding the spin 18 members, and for Fig. 1, the yrast and yrare levels have been grouped together--an yrare level is defined here as the first excited state above the lowest (yrast) state of the same spin. Other levels not included in Fig. 1 have also been observed and these are presently being investigated.

The interband to intraband ratios, given in brackets in Fig. 1, show a dramatic increase from $<10^{-3}$ to 1.4 as I' increases from 12 to 18. It can be shown that unless there is a crossing of the ground- and β -bands, the B(E2) values of the transition from each of the spin-18 members cannot have the comparable magnitudes observed. The observed B(E2) branching ratios thus provides

evidence that there has been a crossing between $I=16$ and 18. It is in fact possible to account for all the observed B(E2) branching ratios for $I=12'-18'$ and $I=18$ by assuming an admixture between the ground- and β -bands. Calculations involving 2-band mixing with a number of suitable interactions have been carried out which predict the B(E2) ratios satisfactorily. These calculations show that the $I=18$ (yrast) level actually contains more of the β -band than the ground-band, while in the $I=18'$ (yrare) level the admixtures are reversed.

A plot (Fig. 2a) of the moment of inertia, $2\mathcal{I}/\hbar^2$, vs the square of the nuclear rotational frequency, ω^2 , yields backbending curves in both the yrast and yrare sequences (filled symbols). The open symbols in Fig. 2a represent the alternative band assignment for the spin-18 levels, i.e., according to the predominant ground- or β -band structure. Clearly no backbending occurs in the predominately ground band: this is a feature of the yrast states. Furthermore, the above discussion leads one to conclude that the backbending arises from a crossing of the ground and β -bands. This is believed to be the first explicit demonstration of backbending from a band-crossing. In this regard, it should be noted that in previously reported cases, the anomalous behavior of backbending was a characteristic of the yrast states, no distinction having been made between the yrast and ground bands. The band-crossing is illustrated in Fig. 2b where the lines connect points with the same predominant (ground- or β -band) structure. Notice that points for $I=12', 14', 16'$ and 18 fall along a straight line, indicating that the β -band behaves like a perfect rotor and with a moment of inertia equal to the rigid rotor value.

For $I>12$, the "perfect rotor" behavior of the β -band, the rigid moment of inertia, and the small matrix elements (25 keV for $I=18$) between its members and those of the ground band at these high spin values, all lead one to question whether it still is the β -band as such. In fact, the data may be satisfactorily interpreted in terms of a new band which intersects the β -band to become the yrare sequence for $I>12$, and further intersects the ground band to form the yrast levels for $I>18$. The evidence for the intersection with the ground band has already been presented; however, we have not yet found any direct evidence for the crossing of the β -band by the postulated "intersecting band", nor is the intrinsic character of this band known. It would however, be difficult to identify it with a band formed by

decoupling two $i_{13/2}$ particles, which Stephens and Simon⁵ suggest is responsible for back-bending in yrast states. Such a band would not be expected to fit the straight line of Fig. 2b since, in the decoupled limit, the band begins to form only after $I=12$, with the spin given by $I=R+12$ and the energy spacing given by $\Delta E(I \rightarrow I-2) \sim \Delta E_{gsb}(R \rightarrow R-2)$ (R , the rotational angular momentum, takes on values of 2, 4, ..., and ΔE_{gsb} is the energy spacing in the ground state band with the appropriate $I=R$ values.) The rigid moment of inertia of this band tempts one to speculate that it arises from a coherently unpaired Mottelson-Valatin⁴ type state.

Before any definite statements can be made about the postulated "intersecting band", it is clear that further experiments are necessary. In particular it is important to determine the intrinsic nature of the yrare levels with $I > 12$. A detailed study of the levels in the vicinity of the $I=12'$ state is being planned to search for explicit evidence for a band-crossing in this region. We propose to perform γ - γ coincidence measurements with the $^{152}\text{Sm}(\alpha, 2n)^{154}\text{Gd}$ reaction, since this reaction tends to populate a broader range of states and might thus be more favorable for such a study than the $(\alpha, 4n)$ or (heavy ion, xn) reactions.

A study of ^{152}Gd , using the $^{152}\text{Sm}(\alpha, 4n)^{152}\text{Gd}$ reaction has also been under taken, in order to determine if the situation here is similar to that in ^{154}Gd . However, the data from this case has yet to be analyzed.

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Fig. 1.---Partial level scheme for ^{154}Gd , showing the yrast and yrare bands. The numbers in brackets give the interband to intra-band $B(E2)$ ratios, $B(E2 I' \rightarrow (I-2)') / B(E2 I' \rightarrow (I-2))$ or $B(E2 I \rightarrow (I-2)') / B(E2 I \rightarrow (I-2))$. The transitions indicated by asterisks are members of unresolved multiplets. The 612 keV line was separated into the $18^+ \rightarrow 16^+$ and $8^+ \rightarrow 8^+$ components based on the branching ratio, $I(8^+ \rightarrow 8^+) / I(8^+ \rightarrow 6^+)$, determined from the $(\alpha, 2n)$ reaction in which the $18^+ \rightarrow 16^+$ component was practically absent.

Fig. 2a.--Plots of the moment of inertia against the nuclear rotational frequency for both the yrast and yrare levels (filled symbols). The open symbols represent the alternative band assignments for the spin 18 levels. The points were obtained in the manner described in Ref. 7.

Fig. 2b.--Plot of the level energy against $I(I+1)$. The circles and squares denote the yrast and yrare levels, respectively; the lines connect states which are either predominantly ground- or β -band. The dashed portion, which is an extrapolation of the straight line through the points for $I=12'$, $14'$, $16'$ and 18 and which extends to $E=1.45$ MeV at $I=0$, illustrates the possible existence of the postulated "intersecting band."

R. A. Warner, F. M. Bernthal, J. S. Boyno, T. L. Khoo, G. Sletten,** and B. D. Jelte

The discovery of phase transitions or backbending in ^{181}W and ^{182}Os , described in the 1971-72 Annual Report could not be understood in terms of the Stephens-Simon model.¹ For this reason we continued the search in other Os isotopes.

Self-supporting foils of separated tungsten isotopes ($^{182},^{184},^{186}\text{W}$) were prepared with the heavy-ion sputtering apparatus at the Niels Bohr Institute, and bombarded with beams of alpha particles from the MSU cyclotron. Gamma-ray spectra accompanying the (α, xn) reactions on these targets have been analyzed to establish the yrast cascades in $^{182},^{184},^{186},^{188}\text{Os}$. Table I contains a partial list of the transitions observed. Selected γ -ray spectra, γ - γ coincidence gates, γ -ray anisotropies, and excitation functions for ^{186}Os are displayed in Figs. 1 through 4 respectively, as representative of the data collected. In the ^{186}Os experiment more than 13 million coincidence events were accumulated, while in each of the other cases, more than 5 million events were recorded.

TABLE I.--Transition energies in keV for yrast and near-yrast cascades in four osmium isotopes.

	^{182}Os	^{184}Os	^{186}Os	^{188}Os
2 $\rightarrow$ 0	127.0	119.8	137.2	155.0
4 $\rightarrow$ 2	273.4	263.8	296.8	322.9
6 $\rightarrow$ 4	393.3	390.3	434.8	462.3
8 $\rightarrow$ 6	483.0	500.7	552.1	574.5
10 $\rightarrow$ 8	533	596.2	647.4	655.1
12 $\rightarrow$ 10	533	675.6	713.1	685.9 ^b
14 $\rightarrow$ 12	493.5	712.7	658.8 776.8 ^a	
16 $\rightarrow$ 14	479.4	528 ^b	494.8	
18 $\rightarrow$ 16			559.5 ^b	

^aThis transition feeds the 12⁺ level in the yrast cascade, and displays an angular distribution and an excitation function consistent with assignment as a stretched quadrupole transition.

^bThe initial spins assigned to these transitions are less certain than are the others in the Table.

The levels shown in Fig. 2 correspond to the transitions listed in Table I. The curves in Fig. 6 result from plotting $2Q/\hbar^2 = \Delta[I(I+1)]/\Delta E$ vs. $\hbar^2\omega^2 = [\Delta E/\Delta\sqrt{I(I+1)}]^2$ for each transition. The values of $\Delta[I(I+1)]$, ΔE and $\Delta\sqrt{I(I+1)}$ are determined from Table I. The $^{178},^{180}\text{Os}$ curves, included for completeness, are computed from published results.² Attention should first be directed to the point in Fig. 6 connected by a dashed line to the other ^{186}Os points. This point is computed from the 776.8-keV transition feeding the 12⁺

g.r.b. state from a non-yrast 14⁺ state. The experimental level spacing and excitation function for this transition are precisely those expected for the g.r.b., while the same measurements for the yrast 14⁺ $\rightarrow$ 12⁺ transition yield quantities anomalous for the g.r.b. Thus the yrast states above spin 12 in ^{186}Os appear to be members of some other band. Furthermore, this band must be relatively unmixed with the g.r.b., as a search for the E2 transition from the yrast 16⁺ state to the g.r.b. 14⁺ state was negative. The B(E2) strength of this unseen line is less than 30% of that for the branch to the yrast 14⁺ state. The intrinsic structure of the band composed of yrast states above spin 12 remains unexplained.

A perfect rotor would be represented in Fig. 6 by a horizontal line. At low spin the heavier Os isotopes appear to be the best rotors, but $^{184},^{186}\text{Os}$ also display two of the most pronounced examples of backbending behavior known. At first glance, this behavior seems at odds with the explanation offered by Stephens and Simon¹ for backbending in other nuclei. However, the location of the Fermi surface among the $i_{13/2}$ neutron states is not the only factor of importance to a discussion of backbending. Coriolis matrix elements also depend on the rotational parameter $\hbar^2/2\mathcal{J}$. This parameter is significantly larger for the Os isotopes than for the more deformed rare-earth nuclei for which backbending has been reported. In addition, the large hexadecapole moments found in the Os region³ lead to a compression of the low- Ω states, thereby enhancing the mixing between the various $i_{13/2}$ Nilsson orbitals. Thus, $i_{13/2}$ neutrons may still be effectively decoupled in the even-mass Os isotopes, despite the location of the Fermi surface far from the low- Ω levels. Alternatively, Stephens, et al. have recently suggested⁴ that decoupling of $h_{9/2}$ protons, apparent in odd-mass Re data,⁵ may contribute to the Os backbending.

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In the past year, the MSU γ -ray spectroscopy group has been very active in the study of backbending in rotational nuclei. This study has employed primarily in-beams γ -ray spectroscopy, using (α, xn) reactions on self-supporting targets to populate levels in various even-mass Os, W, and Gd nuclei^{1,2}. In continuation of the survey of the $Z=74$ nuclei, we decided to deduce the levels of ^{182}W , and to look for backbending in this nucleus.

Levels in ^{182}W were populated via the $^{180}\text{Hf}(\alpha, 2n)^{182}\text{W}$ reaction using a beam of 26 MeV α particles produced by the MSU cyclotron. Figure 1 shows the singles spectrum of γ -rays associated with levels of ^{182}W . It can be seen that the γ -ray energies follow the $I(I+1)$ spacing predicted by the rotational model up to spin 12. At this spin there is a change in the pattern, in that two $12^+ \rightarrow 10^+$ transitions occur.

Three parameter γ - γ coincidence data were taken in-beam, and Fig. 2 shows the spectra resulting from gates set on ground band transitions. It can be seen that the two $12^+ \rightarrow 10^+$ transitions are in coincidence with the rest of the ground band, but not with each other. Thus there can be

no doubt that both γ -rays result from transitions to the 10^+ level, and the conclusion that two distinct 12^+ levels exist must be considered. Preliminary analysis of the γ -ray angular distributions and excitation function data for these transitions allow the indicated spin assignments to be made unambiguously.

Figure 3 is a plot of the moment of inertia, $2\mathcal{J}/h^2$, vs. the square of the rotational frequency, $h^2\omega^2$. The plot clearly displays the backbending nature of the yrast band. In addition, the higher energy 12^+ level fits nicely on the straight line formed by the ground band, which is further evidence for the spin assignment. If these tentative spin assignments are correct, ^{182}W represents a very clear case of backbending and forking in the ground band.

*Supported by the USAEC and the NSF.

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Figure 1.-- ^{182}W γ -ray singles spectrum.

FIGURE 2.--Gated coincidence spectra of ^{182}W ground band. Arrows indicate gates.

FIGURE 3.--Moment of inertia plotted vs. rotational frequency for ^{182}W .

F. M. Bernthal, J. S. Boyno, C. L. Dors, T. L. Khoo and R. A. Warner

Closely related to the in-beam gamma-ray investigations of rotational behavior at very high spins is the rotational band structure in the neighboring odd-A species. Our systematic study of the N=105, 107, 109, and 111 isotones is continuing; data have now been gathered for ^{179}W , ^{181}W , ^{183}Os , and ^{187}Os . Results for these four nuclei are now largely finalized¹ and preliminary data have been gathered on ^{181}Os . The experimental procedure is similar in every case: the (α, xny) reaction is used to populate rotational band structure in the residual nucleus, and (γ, θ) angular distribution, excitation function, and γ - γ coincidence data are gathered to support the assignments.

The initial impetus for this project was the desire to investigate the highly-perturbed unique-parity $i_{13/2}$ neutron orbitals in this region where the $\Omega = 9/2$ and $\Omega = 11/2$ orbitals lie near the Fermi surface. One of the most puzzling aspects of the unique-parity band structure in both odd-N and odd-Z nuclei is the apparent attenuation of the Coriolis matrix elements near the Fermi surface. Such an empirical attenuation is generally found to be requisite to an explanation of the perturbed band structure in these nuclei. Though the difficulty has been and remains oft-noted in the literature, the explanation is still an open question, though recently some promising attempts to explain the experimental data have appeared.²

At the same time, however, a largely unanticipated relevance of the odd-mass rotational band structure to the surprising phenomenon of "backbending" in even-even nuclei has become evident. The interpretation of the now frequently reported effect is still in doubt;³ it is apparent however that the Stephens-Simon⁴ interpretation of the "backbending" effect relies on the very same attenuation of Coriolis matrix elements as has been empirically deduced in the odd-N nuclei. Moreover, extension of the SS model to explain the very sharp effects first observed in this laboratory in the neutron-rich even-even Os and W isotopes requires evidence for decoupling of even higher- $\Omega_{i_{13/2}}$ neutrons from the rotation of the core of the nucleus. This evidence is provided in a qualitative way in Fig. 1, where the data from other laboratories⁵ on the indicated lower- $\Omega_{i_{13/2}}$ bands in ^{161}Er and ^{169}Hf are compared with ^{179}W , ^{183}Os , and ^{187}Os data taken in our laboratory. The former bands are understood to be largely decoupled from the core at high spins, but as the persistence of the $\Omega = 1/2$ perturbation in ^{187}Os indicates, it is possible that even here the $i_{13/2}$ neutrons may decouple from the rotating core to produce at high spins the observed effects in the neighboring even-even species. Finally, we note

that the answer to the question of what is occurring in even-even nuclei at very high spins may lie in an investigation of the odd-A species at comparable core rotational frequencies. An attempt several months ago in our laboratory to observe such very high spins in ^{165}Tm was unsuccessful. Further experiments to explore this latter possibility are planned.

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Fig. 1.--Perturbed rotational band structure for Nilsson orbitals arising from $i_{13/2}$ shell-model state. The data for ^{161}Er and ^{169}Hf are from Refs. 5.

M. Slaughter, R. A. Warner, W. H. Kelly and Wm. C. McHarris

The rotational band structure of ^{182}Re is being studied by the $(\alpha, 3n\gamma)$ reaction on a 0.1 mil ^{181}Ta target. γ - γ coincidence and γ -ray lifetime measurements have been completed. Coincidence data were taken with 4.5% and 7% Ge(Li) detectors (efficiency is given at 1333 keV relative to a 3×3 NaI(Tl) detector) at a geometry of 180° . Also, Cu-Cd absorbers were placed between each detector and the target to reduce coincidences due to Compton backscattering. A tentative decay scheme consisting of the first two rotational bands that have been identified is shown in Figure 1. The rotational band structure is quite evident in the spectrum of all coincidence events shown in Fig. 2. The order of the bandheads is opposite to that reported by Hjorth, *et al.*¹ and is supported by the fact that the 289.2-keV transition is not observed in coincidence with any transitions of the first band (except the 154.1 keV transition which it feeds) but is seen in coincidence with the entire second band. This has also been suggested by Medsker, *et al.*² New transitions

observed are 391.1, 493.8, 539.9, 584.0, 303.1, 321.4, 624.6, 281.8, 585.9, (662.7) and (647.4) keV with new levels at 1331.6 and 1634.7 keV in the first band and 1912.5 and 2233.9 keV in the second band.

Of particular interest are the similarities of the energies of the transitions between the upper members of two bands. This suggests a strong decoupling between the odd proton-odd neutron and the even-even core.

The γ -lifetime measurements were made with the cyclotron beam sweeper and a Low Energy Photon Ge(Li) detector. Ten successive spectra were taken with each counted for 54 nsec. and the results analyzed. The upper band is found to be delayed with a half-life of 91 ± 3 nsec. while the 443.3-keV level is fed by an unidentified prompt transition. Future work planned includes completing the analysis of the coincidence data, obtaining more accurate lifetime measurements and performing angular distributions experiments.

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Fig. 1.--Tentative scheme of levels populated strongly in the $^{181}\text{Ta}(\alpha, 3n)^{182}\text{Re}$ reaction.

Fig. 2.--Integral coincidence spectrum for γ -rays from ^{182}Re .

C. Dors, F. M. Bernthal and R. A. Warner

Investigation of the rotational band structure of ^{183}Os is continuing via in-beam γ -ray spectroscopy. The levels in ^{183}Os are populated in the $(\alpha, 3n\gamma)$ reaction on ^{182}W and in $(p, 3n\gamma)$ on ^{185}Re . The $9/2^+$ [624] ground band in ^{183}Os has been identified up to spin $33/2$, the $7/2^-$ [514] band has been tentatively identified up to spin $15/2$, and there is also evidence for the population of at least one other band, probably the $5/2^-$ [512].

For the $(\alpha, 3n\gamma)$ studies, a self-supporting foil¹ of ^{182}W was bombarded with 38-MeV α -particles from the MSU cyclotron. Prompt γ -ray singles as well as delayed spectra were obtained. Angular distribution and excitation function data were obtained for the γ -ray singles spectrum in the region 50-700 keV with use of a low-energy photon spectrometer (LEPS) (resolution 650 eV at 122 keV). Gamma-Gamma coincidence measurements were also taken using 4.5% and 7% Ge(Li) detectors. In the delayed γ -ray experiment, the cyclotron beam sweeper was used to select one of every nine beam bursts to scan the time region ~ 500 nsec following the beam burst; with the sweeper off, a 500 nsec scan was made between beam bursts to search for very short-lived decays.

Preliminary results show little change from our previously reported data for the $9/2^+$ [624] band² and good agreement with the data recently reported by the Stockholm group.³ In addition, we now tentatively place the $7/2^-$ [514] band head at 392.5 keV, with other members at 558.4, 749.1, 958.5, and 1180.0 keV. Further analysis should yield additional data on this band. Progress is also being made on describing the levels associated with the $5/2^-$ [512] and $1/2^-$ [521] bands, expected to lie near the ^{183}Os ground state. The $^{185}\text{Re}(p, 3n\gamma)$ experiments now beginning should aid in the identification of these non-yrast bands which are populated so weakly in the $(\alpha, 3n\gamma)$ experiments.

T. L. Khoo and F. M. Bernthal

Five high-K 2 quasiparticle bands have recently been identified¹ in the even-even nucleus ^{176}Hf , based on the following high- Ω orbitals: $5/2^-(512)\text{n}$, $7/2^-(514)\text{n}$, $9/2^+(624)\text{n}$, $7/2^+(404)\text{p}$, $9/2^-(514)\text{p}$, $5/2^+(402)\text{p}$. Four quasiparticle states with low-K couplings based on these orbitals have also been observed² in the decay of ^{176}Ta . It is therefore of interest to identify the corresponding high-K couplings of these 4 quasiparticle states. To this end, we have studied the delayed (by up to 0.5 μsec .) gamma rays from the $^{176}\text{Yb}(\alpha, 4\text{n})^{176}\text{Hf}$ reaction at an alpha beam energy of 48 MeV. Delayed transitions from members of two known¹ $K=8^-$ bands have been observed. A preliminary analysis indicates the existence of an isomer ($T_{1/2} > 0.5$ sec.) at 2827 keV, which decays to the 11^- and 12^- members of the two $K=8^-$ bands. Further analysis is necessary for a definite isomer spin assignment, but the decay pattern is consistent with the isomer having a spin of 12. Indeed, from the known 2 quasiparticle energies,¹ the lowest 4 quasiparticle state is expected to be the $K=12^+$ [$7/2^+(404)\text{p}$, $5/2^+(402)\text{p}$, $7/2^-(514)\text{n}$, $5/2^-(512)\text{n}$] configuration at approximately 3 MeV.

At a somewhat higher (100-400 keV) energy two $K=14^-$ states are expected and efforts will focus on identifying them. The energies of the 4 quasiparticle states will then be compared with those predicted from the known 2 quasiparticle energies, taking into account the various residual interactions.

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T. L. Khoo, F. M. Bernthal, J. S. Boyno and R. A. Warner

In the nuclei around ^{176}Hf there is a proliferation of high Ω orbitals in the vicinity of the Fermi level. This leads to the consequence that many of the low-lying two quasi-particle states in this region have large K-values. The rotational bands built on five high-K states have been observed¹ in ^{176}Hf . Similar states are also expected in ^{174}Hf .

One of the most interesting observations from Ref. 1, was that there was an unusually large interaction (210 keV) between a $K^\pi=6^+$ ($7/2^+[404]_{\rho}, 5/2^+[402]_{\rho}$) state and a $K^\pi=6^+$ ($7/2^-[514]_n, 5/2^-[512]_n$) state. Although this phenomenon was initially unexpected it can be accounted for through the residual neutron-proton interaction.^{2,3}

In order to extend our understanding of this problem in the rare earth deformed region, there is a need for more experimental information on other high-K states. We have therefore begun an investigation of ^{174}Hf , using the $^{174}\text{Yb}(\alpha, n)^{174}\text{Hf}$ and $^{172}\text{Yb}(\alpha, 2n)^{174}\text{Hf}$ reactions. Singles γ -spectra have been recorded from both reactions, and γ - γ coincidence measurements have been performed using the $(\alpha, 4n)$ reaction. γ -spectra, delayed up to 0.5 μsec , have also been studied. In addition to the usual analysis of the 3 parameter (E_1 - E_2 - T_{12}) γ - γ coincidence data for prompt coincidences, delayed coincidence relationships have also been obtained by setting appropriate TAC gates during the sorting.

Two rotational bands have been observed; one built on a known $K=6^+$ isomeric state⁴ at 1549.4 keV has been identified to spin 12. Four members of the other band, also built on a new isomer at 1609.9 keV have been tentatively identified. This new isomer with $t_{1/2} > 0.5 \mu\text{sec}$, decays to the known isomer through a 60.5 keV transition. Another newly discovered isomer at 3269.1 keV with a half-life $> 1 \mu\text{sec}$, decays to the $IK^\pi=12, 6^+$ and 11, 6^+ members and must therefore have a very high spin ($I \geq 12$) and a correspondingly high K. With the available Nilsson orbitals, a state of such high K is most likely a 4 quasiparticle state.

The data from the experiments are still being analysed and we expect soon to extract the intrinsic g-factors, g_K , of the observed rotational bands. As described in Ref. 1, this should lead to a knowledge of the intrinsic structure of the states.

Although attention has been focussed mainly on the high-K states, members of the ground state band have also been identified to spin 18. The levels spacings do not indicate any anomalous variation in the moment of inertia, which has been observed in a number of other nuclei (e.g., see p. and in this report).

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J. S. Boyno, F. M. Bernthal, T. L. Khoo and R. A. Warner

A study of the complex γ -spectra obtained in the $^{186}\text{W}(\alpha, 3n)$ reaction is in progress. The level spectrum of ^{187}Os has been previously investigated with γ -ray spectra obtained from the decay of $^{187}\text{Ir}^{1,2,3}$ and with particle spectra obtained from the (d, p) , (d, t) and (d, d) reactions.^{3,4} Low spin members of numerous Nilsson configurations have been identified, and this previous work is complementary to the present study. The $(\alpha, 3n)$ reaction excites both high and low spin states of yrast and near-yrast configurations.

Coincidence measurements were performed with 35 MeV α -particles bombarding a self supporting target of ^{186}W . Two 7% Ge(Li) detectors were used for γ - γ coincidence measurements. In addition, γ -singles were recorded at four angles using a low energy photon spectrometer. This afforded us the high resolution necessary to separate closely spaced peaks and allowed us to determine, from the angular distributions, the multipolarities of the γ -rays. Other measurements were made using the MSU cyclotron beam sweeping system, which allowed us to directly measure the half lives of isomeric transitions in the 0.5-500 nsec. region.

There are approximately 120 γ -rays of between 100-700 keV in the ^{187}Os spectrum. The singles data have been fitted using the peak fitting program SAMPO, which, in one case, was used to satisfactorily ascertain the energies and intensities of a quintuplet, where there are five peaks separated in total by five keV. Preliminary analysis of the coincidence data has been performed by setting gates on approximately sixty of the stronger peaks in the spectrum, using the program IIEVENT RECOVERY. A quick analysis of the data obtained very recently in a beam sweeping experiments has shown that, in addition to the well known 156.6 keV isomer ($\tau_{1/2}=231\mu\text{sec}$), there are approximately ten delayed transitions, with half-lives in the 2-20 nsec range.

A preliminary level scheme is shown in Fig. 1. As expected, we excite the yrast, $11/2^+[615]$ band to high spin. The compression evident in the $\Delta E(I, I-1)$ values for the $17/2 \rightarrow 15/2$, $21/2 \rightarrow 19/2$ and $25/2 \rightarrow 23/2$ transitions is similar to that observed for the lower spin members of the $i 13/2$ neutron band in lighter rare earth nuclei.⁵ This is indicative of the strength of the Coriolis interaction which mixes the $i 13/2$ levels, the alternate compression being due to the effect of the $1/2^+[660]$ level.

Somewhat surprisingly the $3/2^- [512]$ band is rather strongly excited up to the spin $15/2^-$ member. The $(\alpha, 3n)$ reaction is expected to populate yrast and near yrast levels, and both the $9/2^+[624]$ and $7/2^- [503]$ band heads are known to be in the low energy region of this spectrum (cf. Fig. 1). Further analysis will undoubtedly reveal the rotational levels of these latter bands, but the fact remains that the $3/2^- [512]$ configuration is strongly excited.

Further analysis will include recovery of further coincidence gates and the planned running of excitation function experiments which are useful in determining the spin of transitions in (α, xn) reactions.

*Supported by USAEC and NSF.

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Figure 1

Nitrogen Fixation

C. P. Wolk,* Sam M. Austin, and Aaron Galonsky

As part of the long-range goal of understanding the process of cell differentiation, we have been studying nitrogen fixation in long filaments of blue-green algae. A filament contains ~50-100 or more cells, much like a string of beads, a cell being a cylinder of 3-1/2-micron diameter and 4-micron length. The cells are mostly of one type--vegetative cells; about every fifteenth cell in the variety of algae we use is of a different type. This less numerous type, the so-called heterocyst, is somewhat larger than the vegetative cell; it has a different boundary structure; and it appears obviously different when the algae are viewed under a microscope. As a filament grows, the spacing between heterocysts increases until the number of vegetative cells encompassed in ~30. Then a new heterocyst develops from a vegetative cell about halfway between the two older heterocysts--cell differentiation has occurred.

In attempts to understand the value to the organism of this transformation, it has been suggested that nitrogen for algal growth of the filament is fixed solely by the heterocysts. Although numerous, biochemical experiments have not been consistent in supplying evidence either for or against this hypothesis. As described in previous annual reports, we have determined the site of nitrogen fixation by autoradiography of ^{13}N . Under the microscope, the cell of origination was clearly identified for more than 1,000 positron tracks. More than 42,000 cells were examined. About 25% of the tracks came from heterocysts; the rest were uniformly distributed amongst the vegetative cells. The distribution function is shown by the open circles (○) in the figure; n is the number of cells to the nearest heterocyst. For comparison, the solid circles (●) represent the perfectly uniform distribution. The fluctuations of the observed distribution from uniformity are small except at $n=11$ and 12 where the points represent only 3 tracks and 2 tracks, respectively. With a typical spacing of 15 cells between the heterocysts, there are not many cases to be found having $n=11$ or 12.

One may still hold to the 100% heterocyst theory, arguing that all nitrogen enters at heterocysts and then diffuses down the filament. In our experiments the algae lived about 4 minutes between fixation and autoradiography. This time was available for diffusion. The curves through the triangles and squares in the figure are track distributions predicted on the basis of heterocyst fixation followed by diffusion. For the solid squares (■) the diffusion time constant, τ , the time for the square of the displacement from the

originating heterocyst to increase by unity, =60 sec; for the open squares (□) $\tau=10$ sec; for the solid triangles (▲) $\tau=5$ sec. For the open triangles (△) $\tau=6$ sec and a reasonable rate for incorporation of nitrogen into non-diffusible macromolecules is included in the calculation. None of these distributions fits the data. A fit would require $\tau \approx 2$ sec, a value considered by some botanists to be far below the true value.

We may conclude with reasonable certainty that heterocysts, comprising only ~6% of the cells and fixing ~25% of the nitrogen, are ~4 times as effective as are vegetative cells, but vegetative cells also fix nitrogen.

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Target Fabrication

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The MSU target making laboratory has been in operation for several years, but considerable improvements and new developments have occurred during the past year. Approximately 200 targets were made during this period of time for use at the cyclotron. A list of these targets along with some information about technique is given in the table.

Many of the isotopic targets were prepared from compounds which were reduced by Ta, Zr or C and evaporated simultaneously, as indicated in the table. Some of the self-supporting targets were made by evaporation onto a previously evaporated water soluble substrate and subsequent floating on distilled water. NaCl, BaCl₂, and CsI have been used as released agents, with CsI being the best in general. Other self supporting targets were made by scraping the evaporated layer from a glass slide with a razor blade or dissolving a metallic substrate in NaOH or acid. Carbon backed targets have used 10-100 µg/cm² commercially prepared C

foils, with 20 µg/cm² foils being used most often. The carbon backings are often picked up on one or two layers of formvar for extra strength. Most of the targets listed in the table are on frames with 5/8" diameter holes.

New equipment in the target lab includes a homemade vacuum evaporator system with a 4" TM diffusion pump, a commercial electron gun which is used in the new evaporator, and a Cahn vacuum microbalance which is currently being modified to weigh targets during evaporation. There is currently storage space for 120 semi-reactive targets at a vacuum of ~10 microns, as well as a high vacuum (<10⁻⁶ torr) storage chamber and transfer system for 20 reactive targets. Currently under construction is a new fail-safe high vacuum storage and transfer system with a capacity of 90 targets.

TABLE.

Target Element	Chemical form of Target	Starting Material	Method of Fabrication	Backing ¹	Thickness (µg/cm ²)	Amount of Isotope required for 100 µg/cm ² (mg)	Remarks
Be	Be	Be	Vac. Evap. Ta. tube source	S.S.	<50		scraping from glass substrate
N	Melamine	Melamine	Vac. Evap. W dimple boat	C	<1,000		
O	Mo O ₃	Mo O ₃	Vac. Evap. BN crucible	C	<100		
	W O ₃	W O ₃	Vac. Evap. W dimple boat	C	<100		
F	Ca F ₂	Ca F ₂	Vac. Evap. W dimple boat	C	<200		
Na	Na	Na	Vac. Evap. Ta. tube source	C	<200		
Mg	Mg	Mg	Vac. Evap. ³ Ta. point source	Mylar	<5,000		
				C	<200		S.S. foil by scraping from glass substrate
				formvar	<150		
^{24,25,26} Mg	Mg	Mg O	Vac. Evap. Zr point source ³ w/Zr powder & W, Chimney	S.S.	>200	5.0	Ta tube source ⁴ used after reduction S.S. foil by scraping from glass substrate
				C	<200		
				Au	<100		
Al	Al	Al	Vac. Evap. Al ₂ O ₃ coated dimple boat	S.S.	>100		S.S. foil by CSI flotation
				formvar	<25		
				C	<250		
Si	Si O	Si O	Vac. Evap. Ta. point source	C	<500		
P	P	P	Vac. Evap. Ta. point source	C	<150		W-dimple boat also used
S	S	S	Vac. Evap. Ta. tube source	C, Au	<300		Sandwich between 2 layers of Au, also made.

TABLE.--Continued.

Target Element	Chemical form of Target	Starting Material	Method of Fabrication	Backing ¹	Thickness ($\mu\text{g}/\text{cm}^2$)	Amount of Isotope required for 100 $\mu\text{g}/\text{cm}^2$ (mg)	Remarks
35,37Cl	Cds	Cds	Pressing Vac. Evap. W-dimple boat	S.S. C	>20,000 <200		
	Zn S	Zn S	Vac Evap BN crucible	Au	<200		Sandwich between 2 layers of Au, also made. Sol in CS ₂ used.
	Sulfonated Polystyrene	S & Poly St.	Dipping	S.S.	>1,000		
	NaCl	NaCl	Vac Evap Ta point source	C	<200	5.0	Ta tube source also used.
K	K	K	Vac Evap Ta tube source	C	<200		
Ca	Ca	Ca	Vac Evap Ta tube source	C	<200		W-dimple boat also used.
40,42,44,48Ca	Ca	CaCO ₃	Vac Evap Zr point Source w/Zr powder	C Au	<200 <100	5.0	Simultaneous reduction & evaporation
Sc	Sc	Sc	Vac Evap Ta tube source*	C	<100		W-dimple boat also used.
Ti	Ti	Ti	Vac Evap Ta point source*	S.S.	<250		Scraping from glass substrate
	Ti	TiO ₂	Vac Evap Ta point source*	S.S.	<250		
Cr	Cr	Cr ₂ O ₃	Vac Evap C, crucible	C	<200		
Mn	Mn	Mn	Vac Evap Ta tube source*	S.S.	<100		Scraping from glass substrate
54,56Fe	Fe	Fe ₂ O ₃	Vac Evap C-crucible	C	<200	3.0	Simultaneous reduction & evaporation
			C-crucible Reduction	Havor	<1500	5.0	W-dimple boat also used*
			E Bomb C-crucible	C	<200		
Co	Co	Co	Vac Evap C-crucible W-dimple boat*	C C,S.S.	<200		S.S. by scraping from glass substrate.
58,60Ni	Ni	Ni	Vac Evap C-crucible Elec. Bomb C-crucible	C C	<250	3.0	W-dimple boat also used*
63,65Cu	Cu	Cu O	Vac Evap Ta point source Ta tube source	C	<300	2.0	Simultaneous reduction & evaporation.
Zn	Zn	Zn	Vac Evap Ta tube source	S.S.	>500		
		Zn O	Vac Evap Ta tube source	S.S.	>500 (1500)		Zr point source w/z powder also used.
64Zr	Zn	Zn O	Vac Evap Zr point source w/z powder & W. chimney	C	<400	5.0	Ta tube source used after reduction.
Ge	Ge	GeO ₂	Ta point source	C			

TABLE.--Continued.

Target Element	Chemical form of Target	Starting Material	Method of Fabrication	Backing ¹	Thickness ($\mu\text{g}/\text{cm}^2$)	Amount of isotope required for 100 $\mu\text{g}/\text{cm}^2$ (mg)	Remarks
Br	K Br	K Br	Vac Evap Ta tube source	C	<200		Ta. Point source also used.
Mo	Mo O ₃	Mo O ₃	Vac Evap BN crucible	C	<200		
Rh	Rh	Rh	Vac Evap W-dimple boat	C	<250		
Ag	Ag	Ag	Vac Evap Ta tube source	S.S.	>100		S.S. by scraping from glass substrate.
¹⁰⁷ , ¹⁰⁹ Ag	Ag	Ag	Vac Evap W-dimple boat	C	<1000 <1000	1.5	
Cd	Cd	Cd	Vac Evap Ta tube source	S.S.			Scraping from glass substrate
	Cd	Cd O	Vac Evap Ta tube source	S.S.	>100		Disproportion also on heating.
¹¹⁵ In	In	In ₂ O ₃	Vac Evap Ta point source	C.	<300	2.0	
¹¹⁶ , ¹¹⁷ , ¹¹⁹ , ¹¹⁹ , ¹²⁰ Sn	Sn	Sn	Vac Evap Ta tube source W-dimple boat Al ₂ O ₃ coated boat for melting & then rolling	S.S. C	>200 <500	2.0	Thicker targets made by rolling.
	Sn	SnO ₂	Vac Evap Ta point source	C	<250	2.0	Simultaneous reduction & evaporation
Ce	Ce	Ce	Vac Evap W-dimple boat	S.S.	>500		deposition Ta Ta dissolved in 1:1 HF, HNO ₃
¹⁴⁰ Ce	Ce	CeO ₂	Vac Evap Ta point source w/Th powder	C	<100	10.0	Simultaneous reduction & Evap.
Pr	Pr	Pr	Vac Evap W-dimple boat Ta point source Ta tube source	C	<1,000		
Nd	Nd	Nd	Vac Evap Ta tube source	S.S. C	>10,000 <200		Similar to cerium.
¹⁴² Nd	Nd	Nd ₂ O ₃	Vac Evap Ta point source w/Th powder	C	<200	10.0	Similar to cerium.
¹⁴⁴ , ¹⁴⁷ , ¹⁴⁸ , ¹⁴⁹ ¹⁵² , ¹⁵⁴ Sm	Sm	Sm ₂ O ₃	Vac Evap Zr point source with Zr powder & W. Chimney	S.S. C	>500 <400	4.0	S.S. by CSI floatation ⁴ Ta tube source used after reduction. S.S. by deposition Al, Al dissolved in Na OH.
Th	Th	Th	Vac Evap Ta tube source	C	<300		
¹⁶¹ , ¹⁶³ Dy	Dy	Dy ₂ O ₃	Vac Evap Ta point source w/Th powder	C	<200	5.0 mg	Simultaneous redn. & evap.
Ho	Ho	Ho	Vac Evap W-dimple boat	S.S. C	>500 <250		S.S. by deposit on Al, Al dissolved in Na OH.
Tm	Tm	Tm	Vac Evap Ta tube source	S.S. C	>500 <2500		S.S. by Na ₂ Cl floatation.

TABLE.--Continued.

Target Element	Chemical form of Target	Starting Material	Method of Fabrication	Backing ¹	Thickness ($\mu\text{g}/\text{cm}^2$)	Amount of isotope required for 100 $\mu\text{g}/\text{cm}^2$ (mg)	Remarks
172,174,176 _{Yb}	Yb	Yb ₂ O ₃	Vac Evap Zr point source w/zr powder & W. chimney	S.S. C	>500 <200	3.0 mg	Same as ⁴ in Sm. S.S. foil also made by scraping from glass substrate.
Lu	Lu	Lu	Vac Evap Ta tube source	C	<50	4.00	
W	WO ₃	WO ₃	Vac evap W-dimple boat	C	<100		
Au	Au	Au	Vac Evap W-dimple boat Ta tube source	S.S. C Mylar Kapton Formvac	>100 <300 <500 <1,000 <25		S.S. made by CSI floatation
203,205 _{Tl}	Tl	Tl ₂ O ₃	Vac Evap Ta tube source	C	<1,000	1.5	
204,206,207,208 _{Pb}	Pb	Pb	Vac Evap Ta tube source Elec-Bomb C-crucible	Form vac S.S. C S.S. C	<300 <5,000	2.0	S.S. made by scraping from glass substrate
	Pb	Pb O	Vac Evap	C	<5,000	2.0	Pb(NO ₃) ⁴
	Pb	Pb(NO ₃)	Ta point Source Ta tube source				distoroportionates to Pbo, reduced by Ta.
Bi	Bi	Bi	Vac Evap Ta tube source Elec. Bomb C-crucible	S.S. C C	<5,000 <2,000 <2,000		S.S. made by separating from Ta.
	U	U	Elec. Bomb	C	<50		
U	UF ₄	UF ₄	C-Crucible Vac Evap W-dimple boat	C	<200		

¹S.S., means self supporting targets, and C usually means 20 $\mu\text{g}/\text{cm}^2$ carbon plus formvar.

²Amount for evaporation at approximately 3 cms. distance in most cases.

³Ta or Zr point source means tube or ends smashed and small hole drilled in its side.

⁴Reduction is carried out and the isotope is condensed inside Ta tube boat, turned upside down. Also simultaneous reduction & evaporation has been done.

*Impurity from filament likely.

Preparation of Isotope Targets by Heavy Ion Sputtering*

M. Edmiston, F. Bernthal and J. Nolen

Isotope targets of refractory metals can be made by heavy ion sputtering.¹ Due to the small amounts of isotope usually available, cathodic sputtering (in which the material to be sputtered forms the cathode) cannot be used. Current techniques involve bombardment of the isotope with a highly focused 10kV argon beam. The ion gun, focusing assembly, and power supplies involved are complex and costly. Edwards High Vacuum manufactures an Ion Beam Etching Accessory in which an argon beam is produced in a very simple 2-electrode gun.² This accessory is being investigated for its possible application to sputtering refractory targets.

The Edwards equipment can produce a 200 mA beam current at 8kV. This is a factor of five less current and a little less potential than that used by others.¹ The rate of sputtering, S , is related to the current and the potential by the equation:

$$S = Ki(V - V_c)$$

where V_c is a critical voltage below which no sputtering occurs, and K is a constant depending on the metal to be sputtered.³ Thus, using the Edwards accessory at its limit should yield a rate about one-sixth that of the equipment used by Sletten & Knudsen. For making satisfactory targets this would require continuous sputtering for several days. This should not present any problems except replacement of the cathode would be required approximately every 50 hours. We have not yet achieved such long-term, stable operation, though developmental work is continuing. It appears that it may be necessary to add one electrode to the apparatus for a small focusing effect. At present, the gun to isotope distance is 2-3 cm and over this distance the beam spreads to about 5 mm in diameter. It would be best if this could be reduced to 1-2 mm.

In preliminary trials, opaque copper films have been sputtered in about 30 minutes. The sputtering constant, K , is larger for copper than for metals of interest, but should not be more than 10-15 times larger. This would tend to indicate that sputtering yields are about as expected. Thus if the technical difficulty of long term operation can be overcome, it appears that the etching accessory may find application in sputtering.

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For some years now, the M.S.U. cyclotron has produced small energy width (~ 1 part in 10^4), small radial emittance (< 1 mm-mr) beams by using a process known as phase selection.¹ By taking advantage of the longitudinal(E- ϕ)-radial coupling in particle motion, the beam phase width is defined by regulating the beam radial width using properly positioned slits. Given the excellent performance of these phase selective slits, it was deemed worthwhile to undertake a computer study of this coupling phenomenon to obtain a thorough understanding of it and determine how it is affected by various machine parameters.

The calculational procedure began with obtaining a magnetic field from "Fielder".² We then calculated accelerated equilibrium orbits (AEO's),³ using which we found a central ray (CR) and a virtual ion source. We could then compare the orbits of rays with initial conditions deviating from those of the CR.

We found it convenient to define a quality factor Q using the radial separation between the CR and a ray initially displaced from it in phase by $\Delta\phi$ as:

$$Q = \Delta R / \Delta\phi = Q_{EO} + Q_x.$$

Q_{EO} is related to the radial separation between static equilibrium orbits,⁴ a quantity depending mainly on $\phi_F(\tau)$ and the CR energy E , while Q_x pertains to the x component of the distance between representative phase points in the x - p_x phase plane.³ Since Q_{EO} is easily calculated, it is the behavior of Q_x which we discuss below.

The most elegant way to view the growth of Q_x from zero at the source to its maximum (after about 10 turns), is as a resonance phenomenon existing while $|v_r - 1| = 0$ and driven by the asymmetries present in both the particle orbits and the rf times of gap crossings of the CR. The orbit asymmetries, arising from the field sector structure and the gap crossing resonance,⁵ were identified by studying AEO properties. The rf asymmetries arise because the first derivatives of the rf waveform will, in general, be different from gap to gap so that time displaced particles will experience different relative energy gains at each gap. Varying the machine parameters listed below affects the longitudinal-radial coupling by changing one or the other of these driving asymmetries.

Our study concerned the effects of the number of field sectors, N , the Fielder phase curve, $\phi_F(\tau)$, the energy gain per turn, E_1 , the dee angle, α (restricted to $180^\circ \geq \alpha \geq 90^\circ$), the relative orientation between the dees and the field sector structure, θ_{or} , and the acceleration harmonic, h .

We found that machines with $N=3$ have a definite advantage for phase selection over those with $N=4$.

Magnetic fields of the latter type have highly symmetrical AEO's with almost no gap crossing resonance effect and small phase shifts between gaps. These characteristics make Q_x much smaller and insensitive to the other parameters listed above when compared with the results for $N=3$. In general, for $N=4$, $Q_x < Q_{EO}$, while for $N=3$, $Q_x > Q_{EO}$. These statements are valid after the first 10 or 15 turns.

This advantage for $N=3$ fields may be improved upon by raising $\phi_F(\tau)$ on early turns. This increases the rf driving asymmetry and can increase the final Q_x whether the rise in $\phi_F(\tau)$ is caused by a central cone or by proper manipulation of trim coil currents.

Also in fields with $N=3$, Q_x depends on θ_{or} , with a strong tendency for largest Q_x 's to occur when the virtual ion source is located near the azimuthal center of a hill, at least for $h=1$, regardless of dee angle. At a fixed θ_{or} , the variation of Q_x with α is often as much as an order of magnitude, although there is no simple, general rule applicable to all θ_{or} 's and α 's.

Changing acceleration harmonics obviously changes the rf times of gap crossings and, hence, the rf asymmetry effect. It also affects the gap crossing resonance so that for $h=3$, for instance, AEO's are very highly asymmetrical. The net result of these changes is that $h=2$ shows smaller Q_x 's and $h=3$ much larger ones (for $180^\circ \geq \alpha \geq 90^\circ$) when compared with $h=1$ values.

Since all the codes used in our study assume a step-function energy gain at each gap, we investigated the effects of the electric fields present near the center of any machine by comparing the results from Devil with those from "Cyclone", a code utilizing measured M.S.U. electric field data. In general, one finds that the electric fields act to decrease Q_x by about a factor of two and modify the turn number at which the maximum value of Q occurs. The conclusion to be reached is that whenever final design orbit calculations for a phase selection system are to be made, the central region electric fields must be included.

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Operation of the rf Beam Sweeper

T. L. Khoo, L. A. Finlayson and P. Sigg

The pulsed structure of the cyclotron beam makes it ideally suited for the lifetime measurements of short-lived isomers or for particle time of flight (TOF) studies. However, the short interval (46-70 ns) between beam pulses sometimes imposes a restriction on the lifetimes that may be measured or on the flight lengths in TOF studies. In order to extend the interval between pulses a high voltage rf beam sweeper has been constructed for use with the MSU cyclotron.

Briefly, the sweeper is an amplitude stabilized rf amplifier driven at a submultiple of the cyclotron frequency. The output of the sweeper, a sinusoidal voltage of 13-26 kV maximum (depending on the frequency, is applied to a pair of electrostatic deflecting plates, 1 m long and 25 mm apart, and located between quadrupoles 2 and 3. The phase of the applied voltage is then adjusted to deflect unwanted beam pulses onto a pair of downstream slits at Box 3. The displacement pattern of the beam bursts may be observed on a scintillator at Box 3.

The net effect is that the sweeper is used to accept 1 of n beam bursts from the cyclotron. The tuning range of the sweeper, 1.4-5 MHz, effectively imposes a restriction on the maximum value of n that may be used. At the maximum cyclotron frequency n may, in principle, be as large as 14, but over the whole range of available cyclotron frequency n is restricted between 2 and 9. The system has so far been successfully used with n values of up to 9, with particles as energetic as 48 MeV α 's. Beam intervals of up to ~ 0.5 μ sec have thus been achieved.

The present system has been used for the observation of delayed γ -spectra from many nuclides under investigation in this laboratory. Details may be found in individual reports in this volume.

With the cyclotron rf modulation system, intervals of greater than ~ 1 msec have been achieved. There thus remains a gap of from 0.5 - 1000 μ sec that we are unable to cover. We hope to bridge this gap with either a high voltage (>2 kV) pulser or a pulsed ion source.

Gamma Ray Coincidence Spectrum Recovery Program

C. B. Morgan, T. L. Khoo, R. A. Warner & R. Au

As a part of gamma-ray spectroscopic studies a large amount of γ - γ -time coincidence data has been taken, both two and three-dimensional. Because of the large coincidence counting rates which can be obtained in experiments in beam with nuclei containing rotational structure and the large number of transitions involved in odd-odd nuclei, we have, upon occasion, found the need to recover from 50 to 60 million events. With the present computing facilities, the limitation on recovery is the amount of spectra which can be contained within core. If the core requirements become too large, it becomes necessary to store pages temporarily on the disk. The swap time becomes prohibitively large with a small increase in program size and consequently the data recovery was very cumbersome and time consuming.

Our new technique involves the very simple procedure of sorting the data off the tape into a number of files on the diskpack. Each file is then sorted with its own set of gates, keeping within the limitations of the Sigma-7. The savings for a typical experiment can be as much as a factor of 5 or 6 in time and thousands of dollars of computed expenses because of the reduction of the need for expensive core.

M. M. Gordon and D. A. Johnson

Two new computer codes have been developed for calculating the orbits of ions moving in the symmetric magnetic field of the Indiana cyclotron, or of any similar cyclotron. The main input consists of the measured median plane field $B(r, \theta)$ which is stored in a polar grid. This grid extends from $r_{\min}$ to $r_{\max}$ in constant δr steps (equal to the magnet gap), and from $\theta=0$ (valley) to $\theta=45^\circ$ (hill) in constant $\delta\theta=0.5^\circ$ steps. This data is then used to calculate all the field components on or off the median plane as needed by the programs.

With θ as independent variable, the equations of motion are integrated using a very efficient predictor-corrector (Milne-Reynolds) routine with constant integration steps $\Delta\theta$. The value of $\Delta\theta$ must be a multiple of $\delta\theta$ and a submultiple of 45° . We use $\Delta\theta=0.5^\circ$ (the minimum) when results having the greatest accuracy are required, but when some accuracy can be sacrificed for speed, we use $\Delta\theta=1^\circ$. The minimum $\Delta\theta$, and hence $\delta\theta$, should be proportional to the ratio of magnet gap to magnet radius, which is about $1/40$ for the Indiana cyclotron.

One new code "Symeon" calculates as a function of energy all of the important equilibrium orbit properties including: the hill and valley radii, the orbit rotation period, and the focusing oscillation frequencies, ν_r and ν_z . This basic cyclotron code differs from its predecessors by making specific use of the magnet symmetry. Its running speed is about 100 times faster than the previous Indiana code which it replaces. This code will become a subroutine in a least-square fitting program used to determine the trim coil currents required for isochronism.

The general orbit code "Indigo" is designed to study accelerated orbits and provide information on nonlinear effects in the radial and axial oscillations, as well as coupling effects between the radial, axial, and longitudinal motions. The equations of motion in this code utilize magnetic field components off the median plane which are correct to order z^2 , that is, they contain all terms involving first and second derivatives of $B(r, \theta)$. Higher order terms are omitted because a large expenditure of time and space would be required for a relatively small gain in accuracy. The rf system is assumed to consist of two dees having constant angular width (40° in the Indiana case) which are symmetrically located in opposite valleys. It is further assumed that the rf field at each gap is so well localized that it can be represented by a delta function. Consequently, both the energy and the radial momentum change discontinuously at each gap, with the radial impulse being

proportional to the rate of change of the dee voltage with radius.

Some preliminary studies have been carried out with the code Indigo using the 15-200 MeV proton field of the Indiana cyclotron. Although this field data is old and somewhat unrealistic, the results should still be meaningful in most respects. For axial oscillation amplitudes up to 0.2 in., the resultant final energy spread is less than 4 keV and proportional to z^2 . This very encouraging result shows that the axial-longitudinal coupling effects are an order of magnitude smaller than previously reported. For radial oscillations with amplitudes up to 0.05 in., nonlinear effects (associated with the $\nu_r=4/3$ resonance) produce only a 4% increase in amplitude. Moreover, coupling effects between the radial and axial oscillations appear quite unimportant. The only new and significant effect observed results from the radial-longitudinal coupling. This coupling produces a compression in the phase width by a factor of 3.2 which is a direct consequence of the corresponding increase in the dee voltage with radius.

The Indigo code is not presently equipped to study the effects of field imperfections or of magnet displacements. Such effects are crucial, for example, for evaluating the results of accelerating through the $\nu_z=1$ resonance. The code is, however, equipped for a design study of the electrostatic channels required for beam extraction.

The $^{40}\text{Ca}(p,p')$ reaction is currently being studied with the split-pole magnetic spectrograph. In this report we present some of the preliminary experimental results to indicate the capabilities of the high resolution dispersion matching system. The states of interest in this experiment are predominately $f_{7/2}$ -particle $d_{3/2}$ -hole states with spins 2^- , 3^- , 4^- and 5^- and isospin $T=0$ and $T=1$. These levels are found as high as 8.5 MeV in excitation energy and are relatively weakly populated in this reaction. They are important because they are relatively pure particle-hole states and their population in the (p,p') reaction is sensitive to the details of the nucleon-nucleon interaction. It is essential for this experiment to have high resolution and low background at high excitation energy.

An experimental resolution of 4-4.5 keV FWHM was attained in the spectra recorded to date. Data analysis is very preliminary but it appears that all of the particle-hole states of interest are identified and cleanly separated from nearby levels. The two figures show expanded views of the spectra near the $4^-(T=0)$ and $4^-(T=1)$ states at 5.614 MeV and 7.655 MeV excitation, respectively. The former is a member of a 16 keV doublet, while the latter was thought to be in a 4^- , 3^- , 2^+ triplet. It now appears that there may be two new energy levels in this vicinity.

In the 15° spectrum the ^{40}Ca elastic peak height to background ratio is $\sim 10^6:1$ which permits states as weak as $\leq 10 \mu\text{b}/\text{str}$ to be seen above the background even at this low scattering angle. Since there are no slits in the beam transport

system after the last 45° bending magnet, however, this background is very sensitive to the beam position and focussing conditions on target. In practice the background from the target frame is minimized by observing the count rate in a live focal plane detector with a blank target frame in position. The beam is then steered to minimize this rate prior to the plate exposures.

It is also significant that the resolution, which is empirically optimized for elastic scattering, does not deteriorate with excitation energy. Strictly speaking, the condition for simultaneous dispersion matching and kinematic compensation can apply to only one point in the focal plane at a time. The deviation is such a slow function of excitation energy, however, that it is not yet detectable at 10 MeV excitation.

The experimental resolution achievable in practice is a rapidly decreasing function of spectrograph solid angle. The present data was recorded with ~ 0.3 mstr aperture ($1^\circ \times 1^\circ$). Tests indicate that the resolution is $\sim 50\%$ worse with a ~ 1.2 mstr aperture ($2^\circ \times 2^\circ$). The resolution is not, however, sensitive to the slit settings of the beam transport system. These spectra were recorded with $\sim 3 \mu\text{A}$ of 35 MeV protons extracted from the cyclotron and up to $2 \mu\text{A}$ of beam current on target. Even though the energy spread in this beam was probably ~ 15 -25 keV it was not possible to improve the experimental resolution by selecting a narrower energy bite with the beam analysis system.

K. L. Kosanke, Wm. C. McHarris and H. Robertson

Our initial motivation for the construction of the Helium-jet recoil-transport (HeJRT) system was its intended use as the first stage in an on-line mass identification system (see page 93). While this remains the case the HeJRT system has become a popular research tool in itself. It is being used with increasing frequency for the rapid transport of Cyclotron produced activities to a low background area for conventional nuclear counting experiments. We anticipate that the HeJRT system will remain an important research tool in itself even after we have developed an on-line mass identification system. Accordingly, a second research area is being constructed to allow the continuing use and development of the HeJRT system while the mass identification system is built in the area previously used by the HeJRT system.

A large portion of our time during the past three years has been devoted to collecting information on the operation of the HeJRT system both for the purpose of understanding its mechanism and to construct a efficient and reliable system. This collection of information is discussed in detail elsewhere¹ and only a portion of the graphical information is included here as figures 1-8. All descriptions of the experimental procedures and discussion of their results are referred to the above reference.

The target assembly of the HeJRT system has been completely reconstructed and now is of a modular design and is not encased in a larger container of helium. Each of its components is separate, beam window, collimator, target holder, recoil chamber, etc. Accordingly the assembly is quite flexible in design and changes are easily made during a run by simply loosening two wing nuts and sliding in or out new components. This now allows us to make radical changes in the assembly spending a minimum of machine shop time (by not duplicating the remaining components) and a minimum of experimental set-up time. The HeJRT system is now typically run in two configurations (steady flow^{1,2} and pulsed flow³) and work is proceeding on a third configuration (compound gas flow, discussed below). This conversion is accomplished by simply switching recoil chambers. Figure 9 is an assembly drawing of the target assembly set up using the pulsed flow recoil chamber.

The compound gas flow configuration mentioned in the preceding paragraph is the combination of a high purity helium-jet system and an ethylene cluster transport system.⁴ The configuration has a conventional recoil chamber behind the target which is supplied with high purity helium. The

jet of helium exiting the recoil chamber only travels 1 cm before entering a second chamber. Thus recoil activity is supplied to the second chamber which is free of the cluster to which it would normally be attached. A supply of ethylene is fed to the second chamber under conditions favoring the presence of ethylene clusters. Hopefully at this point the recoil activity will become bound to the ethylene clusters. A capillary is used to transport activity from this second chamber to our counting area in the same manner as in a conventional set up. The purpose of attempting to substitute non radiated ethylene clusters for the radiated water or benzene clusters used typically, lies in the nature of the clusters and our intention of coupling the HeJRT system with an on-line mass identification system. It is hoped that the ethylene cluster will be easier to drive from the collecting surface, thereby simplifying the experimental set-up and at the same time increasing the β -recoil yield. To date we have not been very successful in our attempts, primarily because of the residual presence of benzene and pump oil, etc. in the system. The result has been to get a fair transport yield with even high purity helium flowing alone in the system.

*Supported by the U. S. Atomic Energy Commission and the National Science Foundation.

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Fig. 1.--Dependence of HeJRT system efficiency on target assembly pressure using 20 ppm benzene vapor in helium.

Fig. 4.--Short time efficiency profile for HeJRT system after initial cyclotron beam turn on.

Fig. 2.--Relative HeJRT system efficiency as a function of benzene concentration.

Fig. 5.--Non linear relationship between gross gamma count rate and cyclotron beam current for a long and short recoil cylinder.

Fig. 3.--Collecting efficiency, expressed as the gross gamma count rate, as a function of collecting chamber pressure for different capillary to paper tape angles and distances.

Fig. 6.--Transit characteristics of the HeJRT system using 50 feet of 0.055 inch capillary as a function of target assembly pressure.

Fig. 7.--Comparison of the collecting efficiency using paper and the aluminized side of aluminized Mylar type using helium doped with 20 ppm benzene.

Fig. 8.--Angle of divergence of clusters generated from benzene leaving a 0.055 inch capillary under conditions of choked flow.

Fig. 9.--Assembly drawing of the new modular design for the HeJRT target assembly set-up in the "Pulsed Flow" mode.

K. L. Kosanke, M. Slaughter and Wm. C. McHarris

In the operation of the Helium-Jet Recoil-Transport (HeJRT) system we have observed some effects in the transport of activity that suggest the chemical nature of the nuclear recoil and the cluster molecule are important in determining the efficiency of the transport process. Further we have observed that it is possible to preferentially transport different components of a mixture of chemically differing recoils from the same target. In effect, in at least some cases, it is possible to achieve a partial chemical separation in the course of the transportation process. One possible explanation of this effect could be that the chemical nature of the recoil and cluster are effective in determining the cluster's ability to pickup and hold the recoil atoms. If this is the case, that component of a mixture of chemically different recoils which is preferentially picked up and held by clusters will, as a result, also be that component which is preferentially transported through the system. Those remaining components that are not readily picked up and held by the

clusters will not have the benefit of the cluster's high transport efficiency through the system and will tend to become lost on the walls of the capillary leading to the counting area. It is, perhaps, worth pointing out that even if the above explanation is in gross error and the chemical nature of neither recoil nor cluster is the source of the effect, the effect is still real and can be used to achieve a preferential enhancement in the transport yield of chemically differing nuclear recoil in the HeJRT system.

The first observation was simply that the transport efficiency, as measured experimentally, differed substantially for physically similar recoils. For Zn, Cu and Co the total transport efficiencies are 50%, 75% and 90% respectively. These efficiencies were determined on the basis of a direct comparison of the HeJRT performance (collecting on paper tape --- 20 ppm benzene in helium) and the irradiation of thin foils. The only uncertainty in the determination lies in the range of the recoils in the target, taken from

Fig. 1.--By changing the major cluster generating component in the helium supply the absolute system efficiency for a pair of activities can be made to change inversely.

Northcliffe and Schilling.¹ The second observation was that the absolute transport efficiencies for a pair of simultaneously generated activities could be shifted in opposite directions upon changing the major cluster generating component in the helium supply. The principle activities generated by a 30 MeV proton beam on aluminum are ^{23}Mg and ^{26}Si from (p,n) and (p,2n) reactions respectively. Upon changing from compressed air to benzene as the major cluster generating component in the helium supply (there was also a small amount of water vapor present in both cases) first the ^{26}Si then the ^{23}Mg activity was preferentially transported through the HeJRT system, see Figure 1. Accordingly, it would seem the total transport efficiency of the HeJRT system is dependent on both the chemical nature of the nuclear recoil and of the molecular cluster. For a more complete discussion of these observations and their implications see K. L. Kosanke's Ph.D. Thesis.²

More recently when operating the HeJRT system using ethylene as the primary impurity in the helium we have observed a third effect. Again using 30 MeV protons on aluminum to produce ^{26}Si and ^{23}Mg activity it was found that the ratio of ^{26}Si to ^{23}Mg transported through the system was dependent on ethylene concentration. Preliminary results are shown in Figure 2. Both ^{26}Si and ^{23}Mg efficiencies increase with increasing ethylene concentration in the range from 50 to 200 ppm (strikingly different then when using benzene as the impurity) however the ^{23}Mg total transport efficiency increases much more rapidly in the low concentration range. The four points are the averages of a total of sixteen determinations. The error bars in the plot of ratios are just the average deviation of the points. Further runs are planned to fill in points at 25 ppm and at concentrations above 200 ppm.

Thus the observations we have made are consistent with the hope that useful chemical separations can be achieved with in the HeJRT system and further that these separations will be compatible with the on-line mass analysis system described in page 93 of this report.

Fig. 2.--Effect of varying ethylene concentration in the helium supply on the total system efficiency for ^{23}Mg and ^{26}Si recoils.

*Work supported by the USAEC and the National Science Foundation.

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K. Kosanke

After making the observation that it was possible to trap activities transported through the helium-jet recoil-transport (HeJRT) system in aqueous solution it seemed logical to pursue the possibility of performing "wet" chemistry with the trapped activities. This requires a freeing of the recoil activities from the cluster molecular's used to transport the activities through the HeJRT system.^{1,2} Fortunately this seems to occur spontaneously on the introduction of the recoil cluster combination into the aqueous phase. Chemistry was further simplified by the observation that the low pressure end of the HeJRT system could be run at atmospheric pressure and above if necessary. This removes the necessity of performing the chemistry under conditions of a vacuum.

The potential usefulness of coupling aqueous chemistry on-line with the HeJRT system has been demonstrated in earlier reports.^{3,4} These involved the separation of Ga activities from Cu and Zn activities using a set-up similar to the one sketched in Fig. 1. A flow of helium containing the recoil-cluster combination was combined with a flow, generated with a tubing pump, of 8N HCl containing Cu and Zn carrier in a mixing chamber. The mixing is quite turbulent due to the large volume of helium flowing from the HeJRT target assembly, about 40 STD CM³/Sec. Also, the large volume of helium flowing rapidly transports the acid solution to the ion-exchange column, loaded with large mesh DOWEX-1 resin. The eluant solution was then drawn through the resin using a second tubing pump and run to a shielded storage container. A Ge(Li) detector had been set up to look at the Ga activities held up on the column.

The sketch of the present set-up, shown in Fig. 1, differs from that described previously^{3,4} in that the second tubing pump for drawing the eluant through the ion-exchange column has been eliminated by using the helium flow to force the eluant solution through the column. The primary motivation for this change was the simplification of the apparatus. However, it also had the effect of slightly reducing the time consumed in performing the chemistry. We estimate the time to transport the activities to the chemical system to be .1 sec and the time to conduct the chemistry to be .5 sec, such that the time elapsing between the generation and counting of the chemically separated activities is of the order of 1 second.

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Fig. 1.--Simplified, yet faster, chemical set-up for use with the HeJRT System.

*Supported by the US Atomic Energy Commission and the National Science Foundation.

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K. L. Kosanke, M. Edmiston, and Wm. C. McHarris

The second half of the MSU time-of-flight spectrometer and helium-impurity thermalizer-transport system is presently under construction and is patterned directly after R. D. Macfarlane's MAGGIE system.¹ Figure 1 is a cross sectional assembly drawing of the system in which the target assembly of the helium-impurity thermalizer-transport (HeJRT system discussed in Section of this report) has not been included.

Activities generated in the target assembly recoil from the target and are thermalized within the helium atmosphere of the assembly. The thermal recoils then become bound to cluster molecules generated from impurities added to the helium supply within the plasma formed by the passage of the cyclotron beam. The recoil-cluster combination is then swept out of the target assembly and through a capillary tube and is transported to a low background area. This is accomplished by pumping on the remote end of the capillary. Because of the extremely large mass of the cluster molecules (up to 10^8 amu) the recoil-cluster combinations are extremely well collimated as they exit the capillary. At this point most of the helium will be removed by directing the flow at a conical skimming nozzle. Most of the recoil-cluster combinations will pass through the skimmer to a heated surface on which they collect. The heated collecting surface has the primary effect of driving off the cluster molecule material, leaving the nuclear recoil activity only weakly bound to the surface.

As the activities on the collecting surface β decay, a number of β -recoiling atoms are freed from the collecting surface. A β detector located behind the collecting surface provides a start signal used in timing the events to follow. A number of the β recoils experience electron shake-off and will be accelerated away from the collecting surface at +10-20 kV to a grid at ground potential. The accelerated recoils that pass through the grid travel down the time-of-flight path to a chevron detector. The chevron detector generates a time-of-flight stop signal, so that time of flight is proportional to m/e of the recoil and provides a "mass signature" for the β -decay event.

It should be pointed out that the system described to this point is in no way speculative but has proven itself as R. D. MacFarlane's MAGGIE system.² There have, however, been significant modifications to the MAGGIE system in the time since the writing of references 1 and 2. The modifications³ were the result of the observation that significant thermalization of the β -recoils occurred before they became free

of the collecting surface. As a result, the accelerating grid in front of the collecting surface was added to supply energy to the recoil. Further, the thermalization and subsequent acceleration was so effective in aligning the path of the recoil along the time-of-flight line that the necessity of having the particle guide was eliminated and it was removed.

It is our intention to mount one, and possibly a second, detector in the region of the collecting surface. In most instances these detectors will be Ge(Li) γ -detectors but may also be x-ray and/or β -detectors. In all cases, excepting those involving isomeric transitions, the γ deexcitation of the nuclei after β decay will be complete before the recoiling nucleus has traveled a significant distance from the collecting surface and the detector located there will be capable of recording the deexcitation process. Running in a coincidence mode, we will then take the mass (i.e. time) information from the time-of-flight and the γ energy information and list the coincidence events on magnetic tape. A play-back of the tape will generate a series of spectra which will be characterized according to the mass of the recoil resulting from the β decay. There is some hope that it will be possible to resolve isobars in the time-of-flight² spectrum using a long flight path. However, if that is not possible, an effective differentiation could also be achieved by imposing the additional requirement of an x-ray coincidence either on- or off-line with the collection of the mass information, depending on the count rate that is achieved. Also, it is possible to consider determining β energies by using a larger, full-energy β detector.

*Supported by the U. S. Atomic Energy Commission and the National Science Foundation.

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- 1) CAPILLARY FROM TARGET ASSEMBLY
- 2) CAPILLARY FEED-THROUGH
- 3) CAPILLARY ORIENTATION FEED-THROUGH
- 4) SYSTEM ROUGHING PORT
- 5) 1884 BOOSTER PUMP PORT
- 6) CAPILLARY ALIGNMENT SLEEVE
- 7) HELIUM SKIMMER
- 8) BETA DETECTOR PORT
- 9) PRIMARY GAMMA DETECTOR PORT
- 10) SECONDARY GAMMA DETECTOR PORT
- 11) 10" DIFFUSION PUMP PORT
- 12) TIME OF FLIGHT PORT
- 13) 10" DIFFUSION PUMP PORT
- 14) GAMMA DETECTOR WINDOW
- 15) BETA (TOF START) DETECTOR
- 16) HELIUM JET COLLECTING SURFACE (AT + 10 KV)
- 17) ACCELERATING GRID (AT GROUND POTENTIAL)
- 18) HOLES TO AID IN PUMPING TOF LINE
- 19) SHIELDING GRID (AT GROUND POTENTIAL)
- 20) CHEVRON HEAVY ION (TOF STOP) DETECTOR
- 21) HARD RUBBER ALIGNMENT MOUNT

MICHIGAN STATE UNIVERSITY CYCLOTRON LABORATORY		EAST LANSING, MICHIGAN	
SCALE 1:2	DESIGNED BY K. K. K.	REVIEWED	
Time of Flight Spectrometer & Helium-Impurity Thermalizer			
DATE 8-14-73	APPROVED BY	DRAWING NUMBER	

Fig. 1.--The M.S.U. time of flight spectrometer and helium-impurity thermalizer-transport system, presently under construction.

Delayed Coincidence Experiments with
Accelerator Beams

R.G.H. Robertson and T. L. Khoo

Techniques for studying the decays of isomeric states with half-lives longer than a few microseconds are well known. Often, however, it is of greater interest to know what transitions populate the isomer from higher excited states. The delayed coincidence method has been applied successfully for cascades through isomers where the half-life does not exceed a few hundred nanoseconds, but severe difficulties due to random coincidences can arise as the coincidence resolving time is made larger to accommodate longer half-lives.

When the isomer can be populated in a nuclear reaction, these problems may be alleviated by pulsing the accelerator beam and observing isomeric decays only during the beam-off intervals, when the background is low. Three types of delayed coincidence experiment can be distinguished. Method 1, in which the beam runs continuously, is the conventional practice and is equivalent to radioactive source experiments. In Method 2 the accelerator beam is pulsed periodically, and delayed coincidences are observed between γ -rays occurring during the beam burst and the isomeric decays occurring in the beam-off periods. Method 3 is a new procedure in which the beam is allowed to run continuously until a γ -ray is detected, whereupon it is interrupted to see whether an isomeric decay follows the 'start' event within a few mean lives. The third method thus consists of event-initiated, aperiodic beam pulsing, and offers some important advantages over the previous techniques. We have applied it to observation of cascades through the $10\ \mu\text{s}$ 53 keV isomer in ^{58}Co ,¹ and the $9.5\ \mu\text{s}$ 1333 keV and $9.8\ \mu\text{s}$ 1559 keV isomers in ^{176}Hf .²

Presently we are carrying out detailed calculations of the true and chance coincidence rates to be expected for each method as functions of all relevant parameters to permit the optimization of experiments. A number of interesting general results have been found; for example, in a Method 2 experiment it is best to use the shortest possible beam burst width, and a beam-off period of approximately 0.8 mean lives. Method 3 experiments can offer a two-fold improvement in running time for a given statistical accuracy (or permit correspondingly longer-lived isomers to be investigated), and in addition are less sensitive to non-optimum settings of the beam current than Method 2 experiments. They do, however, require more complex electronic and beam-control apparatus. The diagram shows a figure-of-merit (inversely proportional to the time it takes to do an experiment to some specified accuracy) plotted for Methods 2 and 3 as

a function of the beam current, which has been normalized to the optimum current for each method. The advantages of Method 3 are evident.

1. R.G.H. Robertson and R. G. Summers-Gill, Can. J. Phys. **49**, 1186(1971).
2. T. L. Khoo, J. C. Waddington, R. A. O'Neil, Z. Preibisz, D. G. Burke, and M. W. Johns, Phys. Rev. Letters **28**, 1717(1972); and Can. J. Phys., to be published.

Progress Report on an Automated Plate Scanner

J. A. Nolen, R.G.H. Robertson and D. Show

An automated nuclear track plate scanner is in preliminary stages of operation at MSU. Since there are currently no broad range live focal plane detection systems capable of recording intrinsic line widths ~ 0.1 - 0.2 mm without adversely affecting the experimental resolution, the continued use of nuclear emulsions is necessary. The large number of tracks per mm^2 in these narrow peaks also requires the use of thin emulsions ($25\mu\text{m}$ or $10\mu\text{m}$) and high resolution scanning optics.

The present scanner design incorporates a monolithic array of silicon photo-diodes in the focal plane of a conventional microscope to obtain an overall resolution of 1 - $2\mu\text{m}$ in the detection of nuclear tracks. The scanning is done via a commercial motorized stage which moves the plate in a square wave pattern beneath the microscope objective. In the current simplified mode of operation a single photodiode views a rectangular area $0.6\mu\text{m} \times 25\mu\text{m}$ on the plate oriented parallel to the tracks. Tracks are detected as sharp pulses at the output of a charge sensitive preamp as they move across this slit in a direction perpendicular to its long dimension. Bright field illumination is used so the pulses represent darkening of the detector slit. The signal to noise ratio and signal height reproducibility of this detection system are very good.

With this single channel detector, tracks are discriminated electronically from dirt and scratches by the following criteria: (1) the pulse must exceed a D.C. discriminator level, (2) the pulse must stay above this level for less than a preset time interval, and (3) the pulse must have a rise time less than a preset value. The events which satisfy these criteria during a scan across the plate are scaled in a single

channel of a computer or multichannel analyzer. The plate is advanced a distance equal to the length of the diode array after each scan across the band of tracks. The plate advance is accompanied by a channel advance signal to the computer or analyzer. The scanning process is computer independent except for this storage of the data. In the present mode the scans are in $25\mu\text{m}$ strips which is ideal for the narrowest lines but adjacent channels can be summed when the experimental resolution does not require such narrow strips.

In the figure an automated scan of 20 MeV deuterons tracks in $25\mu\text{m}$ thick emulsion is compared with a hand scan done in $100\mu\text{m}$ strips. The track counting efficiency varies by about a factor of two in this spectrum, due mainly to two problems which are currently being worked on. Firstly, the illuminator was a 10 Watt Zr arc lamp which has position and intensity instabilities. This light source will be replaced with a different type. Secondly, the very small optical depth of field causes focussing problems which will ultimately be overcome by a continuous focussing feedback system which is currently being designed.

Even with these problems, however, the preliminary results in this simple mode of operation are promising. Results similar to those shown in the figure have also been obtained with deuterons in $10\mu\text{m}$ thick emulsion and 25 MeV proton tracks in $25\mu\text{m}$ emulsion. The scanner is already useful in peak centroid determinations for excitation energy and Q-value measurements as well as for scanning of closely spaced doublets which are very difficult to scan in such fine ($25\mu\text{m}$) steps by hand.

SECTION II

ABSTRACTS OF TALKS AT MEETINGS

(July 1972-June 1973)

$^{43}\text{Ca}(p,t)^{41}\text{Ca}$ and $^{42}\text{Ca}(p,t)^{40}\text{Ca}$ Reactions
at 42 MeV. KAMAL K. SETH, Northwestern University, W. STEWART, Lewis Research Center (NASA), and W.A. LANFORD, W. BENENSON, and B.H. WILDENTHAL, Mich. State Univ. — In a previous (p,t) experiment¹ at 52 MeV on ^{45}Sc and ^{44}Ca almost identical L=0 transitions to the 1.838 MeV 0^+ state in ^{42}Ca and the 1.410 $7/2^-$ state in ^{43}Sc were found. It was suggested that the 1.410 state in ^{43}Sc consists largely of the $7/2^-$ proton weakly coupled to the 1.838 MeV 0^+ state of the core ^{42}Ca . We now report (p,t) experiments at 42 MeV on ^{43}Ca and ^{42}Ca targets using MSU cyclotron a position sensitive proportional counter in the focal plane of the split-pole spectrograph. Differential cross sections for states in $^{40,41}\text{Ca}$ up to about 6 MeV excitation were measured from 3° to 50° with an energy resolution of about 30 keV. "Pure" L=0 transitions were found both to the g.s. and the 2.959 MeV state in ^{41}Ca . Comparison of these with the L=0 transition to the g.s. and the 3.353 MeV 0^+ state in ^{40}Ca once again suggests that the 2.959 MeV $7/2^-$ state in ^{41}Ca consists largely of a $f_{7/2}$ neutron weakly coupled to the 3.35 MeV 0^+ excited state of the core ^{40}Ca .

*Supported by the National Science Foundation.
¹K.K. Seth et al., Bull. Amer. Phys. Soc. **17**, 535 (1972) GG9.

The $^{60}\text{Ni}(p,d)^{59}\text{Ni}$ Reaction at 35 MeV,
J.A. NOLEN, Jr., R.G.H. ROBERTSON, and S.C. EWALD, Mich. State Univ. — The $^{60}\text{Ni}(p,d)^{59}\text{Ni}$ reaction has been studied with the MSU cyclotron-magnetic spectrograph system. Angular distributions have been measured from 3° to 90° using a resistive wire gas proportional counter. Additional data were recorded at 4 angles in nuclear emulsions with a resolution of ~ 5 keV. The angular distributions display more pronounced $\ell=3$ j-dependence and less $\ell=1$ j-dependence than seen at lower energies.¹ Good fits to the $\ell=1$ shapes have been obtained with DWBA calculations, but these calculations do not fit the $\ell=3$ angular distributions. Accurate excitation energies and several new spin assignments have been determined for many levels up to 7.5 MeV excitation in ^{59}Ni .

*Supported by the National Science Foundation.
¹C. Glashauser and M.E. Rickey, Phys. Rev. **154**, 1033(1967).

The Decay of ^{199}Pb , * R.E. DOEBLER, WM. C. McHARRIS, and W.H. KELLY, Mich. State Univ., and Lawrence Berkeley Laboratory, Berkeley, Calif. — ^{199}Pb was produced using ~ 35 MeV ^3He beams from the MSU Cyclotron to induce the ($^3\text{He},4n$) reaction on separated isotope ^{200}Hg . Gamma rays emitted in the decay of 90-min ^{199}Pb were studied with Ge(Li) and NaI(Tl) detectors in a variety of singles and coincidence experiments, including a two-dimensional γ - γ coincidence experiment of 4096×4096 channels. A total of 117 γ transitions have been observed. Excited states in ^{199}Tl accommodating 89 of these transitions have been placed at 0, 366.90, 720.26, 1120.90, 1241.67, 1482.25, 1502.00, 1528.2, 1554.10, 1632.00, 1658.47, 1695.25, 1725.4, 1749.6, 1768.5, 1891.0, 1898.1, 1930.4, 1959.45, 1977.8, 2031.5, 2159.0, 2206.7, 2226.5, 2237.3, 2367.3, 2433.5, 2547.4, and 2643.2 keV. The systematics of the odd-A Tl nuclei, including ^{201}Tl and ^{199}Tl , will be discussed in terms of single-particle shell

model states coupled to core states of the corresponding Pb nuclei.

*Supported in part by the U.S. Atomic Energy Commission and by the National Science Foundation.

Study of the (p,t) Reaction on the Even Isotopes of Lead, * W.A. LANFORD, Mich. State Univ. — The (p,t) reaction has been studied on ^{208}Pb , ^{206}Pb , and ^{204}Pb using the 35 MeV proton beam from the MSU Cyclotron. Angular distributions have been measured from 3° to 68° using a position sensitive proportional counter in the focal plane of a magnetic spectrometer. This system gave 30 keV (FWHM) resolution. Additional exposures were taken with nuclear emulsions which gave 15 keV resolution. Comparison of the observed relative cross sections for a given L-transfer with the DWBA prediction using the shell-model wave functions of J.B. McGroory to describe ^{208}Pb , ^{206}Pb , and ^{204}Pb show generally good agreement. A forward peaked angular distribution was observed for the transition to the 3^+ unnatural parity state at 1.340 MeV in ^{206}Pb .

*Supported by the National Science Foundation.

Rotational Bands in ^{183}Os Excited in the $^{182}\text{W}(\alpha,3n\gamma)$ Reaction, * F.M. BERNTHAL, R.A. WARNER, and C.L. DORS, Mich. State Univ. — The in-beam γ -ray study of $N = 105$ and 107 isotones has been extended to the odd-mass osmium nuclei. Gamma-ray energies, intensities, and γ - γ coincidence data have been used to construct a preliminary ^{183}Os level scheme. Members of the $9/2^+[624]$ ground band at 96.5, 219.3, 375.6, 541.7, 764.2, 951.5, 1256.0, 1442.5, 1844.6, and 2017.3 keV have been established up to spin $29/2^-$. The $9/2^+[624]$ band is found to be nearly as strongly perturbed by the Coriolis interaction as is the analogous band in ^{179}W . The data for this band in ^{183}Os have also been analyzed by diagonalization of the Coriolis interaction matrix.

*Supported by the US Atomic Energy Commission and the National Science Foundation.

Electron-Nucleus Inelastic Scattering Calculations Using the WKB Distorted Wave Born Approximation, * G.R. HAMMERSTEIN and H. MCMANUS, Mich. State Univ. — Cross sections for inelastic electron-nucleus scattering are calculated in Born approximation taking Coulomb distortion of the electron waves into account via a three-dimensional WKB approximation. The results are compared with experiment and with the results of exact numerical partial wave calculations.

*Supported in part by the National Science Foundation.

Levels to Spin 16 in ^{180}W and ^{182}Os Excited in the $(\alpha, 4n)$ Reaction, * R.A. WARNER, and F.M. BERNTHAL, Mich. State Univ.—The γ -ray spectra accompanying $^{180}\text{W}(\alpha, 4n)$ and $^{182}\text{Os}(\alpha, 4n)$ reactions have been studied as part of a systematic investigation of the spin dependence of moments of inertia (I) in nuclei for which the $i_{3/2}$ family of neutron orbitals is nearly filled. The ground-band cascades have been determined with the aid of γ - γ coincidence data, and a preliminary analysis places the 10^+ , 12^+ , 14^+ , and 16^+ levels at 1664, 2236, 2824, and 3415 keV, respectively in ^{180}W , and at 1810, 2343, 2836, and 3314 keV in ^{182}Os . The sharp increase in reported in more neutron-deficient nuclei by several groups is also seen in these nuclei. Analysis in progress will yield more precise results for these and other $N=106$ -110 species. The results will be discussed in light of a recently proposed model.¹

*Work supported by the U.S. Atomic Energy Commission and the National Science Foundation.
1 F.S. Stephens and R.S. Simon, Nucl. Phys. A183 (1972) 257.

A Charge Division Position Sensitive Proportional Counter System, * W.A. LANFORD, W. BENENSON, G.M. CRAWLEY, E. KASHY, I.D. PROCTOR, and W.F. STEELE, Mich. State Univ.—We describe a charge division position sensitive proportional counter system which is extensively used in the focal plane of the MSU magnetic spectrometer. The system has the following characteristics: the position resolution is about 1 mm (FWHM); the active length is 25 cm; the maximum counting rate is more than 5×10^3 cps. The normal operating configuration is the proportional counter backed with a plastic scintillation counter. This system has available for particle identification: the ΔE signal from the proportional counter, the time-of-flight of the particle through the spectrograph, the total energy of the particle from the scintillation counter, and the momentum of the particle from its position in the focal plane. Spectra of various reactions studied with this counter will be shown.

*Supported by the National Science Foundation.

A=25 Mass Quartets, * W. BENENSON, E. KASHY, and I.D. PROCTOR, Mich. State Univ.—The mass excesses of the lowest $T=3/2$ states in ^{25}Al and ^{25}Mg and of the ground state of ^{25}Na have been measured with high precision. The states were excited by the $^{27}\text{Al}(p, t)$, $^{27}\text{Al}(p, ^3\text{He})$, $^{26}\text{Mg}(p, d)$, and $^{26}\text{Mg}(d, ^3\text{He})$ reactions. The same reactions on ^{12}C and ^{16}O present in the targets served as calibrations. The results were fit with the isobaric multiplet mass equation to obtain the coefficients for both the $5/2^+$ and $3/2^+$ multiplets. A small positive cubic term is indicated for the $3/2^+$ multiplet.

*Work supported by the National Science Foundation.

AMERICAN PHYS. SOC. NEW YORK MEETING, JAN. 1973

(p,d) Studies of the Germanium Isotopes, * D.L. SHOW, B.H. WILDENTHAL, and J.A. NOLEN, Mich. State Univ.—Angular distributions have been measured for the states in ^{71}Ge and ^{73}Ge up through an excitation energy of 4 MeV. Spectra were taken between the angles of 6° and 60° in the lab with an energy resolution of 8-12 keV FWHM. The proton bombarding energy was 35 MeV. In most cases the j -dependence observed in the $\ell=3$ transfers allow unique spin assignments to the $5/2^-$ and $7/2^-$ states. Preliminary studies of the $^{70}\text{Ge}(p, d)$ reaction at a proton energy of 24 MeV and at angles $>90^\circ$ indicate the presence of sufficient j -dependence in the $\ell=1$ transfers to distinguish between the $1/2^-$ and $3/2^-$ states.

*Work supported by the National Science Foundation.

Studying Nuclei with 30 to 40 MeV Protons and 3 to 4 keV Resolution, * H.G. BLOSSER, Mich. State Univ.—An energy-loss spectrograph system is in use at the MSU Cyclotron Laboratory; overall energy resolutions in 1 in 10,000 or better have been achieved in a number of experiments. The resolution of an energy-loss system is mainly determined by the luminosity of the effective beam source.¹ This condition is then ideal for a "single-turn" cyclotron with its intense position-ion source. Spectra with 3 keV resolution at 30 MeV typically require 30 minutes running time. Several beam-sensing feedback loops are important elements in the practical application of this technique as is a computerized on-line resolution meter.² A momentum matching calibration procedure allows absolute measurements with an accuracy of 3 to 4 keV.³

*Supported by the National Science Foundation.
1 B.L. Cohen, Rev. Sci. Instr. 33, 85(1962).
2 Blosser, et al., Nucl. Instr. Meth. 91, 61(1971).
3 Trentleman & Kashy, Nucl. Instr. Meth. 82, 304(1970).

γ - γ Coincidences from the $^{48}\text{Ti}(p, n\gamma)^{48}\text{V}$ Reaction below 3.36 MeV of Excitation, * L.E. SAMUELSON, R.A. WARNER, and W.H. KELLY, Mich. State Univ., E.M. BERNSTEIN, R. SHAMU, Western Mich. Univ.—A Ge(Li)-Ge(Li) spectrometer was used to study γ - γ coincidences from the $^{48}\text{Ti}(p, n\gamma)^{48}\text{V}$ reaction at proton bombarding energies of 5.97, 6.48, 7.03, and 8.33 MeV. Based upon coincidence evidence and γ -ray energy sums, we have placed 62 definite and 8 possible γ -ray transitions from 41 excited states in ^{48}V . The energies in keV of states from which deexcitation rays are observed to be in coincidence are 308.3 ± 0.1 , 420.8 ± 0.1 , 427.9 ± 0.1 , 518.8 ± 0.1 , 613.4 ± 0.1 , 627.3 ± 0.1 , 745.1 ± 0.1 , 765.0 ± 0.1 , 1055.9 ± 0.1 , 1099.3 ± 0.1 , 1264.6 ± 0.2 , 1521.5 ± 0.2 , 1557.5 ± 0.2 , 1685.6 ± 0.2 , 1781.0 ± 0.2 , 1998.6 ± 0.2 , 2096.9 ± 0.3 , 2118.5 ± 0.5 , 2179.5 ± 0.5 , 2258.1 ± 0.9 , 228.9 ± 1.0 , 2321.7 ± 1.2 , 2333.1 ± 0.6 , 2372.7 ± 0.6 , 2391.2 ± 0.7 , 2408.2 ± 0.7 , 2458.2 ± 1.2 , 2471.8 ± 1.2 , 2574.8 ± 1.0 , 2579.1 ± 1.2 , 2586.6 ± 1.2 , 2604.7 ± 1.4 , 2607.4 ± 1.4 , 2715.7 ± 1.5 , 2793.0 ± 1.6 , (2823.1 ± 1.2) , 2915.2 ± 1.8 , 2969.2 ± 1.8 , 3022.6 ± 2.0 , 3048.7 ± 2.0 , and (3200.5 ± 2.5) .

*Work supported in part by the National Science Foundation, Atomic Energy Commission and the Research Corporation.

Excited States in ^{140}Pr below 1.2 MeV as Determined by $^{141}\text{Pr}(p,d)$ and $^{140}\text{Ce}(p,n\gamma)$ Reaction Studies, JEAN GUILE, R.W. GOLES, C.B. MORGAN, R.A. WARNER, Wm. C. McHARRIS, and W.H. KELLY, Mich. State Univ. and E.M. BERNSTEIN and R. SHAMU, Western Mich. Univ.—Seven-keV FWHM resolution $^{141}\text{Pr}(p,d)$ data taken at 35 MeV have been used to determine the states below 1.5 MeV excitation in the odd-odd nucleus $^{140}\text{Pr}_{81}$. The γ decays of these states are being studied using the $^{140}\text{Ce}(p,n\gamma)$ reaction. Gamma-ray excitation functions, γ -ray singles, and Ge(Li)-Ge(Li) coincidence experiments have been performed. A partial level scheme can be constructed with states at 0, 28, 191.9, 270.9, 286.7, 419.7, 574.4, 604.3, 861.6, 888.0, 904.1, 966.6, 1053.5, 1182.9, and 1228 keV. The more complex and more complete scheme is being constructed from the γ -ray data.

*Supported in part by the National Science Foundation, the Atomic Energy Commission, and the Research Corporation.

Current States of A=101 Nuclei, R.R. TODD,*† W.H. KELLY, Wm. C. McHARRIS, F.M. BERNTHAL, and R.A. WARNER, Mich. State Univ.—The Nuclear Data sheets for nuclei in the A=101 mass chain have been revised. Nuclear structure data from particle reactions, radioactive decay, and Coulomb excitation studies have been evaluated and compiled. Adopted level properties and decay schemes will be briefly summarized. Disagreements and gaps in the current data will be discussed.

*Nuclear Information Research Associate. Work supported by the National Science Foundation through the National Academy of Sciences - National Research Council.

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††Work also supported in part by the National Science Foundation and the U.S. Atomic Energy Commission.

Helium Jet Recoil Transport Plus Aqueous Chemistry, K.L. KOSANKE, Wm. C. McHARRIS, Mich. State Univ.—The helium-jet recoil transport (HeJRT) method has been used as part of a system performing fast aqueous chemical separations. The HeJRT system¹ is used to generate activities and to transport them into the chemical system. Entrapment of the activities in the aqueous solution is accomplished by merely allowing a mixing of the flow of aqueous solution feeding the chemical apparatus. The low pressure (down stream) end of the HeJRT system is operated at atmospheric pressure to allow easy performance of the chemistry and sample handling. The operation of the system was demonstrated by a separation of Ga activities from Zn and Cu activities (resulting from 30 MeV protons on natural Zn targets) using ion exchange techniques. The total time elapsing between the production of activities and the completion of the chemistry was 51 second.

K.L. Kosanke, G.C. Giesler, Wm. C. McHarris, MSU Cyclotron Laboratory Annual Report 1970-71, p. 42.

The ϵ/β^+ Decay of ^{143}Eu , R.B. FIRESTONE, Wm. C. McHARRIS, and W.H. KELLY, Michigan State Univ.— ^{143}Eu was produced by 28-MeV protons on enriched (95.10%) $^{144}\text{Sm}_{203}$ targets at the

Michigan State University Sector-Focused Cyclotron. Activities produced were transported by means of a rabbit transport system to counting areas where the predominant 2.3-min ^{143}Eu was counted for 10 min. The 8.8-min daughter activity, ^{143}Sm , was studied in separate experiments, and transitions related to ^{143}Eu decay generally were easily elucidated. Both γ -ray singles and Ge(Li)-Ge(Li) megachannel coincidence experiments involving large Ge(Li) detectors were performed, and, with the aid of (p,d) reaction studies on ^{144}Sm , definite levels in ^{143}Sm were found at 0(3/2⁺), 107.6(1/2⁺), 1106.6(5/2⁺), 1368.5(7/2⁺), 1536.2(5/2⁺), 1565.3, 1714.7(5/2⁺), 1912.1, and 2069.5 keV (5/2⁺). Additional levels are strongly indicated at 2101.7, 2166.7, 2227.5, 2270.2, 2312.4, 2356.5, 2409.4, 2557.3, and 2586.4 keV but are fed too weakly to be confirmed in coincidence experiments. ϵ/β^+ feeding branching ratios were measured and indicated anomalous β^+ enhancement to the 1565.3-keV level; this is currently under investigation.

The ϵ/β^+ Decay of ^{143}Sm , Wm. C. McHARRIS, R.B. FIRESTONE, and W.H. KELLY, Mich. State Univ.— ^{143}Sm was produced from the decay of ^{143}Eu , which was made in copious yields by 28-MeV protons on enriched (95.10%) $^{144}\text{Sm}_{203}$ targets at the Michigan State University Sector-Focused Cyclotron. Activities produced were transported by a rabbit transport system to counting areas where the 2.3-min parent, ^{143}Eu , was allowed to decay for at least 10 min after which the 8.8-min ^{143}Sm was counted for about 30 min. Both γ -ray singles and Ge(Li)-Ge(Li) megachannel coincidence experiments involving large Ge(Li) detectors were performed, and, with the aid of (p,d) reaction studies and previous work [D. DeFrenne, E. Jacobs, and J. Demuynek, Z. Phys. 237, 327(1970)], levels were placed definitely at 0(5/2⁺), 271.9(7/2⁺), 1056.2(3/2⁺), 1173.0(1/2⁺), 1402.5(3/2⁺), 1514.5(3/2⁺), 1613.3, 1816.8, and 2081.1 keV. Levels were strongly indicated at 1854.2, 2008.9, 2192.9, 2445.6, 2613.7, 2920.6, 3050.1, and 3156.8 keV, but were fed too weakly to appear in coincidence experiments. ϵ/β^+ feeding branching ratios were measured and indicated anomalous β^+ retardation to the 1173.0-, 1402.5-, and 1514.5-keV levels. This anomaly is currently under investigation.

The Low Lying Levels of ^{118}Sb ,* W.B. CHAFFEE, C.B. MORGAN, R.A. WARNER, W.C. McHARRIS, W.H. KELLY, Mich. State Univ., E.M. BERNSTEIN, and R. SHAMU, Western Mich. Univ.—The charged particle reactions $^{118}\text{Sn}(^3\text{He},t)$, $^{117}\text{Sn}(^4\text{He},t)$, $^{117}\text{Sn}(^3\text{He},d)$ and the gamma rays from the reaction $^{118}\text{Sn}(p,n\gamma)^{118}\text{Sb}$ have been used to identify the energy levels of ^{118}Sb lying below 1200 keV of excitation. 86 gamma rays have been observed in the (p,n γ) reaction as probably associated with the de-excitation of ^{118}Sb . Of these 52 gammas have been observed in (p,n $\gamma\gamma$) coincidence experiments. A tentative decay scheme has been constructed incorporating 24 levels at the following energies (in KeV): 51, 166, 238, 324, 403, 540, 606, 622, 628, 652, 740, 788, 802, 862, 937, 953, 985, 1019, 1041, 1096, 1117, and 1159, and 1182.

*Work supported in part by the National Science Foundation and Atomic Energy Commission (MSU) and a grant from the Research Corporation (WMU).

The $^{64}\text{Zn}(p,t)^{62}\text{Zn}$ Reaction at 35 MeV.*
 R.A. HINRICHS, Mich. State Univ. and SUNY-College at Oswego.—The $^{64}\text{Zn}(p,t)$ reaction to states in ^{62}Zn has been studied at a bombarding energy of 35 MeV using the Mich. State Cyclotron. Angular distributions were taken between 6° and 60° using a wire counter and emulsion plates in an Enge split-pole spectrograph. 35 levels in ^{62}Zn , many unreported, were observed up to an excitation energy of 5.4 MeV. Spin-parity assignments have been made for most of these levels by comparison both with DWBA calculations and with empirical characteristic shapes of known states. 0^+ states were tentatively identified at 1.88, 3.96 and 5.17 MeV; the state at 1.88 MeV may be the 0^+ member of the two phonon triplet, previously identified in other Zn isotopes but not in ^{62}Zn .¹

*Work supported in part by the National Science Foundation.
¹L.C. Farwell, J.J. Kraushaar and H.W. Baer, to be published.

A Survey of the $(^3\text{He}, ^7\text{Be})$ Reaction at 70 MeV.* W.F. STEELE, G.M. CRAWLEY, and S. MARIPUU, Mich. State Univ.—The 70 MeV ^3He beam of the Michigan State University Cyclotron has been used to observe spectra and angular distributions from the $(^3\text{He}, ^7\text{Be})$ reaction on a number of different targets. A position sensitive gas proportional counter system is used in the focal plane of an Enge split-pole broad range magnetic spectrograph to measure the momentum of $^7\text{Be}(4^+)$ ions. Particle identification is achieved through the use of the differential energy loss of the particles in the gas counter, and the time-of-flight of the ions in the spectrograph. Results will be presented for targets of ^{12}C , ^{16}O , and ^{24}Mg . In the $^{24}\text{Mg}(^3\text{He}, ^7\text{Be})^{20}\text{Ne}$ spectrum the 4.97 MeV 2^- level is only weakly excited while the 5.62 MeV 3^- state has the strongest cross-section observed.

*Supported by the National Science Foundation.

A Study of Proton Inelastic Scattering on ^{207}Pb , ^{208}Pb , and ^{209}Bi .* W.T. WAGNER and G.M. CRAWLEY, Mich. State Univ.—Low-lying states in these isotopes have been studied using the 35 MeV proton beam from the MSU cyclotron. Angular distributions from 10° to 100° were measured using both photographic emulsions and a position sensitive proportional counter in the focal plane of a magnetic spectrograph. Using a dispersion matching technique, the data obtained with the nuclear emulsions had a resolution of 5-8 keV FWHM. In addition to the weak coupling states in ^{207}Pb and ^{209}Bi many other excited states were seen in the three nuclei. Microscopic DWBA calculations for some of these states will be presented.

*Supported by the National Science Foundation.

AMERICAN PHYS. SOC. WASHINGTON MEETING, APR. 1973

Yrast States of $^{182,184,186,188}\text{Os}$
 Populated by (α, xn) Reactions. R.A. WARNER, F.M. BERNTHAL, J.S. BOYNO, and T.L. KHOO, Mich. State Univ.—The γ -ray spectra accompanying $^{182,184,186}\text{W}(\alpha, 4n)$ and $^{186}\text{W}(\alpha, 2n)$ reactions

have been studied to establish the ground-band cascade in four Os isotopes. Anisotropy and γ - γ coincidence data lead to the moments of inertia plotted below against rotational energy as defined by Johnson et al.¹

*Work supported by the US Atomic Energy Commission and National Science Foundation.
¹A. Johnson, H. Ryde, and J. Sztarkier, Phys. Letters **34B**, 605(1971).

Twin Back-Bending Curves in ^{154}Gd .*
 T.L. KHOO, F.M. BERNTHAL, J.S. BOYNO and R.A. WARNER, Mich. State Univ.—The even-even nucleus ^{154}Gd has been studied by means of the $^{154}\text{Sm}(\alpha, 4n\gamma)^{154}\text{Gd}$ reaction at a bombarding energy of 48 MeV. Both γ -singles and γ - γ coincidence measurements were performed. The members of both the ground and β -bands were determined up to spin 18. A conventional plot¹ of I vs ω^2 confirmed the backbending effect previously observed² in the β -band. In addition, the ground band exhibits the same effect at a critical spin value of 18. These phenomena may be explained in terms of the Stephens & Simon model³ by considering a decoupled 2 quasi-particle band which intersects both the β - and ground bands.

*Work supported by US Atomic Energy Commission and National Science Foundation.
¹A. Johnson, H. Ryde and J. Sztarkier, Nucl. Phys. **A179**, 753(1972).
²D. Ward, R.L. Graham, J.S. Geiger and H.R. Andrews, Bull. Am. Phys. Soc. **18**, 36(1973).
³F.S. Stephens and R.S. Simon, Nucl. Phys. **A183**, 257(1972).

β^+ Decay of ^{65}Ge .* R.G.H. ROBERTSON and SAM. M. AUSTIN, Mich. State Univ.—The experiments by which the new isotope ^{64}Ge was produced¹ have also yielded information on the decay of ^{65}Ge . Enriched ^{64}Zn targets were bombarded with 50 MeV ^3He ions from the MSU cyclotron, and Ge chemically separated. The half-life of ^{65}Ge was found to be only 30.0 ± 1.2 sec, in contrast to the previous measurement² of 1.5 min. Nine γ -rays were assigned to ^{65}Ge with energies (and absolute intensities per 100 ± 10 decays) of 62.0 (24), 190.7(10), 587.8(2.5), 649.8(33), 809.3(21), 1070.4(1.3), 1229.8(2.2), 1688.4(3.6) and 1879.6(3.6) keV. Energy sums and the $^{64}\text{Zn}(\text{He}, d)^{65}\text{Ga}$ reaction³ indicate that levels at 0.0, 62.0, 190.7, 649.8, 809.3 and 1879.6 keV are populated in the β^+ decay.

*Supported by the National Science Foundation.
¹R.G.H. Robertson and S.M. Austin, Phys. Rev. Lett. **29**, 130(1972).
²N.T. Porile, Phys. Rev. **112**, 1954(1958).
³M.G. Betigeri et al., Nucl. Phys. **A100**, 416(1967).

(p,n) Reactions to the Isobaric Analog States of ^{48}Ca , ^{90}Zr , ^{120}Sn , and ^{208}Pb at 25 MeV. * D.M. PATTERSON, R.R. DOERING, and A.I. GALONSKY, Mich. State Univ.—Differential cross sections have been measured for the reactions $^{48}\text{Ca}(p,n)^{48}\text{Sc}$, $^{90}\text{Zr}(p,n)^{90}\text{Nb}$, $^{120}\text{Sn}(p,n)^{120}\text{Sb}$, and $^{208}\text{Pb}(p,n)^{208}\text{Bi}$ exciting the isobaric analogs of the target ground states. The incident proton energy was 25 MeV. The neutron spectra were obtained using the time-of-flight technique. The time resolution was typically 0.5 nsec (FWHM). The angular distributions generally extend from 0° to 160° (in the lab) in 5° steps. The current status of the DWBA analysis will be presented.

* Supported by the National Science Foundation and the Office of Naval Research.

Shell Model Calculation of Exotic (od-1s)-Shell Nuclei: The Heavy Oxygen and Fluorine Isotopes. * W.A. LANFORD and B.H. WILDENTHAL, Mich. State Univ.—The spectra and wave functions of $^{17-24}\text{O}$ and $^{17-24}\text{F}$ have been calculated in the complete space of (A-16) nucleons in $d_{5/2}$, $s_{1/2}$, $d_{3/2}$ shell model space. There is very good agreement between the predictions and experiment for the nuclei for which there exist experimental data. The oxygen isotopes corresponding to filling the $d_{5/2}$ shell (^{22}O) and the $s_{1/2}$ shell (^{24}O) are predicted to have first excited states at 3.22 and 5.38 MeV, respectively. It is hoped such shell model calculations may be helpful in designing experiments to study these nuclei.

* Supported by the National Science Foundation.

A High Resolution Study of the $^{208}\text{Pb}(p,d)^{207}\text{Pb}$ and $^{207}\text{Pb}(p,d)^{206}\text{Pb}$ Reactions. * W.A. LANFORD and G.M. CRAWLEY, Mich. State Univ.—The $^{208}\text{Pb}(p,d)^{207}\text{Pb}$ and $^{206}\text{Pb}(p,d)^{206}\text{Pb}$ reactions have been studied with 35 MeV protons using the high resolution (5-7 keV FWHM) cyclotron-spectrometer system at MSU. Angular distributions were measured from 6° to 50° for both reactions. By carefully measuring the relative cross-sections on these two isotopes, spectroscopic factors for the $^{207}\text{Pb}(p,d)^{206}\text{Pb}$ reactions were deduced relative to the spectroscopic factors for the $^{208}\text{Pb}(p,d)^{207}\text{Pb}$ reactions to the $2p_{1/2}$, $1f_{5/2}$, $2p_{3/2}$, $1i_{3/2}$, $1f_{7/2}$, and $h_{9/2}$ "single-hole-state". These "relative-spectroscopic" factors are in remarkably good agreement with the shell model predictions of McGrory.¹

* Supported by the National Science Foundation.
¹J.B. McGrory, Bull. Am. Phys. Soc. **17**, 579 (1972).

Studies of Giant Multipole Resonance in Inelastic Scattering of 70 MeV ^3He . * A. MOALEM, W. BENENSON and G.M. CRAWLEY, Mich. State Univ.—The giant dipole resonance (G.D.R.) region in ^{209}Bi , ^{208}Pb , ^{197}Au , ^{90}Zr , ^{40}Ca and ^{27}Al was studied using inelastic scattering of 70 MeV ^3He particles. Measured spectra at forward angles exhibit a wide peak approximately 3 MeV below the excitation energy of the G.D.R. The FWHM of the peak is larger than that obtained for the G.D.R. from photoneutron reactions. This suggests the excitation of another resonance at about 11 MeV. Similar results have been obtained in other inelastic

scattering experiments^{1,2} and has been interpreted as a giant resonance is discussed and the transition strength is compared with calculations from a nuclear scattering model for the G.D. and quadrupole states.

* Supported by the National Science Foundation.
¹M.B. Lewis and F.E. Bertrand, Nucl. Phys. A196, 337(1972).
²F.R. Buskirk et al. Phys. Lett. **42B**, 194 (1972).

Shell Model Calculations in the A=52-56 Nuclei. * P. HAUGE and B.H. WILDENTHAL, Mich. State Univ.—A modified surface-delta interaction is obtained for the A=52-56 nuclei by a least-squares fitting to numerous experimental levels in the region. The truncated basis includes up to four holes in the $F_{7/2}$ shell and all possible particle excitations in the $p_{3/2}$ orbit. The rms deviation to the fitted levels is then further reduced by allowing some of the two-body matrix elements to vary. From this resultant effective interaction, we calculate spectroscopic factors and various electromagnetic properties of these nuclei. Comparison with other shell model calculations as well as possible improvements in the model space are also considered.

* Supported by the National Science Foundation.

Shell Model Study of Argon and Potassium Nuclei. * A.O. EVWARAYE, Antioch College, Yellow Springs, Ohio and S. MARIPUU, Mich. State Univ.—Shell model calculations have been performed for argon and potassium nuclei with A=38-46. Excitation energies, M1 transition probabilities, magnetic moments and s-factors for one-nucleon transfer reactions have been calculated. Different model spaces and different realistic and phenomenological interactions have been tried. The effect of particle-hole states is discussed.

* Supported by the National Science Foundation.

High Resolution Proton Inelastic Scattering on ^{208}Pb . * W.T. WAGNER and G.M. CRAWLEY, Mich. State Univ.—Angular distributions for protons scattered from ^{208}Pb have been measured at 35 MeV bombarding energy. Use of nuclear emulsions in a Enge split-pole spectrograph and dispersion matching enable a typical resolution of 5-8 keV FWHM to be obtained. The first excited 3^- state and first two 5^- states were fairly strongly excited in this reaction as were low lying 2^+ , 4^+ , 6^+ , and 8^+ states. States previously identified as unnatural parity 4^- and 6^- configurations were clearly observed although weakly populated as was a natural parity 7^- state. Distorted Wave calculations including exchange and using the wave functions of True, et al.¹ and an effective interaction with both tensor and spin orbit components will be presented.

* Supported by the National Science Foundation.
¹W.W. True, et al., Phys. Rev. C3, 2421(1971).

Current Status of A=104 Nuclei.* L.E. SAMUELSON, ** W.H. KELLY, Wm. C. MCHARRIS, F.M. BERNTHAL, and R.R. TODD, *** Mich. State Univ.—The Nuclear Data sheets for all known nuclei in the A=104 mass chain from A=40 to 50 have been revised. Nuclear structure data from particle reactions, radioactive decay, Coulomb excitation, and nuclear fission products have been evaluated and compiled. Adopted level properties and decay schemes will be briefly summarized. Disagreements and gaps in the current data will be discussed.

- * Supported in part by the National Science Foundation and the U.S. Atomic Energy Comm.
 ** Nuclear Information Research Associate. Work supported by the National Science Foundation through the National Academy of Sciences-National Research Council.
 *** Now at Dept. of Phys. Western Mich. Univ.; Kalamazoo, Michigan 49001

Isospin Mixing in $f_{7/2}$ Shell. G. BERTSCH and B.H. WILDENTHAL, Mich. State Univ.—Isospin mixing in $f_{7/2}$ nuclei is calculated using the pure $f_{7/2}$ model space and the empirical interaction from the mass 42 spectra. The level shifts among the different members of the mass 42 multiplet give rise to the isospin mixing. Mixing in six nuclear states has been measured experimentally; we find reasonable agreement in magnitude and sign in four cases. The case of Sc^{44} confirms the evidence from the A=42 spectra that there is a non-Coulomb charge dependence of the effective interaction. In the table below, theoretical and experimental amplitudes of the T> state are listed ($\times 1000$).

Nucleus	$\alpha(T>)$ Theory	$\alpha(T>)$ Exp.
$Sc^{44}(2^+)$	4 $\times 10^{-3}$	4 $\times 10^{-3}$
$Ti^{46}(4^+)$	2	0.4
$Ti^{48}(6^+)$	3	-0.2 ± 0.2
$V^{48}(4^+)$	2	2
$Mn^{52}(6^+)$	1.7	3
$Mn^{52}(2^+m)$	2	2

Energy Levels of ^{116}Sb Below 1.5 MeV.* C.B. MORGAN, J.A. GULE, R.A. WARNER, L.E. SAMUELSON, Wm. C. MCHARRIS, W.H. KELLY, Mich. State Univ. E.M. BERNSTEIN, and R. SHAMU, Western Mich. Univ.—The reaction $^{116}Sn(p,n)$ was used to identify the energy levels of ^{116}Sb below 1500 keV of excitation. Eighty-nine γ rays appear to belong to the de-excitation of ^{116}Sb . A tentative decay scheme has been constructed incorporating levels at the following energies (in keV): 94, 103, 411, 455, 468, 518, 576, 613, 654, 732, 815, 824, 883, 999, 1021, 1127, 1157, 1124, 1441. Gamma ray angular distribution measurements have been used to determine the spins of the lower energy states. These results will be discussed.

- * Work supported by the National Science Foundation and Atomic Energy Commission (MSU) and a grant from the Research Corporation (WMU).

Higher-Order Effects shown by the (p,t) Reaction on the Deformed Nucleus, ^{165}Ho .* R.W. GOLES,† R.A. WARNER, Wm. C. MCHARRIS, and W.H. KELLY, Mich. State Univ.—30-MeV protons from the MSU Sector-Focused Cyclotron were used to study the $^{165}Ho(p,t)^{163}Ho$ reaction. Triton spectra were taken at 5° intervals between 10° and 75°, using an

Enge split-pole magnetic spectrograph; the overall resolution was typically better than 10 keV FWHM. The $7/2^- [523]$ ground-state rotational band was strongly excited at least up to the $17/2^-$ member at 720 keV, as was the $k=2=3/2^-$ γ -vibrational band, where members up to $13/2^-$ at 1075 keV were seen. However, no evidence was seen of a $k=2$ γ -vibrational or the (predicted to be high-lying) β -vibrational band. The angular distributions were complex and reminiscent of those found in the $^{159}Tb(p,t)^{157}Tb$ reaction [Goles, Warner, McHarris, and Kelly, Phys. Rev. Letters 24, 802(1972)], indicating that collective and higher-order effects play an important role.

- * Supported in part by the National Science Foundation and the U.S. Atomic Energy Comm.
 † Present Address: Bettelle Northwest Labs.

Errors in Charge Densities from Electron Scattering. J. BORYSOWICZ and J.H. HETHERINGTON, Mich. State Univ.—Errors on the charge distribution as derived from electron scattering are determined and it is shown that they depend largely on assumptions about the possible large q behavior of the form factor (i.e. at larger q-values than have been measured). We use rather general expansions for $\rho(r)$, for example the cosine series or a set of spline well determined and not very dependent on the set of functions used for expansion. The error in the charge distribution depends on assumptions about and knowledge of the errors in $f(q)$. Charge densities and their errors will be presented for He^3 and for He^4 based on electron scattering data. Some previous studies¹ of the errors in charge distributions have not precisely stated the assumptions about $f(q)$ at large q-values and have obtained rather large errors in $\rho(r)$. Our method is applicable to nuclei of larger z.

- ¹ J. Friedrich and F. Lenz, Nucl. Phys., A183, 523(1972).

A Study of the $^{43}Ca(p,d)^{42}Ca$ Reaction at 42 MeV. KAMAL K. SETH, A. SAHA, Northwestern University, W. STEWART, Lewis Research Center (NASA), and W.A. LANFORD, W. BENENSON, and B.H. WILDENTHAL, Mich. State Univ.—The neutron pickup reaction, $^{43}Ca(p,d)^{42}Ca$ has been studied at $E_p=42$ MeV using the MSU cyclotron. Deuteron were detected in a position sensitive proportional counter (backed by a plastic scintillation counter to permit particle identification) mounted in the focal plane of a split-pole magnetic spectrometer. An energy resolution of about 30 keV was obtained. Differential cross sections were measured in 3° steps from 6° to 55° for about 30 transitions to states in ^{42}Ca upto about 7.5 MeV excitation. It is found that the ℓ -assignment ambiguities in earlier ($^3He,\alpha$) experiment of comparable resolution are removed in our work and a much more reliable determination of spectroscopic strengths is made possible.

- * Supported by the National Science Foundation.
 † U. Lynen, H. Oeschler, R. Santo, and R. Stock, Nucl. Phys. A127, 343(1969).

Review of Instrumentation Systems of the MSU Cyclotron Laboratory. H.G. BLOSSER, Mich. State Univ.—The cyclotron is a variable-energy isochronous machine of nominal 50 MeV energy and provides beams of protons, deuterons, helions, and alphas. The cyclotron provides unusually precise beams; with careful adjustment 0.05% energy spread, 0.5 mm/mrad horizontal emittance, and 5.0 mm/mrad axial emittance. Internal selection slits give routine 100% extraction efficiency. Using a dispersion matching 1 in 10,000 energy resolution can be obtained in the 90 cm Enge split-pole spectrograph. The laboratory also has a modern computer system with a locally designed timesharing monitor which is able to handle major computing assignments (including distorted wave calculations, shell-model calculations, etc.) while concurrently offering a wide variety of data taking options to the experimentalist. Other major facilities include a 40" precision scattering chamber, a neutron time-of-flight facility and a helium jet transport system.

* Supported by the National Science Foundation.

(p,n) Reactions to the Isobaric Analog States of ^{48}Ca , ^{90}Zr , ^{120}Sn , and ^{208}Pb at 25 and 35 MeV. R.R. DOERING, D.M. PATTERSON, AARON GALONSKY, and J.G. BRANSON, Mich. State Univ.—Differential cross sections have been measured for the reactions $^{48}\text{Ca}(p,n)^{48}\text{Sc}$, $^{90}\text{Zr}(p,n)^{90}\text{Nb}$, $^{120}\text{Sn}(p,n)^{120}\text{Sb}$, and $^{208}\text{Pb}(p,n)^{208}\text{Bi}$ to the isobaric analogs of the target ground states. Proton energies of 25 and 35 MeV were used. The angular distributions were taken at 0° and in 5° steps between 10° and 160° . Macroscopic and microscopic DWBA fits to the data will be presented.

* Supported by the National Science Foundation and the Office of Naval Research.

The $^{48}\text{Ca}(^3\text{He}, ^7\text{Be})^{44}\text{Ar}$ Reaction at 70 MeV. W.F. STEELE, G.M. CRAWLEY, and S. MARIPUU, Mich. State Univ.—Lifetime measurements of ^{44}Ar have been made,^{1,2} but by techniques not permitting extraction of the mass or spectrum. Using the α -pickup reaction, ($^3\text{He}, ^7\text{Be}$), on a ^{48}Ca target, we have been able to observe the spectrum of ^{44}Ar , hence permitting a mass determination. Although we observe 4 or 5 states in ^{44}Ar , measurement of an angular distribution of any of them is impractical because of the very low differential cross section ($<1 \mu\text{b/str}$) and the dominance of Carbon and Oxygen contamination. A comparison will be made with the $^{40}\text{Ca}(^3\text{He}, ^7\text{Be})^{36}\text{Ar}$ reaction which yields differential cross sections on the order of 50 times greater.

* Supported by the National Science Foundation.
¹J. Hudis, et al., Nucl. Phys. A151, 634(1970).
²R.E. Larson and C.M. Gordon, Nucl. Phys. A133, 237(1969).

Anomalous ϵ/β^+ Decay Branching Ratios. R.B. FIRESTONE and Wm. C. McHARRIS, Mich. State Univ.—The ϵ/β^+ decay branching ratios for decays of ^{145}Gd , ^{143}Sm and ^{143}Eu were measured for transitions to numerous daughter levels. $\beta^+\gamma$ coincidence experiments were used to get relative positron feedings, and x-ray-coincidence experiments provided relative electron capture feedings. Instances of severe anomalies in the ϵ/β^+ ratios were observed for transitions to the 808.5-keV level of ^{145}Eu , the 1173.8-, 1403.9- and 1515.7-keV levels of ^{143}Pm , and the 1566.3-keV level of ^{143}Sm . These ratios deviated from theoretical ratios by factors of 20, 5, 5, 5 and 0.4 respectively. All were allowed transitions with relatively high log ft values. It is generally assumed that such results are evidence of Fierz interference which would bring into question the V-A Theory of beta decay.

* Supported in part by the U.S. Atomic Energy Commission and the National Science Foundation.

Decay of ^{177}Ta to Levels in ^{177}Hf . B.D. JELTEMA and F.M. BERNTHAL, Mich. State Univ.—Levels in ^{177}Hf populated by decay of 56.6 hr ^{177}Ta have been studied by γ -ray singles and γ -ray coincidence spectroscopy. The activity was produced by bombarding natural Lu foil with a beam of 30 MeV alpha particles produced by the MSU cyclotron. Several new levels have been added to the decay scheme proposed by West, et al.,¹ and multipolarities have been assigned for 24 of the 42 observed transitions with use of the conversion electron data of West. The previously proposed isomeric level at 421.0 keV thought to be $I^\pi=3/2^+$ is excluded by our data. A doublet is identified at 742.1 and 745.9 keV with the upper member being the $7/2^+[633]$ state proposed earlier. The presence of this doublet may alter the interpretation of transfer reaction data.²

* Supported in part by the U.S. Atomic Energy Commission and the National Science Foundation.
¹H.I. West, et al., Phys. Rev. 124, 527(1971).
²F.A. Rickey, Jr., et al., Phys. Rev. 170, 1157(1968).

Half-lives of the 308.3- and 518.8-keV States of ^{48}V . L.E. SAMUELSON, C.B. MORGAN, T.L. KHOO, and W.H. KELLY, Mich. State Univ.—The reaction $^{48}\text{Ti}(p,n\gamma)$ with $E_p=7.20$ MeV was used to measure the half-lives of the 308.3- and 518.8-keV states of ^{48}V . The ^{48}V γ rays were counted with a high-resolution, small-volume planar Ge(Li) spectrometer in 5.19-nsec time bands between 62.3-nsec spaced beam bursts of the MSU Sector-Focused Cyclotron. The measured half-lives are 7.12 ± 0.04 and 2.72 ± 0.06 nsec for the 308.3- and 518.8-keV states, respectively. No other ^{48}V states below 1.7 MeV of excitation were observed to have half-lives greater than 1 nsec.

* Supported in part by the National Science Foundation and the U.S. Atomic Energy Comm.

Barely Deformed Nuclei at High Spin.*

(Invited paper) R.A. WARNER, Mich. State Univ.—Some high-spin states of even-even nuclei lying just within the boundary of the rare-earth deformed region appear at energies surprisingly low, considering the well-behaved spacing of levels in the cascade de-exciting them.¹ When similar behavior was first discovered² in ¹⁶⁰Dy, it was interpreted as a sharp change in the moment of inertia caused by a nuclear phase transition. The effect was subsequently found in other nuclei with neutron number $90 \leq N \leq 96$. A specific explanation³ involving two-quasiparticle states is put to the test by the recent data on nuclei with as many as 112 neutrons. Yrast levels above spin 14 appear depressed in ¹⁸²,¹⁸⁴,¹⁸⁶Os. In ¹⁵⁴Gd, at the lower edge of deformation, levels in both the ground and β bands are affected. These new results, particularly those for the osmium isotopes, reveal the phenomenon to be more general than was expected by many investigators. The multiple γ feeding observed proceeding to many of these high-spin states is of additional interest.

*Supported by the U.S. Atomic Energy Comm. and National Science Foundation.

¹R.A. Warner and F.M. Bernthal, Bull. Am. Phys. Soc. **17**, 899(1972); R.A. Warner, F.M. Bernthal, J.S. Boyno, T.L. Khoo, and G. Sletten, to be published.

²A. Johnson, H. Ryde and J. Sztarkier, Phys. Letters **34B**, 605(1971).

³F.S. Stephens and R. Simon, Nucl. Phys. **A183**, 257(1972).

SECTION III
TITLE PAGE OF PUBLISHED PAPERS
(July 1972-June 1973)

Proton Decay of the Isobaric Analogs of the Ground States of ^{206}Pb , ^{207}Pb , ^{208}Pb , and $^{209}\text{Bi}^\dagger$

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(Received 30 December 1971)

The $(p, n\bar{p})$ reaction has been measured on the lead isotopes ^{206}Pb , ^{207}Pb , and ^{208}Pb and on ^{209}Bi . Coulomb-energy differences are extracted from the positions of the $\bar{p}$ peaks. Proton decay widths are also obtained and compared with values from resonance experiments and with a previous value from $^{208}\text{Bi}(p, n\bar{p})$.

I. INTRODUCTION

The $(p, n\bar{p})$ reaction¹ has been observed in a number of nuclei from ^{67}Zn to ^{209}Bi .²⁻⁴ This reaction allows one to study the position and width of the isobaric analog state⁵ (IAS) populated in the (p, n) reaction without the difficulty of neutron detection. In principle, proton decay widths of the IAS can also be measured if the (p, n) cross section leading to the IAS is known. However, for nuclei in the lead region, decays to more than one final state are observed and therefore *relative* proton decay widths can be obtained independent of the (p, n) cross section. These same widths can also be obtained by resonant elastic and inelastic proton scattering on a target with one less neutron than is required for the $(p, n\bar{p})$ experiments. This illustrates another feature of the $(p, n\bar{p})$ reaction. Since it can be used to study nuclei that cannot be reached by resonance reactions on stable nuclei, it provides complementary information. For example, the IAS studied by $^{206}\text{Pb}(p, n\bar{p})$ can only be reached by a resonance reaction on the unstable nucleus ^{205}Pb .

Earlier measurements of the partial widths for decay of the IAS in ^{208}Bi had shown agreement between the resonance measurements and the $^{208}\text{Pb}(p, n\bar{p})$ experiment. However, measurements of the $^{209}\text{Bi}(p, n\bar{p})$ reaction gave a relative proton width for the IAS in ^{209}Po which differed significantly from the measurements in ^{208}Bi . This was surprising, since one would not expect the extra $h_{9/2}$ proton in the ^{209}Bi parent nucleus to make a significant difference to the proton decay widths. This discrepancy encouraged us to repeat the $^{208}\text{Pb}(p, n\bar{p})$ experiment as a check on the earlier measurements. In addition, measurements on ^{206}Pb and ^{207}Pb were also made, and the $^{209}\text{Bi}(p, n\bar{p})$ experiment was repeated.

II. EXPERIMENT

The experimental arrangement is similar to that

discussed in an earlier paper on ^{209}Bi .⁴ The reactions were studied at many energies from 21.3 to 35 MeV using the proton beam from the Michigan State University isochronous cyclotron. A standard counter telescope of cooled silicon detectors was used to detect the protons. Deuteron spectra were taken simultaneously, since the (p, d) reaction produces the same final nuclei and therefore provides an energy calibration. The deuteron resolution also gives an accurate check of the target thickness measurement. Spectra were taken at many angles to avoid contaminant peaks and to check kinematic effects. Various targets of thickness from 1 to 6 mg/cm² were used in the experiment.

Kinematic effects are very important in a discussion of the $(p, n\bar{p})$ reaction, since both the energy of the detected protons and the shape of the peak depend on the angle of detection. This dependence arises from the angular distribution of the recoiling nuclei and therefore depends on the (p, n) angular distribution, which changes as the bombarding energy is changed. Calculations of both of these effects for model (p, n) angular distributions were shown in a previous paper.⁴ Even for heavy nuclei the shift and the broadening of the peak is significant and must be taken into account when extracting widths, even though the intrinsic width of the analog state is large (>200 keV) and dominates the observed width of the peak. A calculation for the energy shift of the $\bar{p}$ peak using a measured (p, n) angular distribution⁶ at 24.8 MeV is shown in Fig. 1 together with the experimental kinematic shifts for ^{209}Bi . The Bi target is quite free of impurities and allows a more complete angular distribution to be obtained than could be done for lead. Line-shape calculations at various angles are shown in Fig. 2 for the same (p, n) angular distribution. A Lorentzian function with a 220-keV total width is also shown on the same scale. The line shapes fold in such a way that the total observed full width at half maximum (FWHM)

$^{19}\text{F}(d, p)^{20}\text{F}$ and the Nuclear Structure of $^{20}\text{F}^\dagger$

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The reaction $^{19}\text{F}(d, p)^{20}\text{F}$ has been studied with 16-MeV deuterons. Outgoing protons were detected in photographic emulsions in a magnetic spectrograph. Spectroscopic factors were extracted and combined with previous information and compared with results of shell-model calculations performed in a complete sd -shell basis. Of the previously known 25 states below $E_x = 4.5$ MeV, angular distributions measured at 14 angles were obtained for all but the 5 at $E_x = 1.824, 2.871, 3.761, 4.20,$ and 4.21 MeV. Strong stripping angular distributions were observed for 10 states – 6 dominated by $l = 2$, and 4 by $l = 0$. These 10 states agree reasonably well in position and strength with the 10 lowest shell-model states predicted to have appreciable amounts of the configuration [$^{19}\text{F}(\text{g.s.}) \otimes 1d_{5/2}$ or $2s_{1/2}$ neutron].

I. INTRODUCTION

The spectroscopy of ^{20}F is typical of non-self-conjugate odd-odd nuclei; the knowledge about it is extremely scant in view of the effort that has been expended. The most notable early work on its structure was that of El Bedewi¹ in 1956. Using an 8.9-MeV deuteron beam and one of the first heavy-particle spectrographs, he was able to obtain excitation energies and angular distributions for a great many of the states in ^{20}F . His analysis of the angular distributions was limited by the use of the plane-wave Born approximation (PWBA). However, as we shall see below, his results for the few strong states were qualitatively correct.

Accurate excitation energies have been mea-

sured² up to $E_x = 6.043$ MeV by use of the reactions $^{18}\text{O}(^3\text{He}, p)^{20}\text{F}$ and $^{19}\text{F}(d, p)^{20}\text{F}$ at low bombarding energies. Information on the γ decay of levels of ^{20}F has been obtained in studies of the reactions $^{18}\text{O}(^3\text{He}, p\gamma)^{20}\text{F}$,³⁻⁷ $^{19}\text{F}(d, p\gamma)^{20}\text{F}$,^{3,8} $^{19}\text{F}(n, \gamma)^{20}\text{F}$,⁹⁻¹² and $^{18}\text{O}(t, n\gamma)^{20}\text{F}$.¹³ Further studies include measurements of lifetimes¹³⁻¹⁶ of excited ^{20}F levels, angular-distribution measurements of the reaction $^{19}\text{F}(d, p)^{20}\text{F}$ obtained with a polarized deuteron beam,¹⁷ and a study of the reaction $^{22}\text{Ne}(p, ^3\text{He})^{20}\text{F}$.¹⁸ Studies of the reactions $^{18}\text{O}(^3\text{He}, p)^{20}\text{F}$ and $^{22}\text{Ne}(d, \alpha)^{20}\text{F}$ have also been reported recently.¹⁹ The experimental results concerning ^{20}F are excellently summarized in the review by Ajzenberg-Selove.²⁰

Directional-correlation measurements⁷ in the re-

Collective Effects Shown by the (p, t) Reaction on the Closed-Shell Nucleus, ^{141}Pr

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The reaction $^{141}\text{Pr}(p, t)^{139}\text{Pr}$ at 40 MeV strongly populates collective states in the residual nucleus. The shapes of the angular distributions, taken at 5° intervals between 15° and 65° , show the inadequacies even of finite-range, two-nucleon-pickup distorted-wave Born-approximation calculations and the need for inclusion of higher-order effects.

The (p, t) reaction on ^{141}Pr has been studied as part of a general investigation of the systematics of the (p, t) reaction on spherical and deformed rare-earth nuclei. The residual nucleus of this reaction, ^{139}Pr , has been extensively studied through the ϵ/β^+ decays of the ground and metastable states of ^{139}Nd .¹ Because of the large number of very dissimilar states established in this decay scheme, 23 below 2.2 MeV, it was thought that here would be an excellent place to begin this general investigation.

In the present work, $\approx 800\text{-}\mu\text{g}/\text{cm}^2$ ^{141}Pr targets prepared by vacuum evaporation on $25\text{-}\mu\text{g}/\text{cm}^2$ carbon backings were bombarded with 500-nA beams of 40-MeV protons from the Michigan State University sector-focused cyclotron. A dE/dX , E counter telescope consisting of two cooled Si surface-barrier detectors was used to identify and measure the energies of the outgoing scattered particles. Triton spectra were taken between 15° and 65° at 5° intervals. Figure 1 contains triton spectra taken at the laboratory scattering angles of 25° and 35° . The over-all experimental resolution was 50 keV full width at half maximum. The excitation energies corresponding to the various triton peaks were determined internally by making a correspondence between some of the more obvious triton groups and the previously determined states in ^{139}Pr . In addition, an independent energy measurement of some of the more intense triton groups was conducted using a broad-range magnetic spectrometer, utilizing a 3-cm Si position-sensitive detector.

The experimental angular distributions, together with distorted-wave Born-approximation (DWBA) predictions, are displayed in Fig. 2. The distorted-wave predictions for various l transfers were cal-

culated using a zero-range, cluster-transfer approach² as well as a more rigorous finite-range, two-nucleon-pickup formalism.³ These are denoted by broken and continuous curves, respectively. Optical-model and bound-state parameters used in generating these theoretical curves appear in Table I.

The angular distribution corresponding to the $\frac{5}{2}^+$ $\rightarrow \frac{3}{2}^+$ ground-state transition corresponds to an ap-

FIG. 1. Two spectra ($\theta_{\text{lab}} = 25$ and 35°) of tritons from the $^{141}\text{Pr}(p, t)$ reaction at 40 MeV.

Proton Inelastic Scattering from $^{48}\text{Ca}^\dagger$

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Inelastic proton scattering from ^{48}Ca has been measured at beam energies 25, 30, 35, and 40 MeV. Angular distributions from 13 to 97° for 22 inelastic states were obtained. Analyses with the collective distorted-wave Born approximation are presented. A direct comparison of the excitation of the ^{48}Ca 3.830-MeV 2^+ and 6.342-MeV 4^+ states is made with the low-lying excited 2^+ and 4^+ states of ^{50}Ti and ^{52}Co .

I. INTRODUCTION

Doubly magic nuclei, in general, have been studied in great detail both experimentally and theoretically. Perhaps the exception to this statement is ^{48}Ca . From the experimental standpoint only a few of the low-lying states of ^{48}Ca have well established spin and parity. From the theoretical point of view ^{48}Ca is of interest because of the purity of its double-closed-shell structure. Jafarin and Ripka¹ have tested the occupation numbers and find that the $1f_{7/2}$ shell and the inner neutron shells are at least 97% closed. It is because of the strong theoretical motivation and of our interest in developing the (p, p') reaction as a probe in microscopic structure that we undertook the present (p, p') experiment on ^{48}Ca .

The level structure of ^{48}Ca has also been investigated in other experiments such as (α, α') ,^{2,3} (e, e') ,⁴ (t, p) ,⁵ (p, p') ,⁶ and $(p, p'\gamma)$.⁷ The (α, α') and (e, e') experiments probably should be repeated with the now available better resolutions. In principle, then, at least some of the ambiguities in the present assignments of the low-lying levels could be removed.

II. DESCRIPTION OF EXPERIMENT

The experiment was carried out using the proton beam from the Michigan State University sector-focused cyclotron. Figure 1 shows the cyclotron and beam-handling system. The two horizontal bending magnets M3 and M4 are used to momentum analyze the beam and M5 deflects the beam into

the goniometer.⁸ More complete descriptions of the properties of the energy analysis system have been published elsewhere.^{9,10} During this experiment the slits S1 and S3 were set at 15 mils for beam energy resolution of ± 5 keV. S2 was set at 100 mils to yield a beam divergence of ± 2 mrad. The Faraday cup is located in a shielded beam dump 12 ft beyond the goniometer.

The scattered protons were detected with two surface-barrier Ge(Li) detectors designed specifically for this experiment.¹¹ The two detectors were separated by 14.7° and were located outside the 16-in. scattering chamber. The detectors coupled to the scattering chamber vacuum via a sliding seal. A monitor counter at a fixed angle viewed the scattered beam through a 1-mil Kapton window.

The target was a commercially prepared self-supporting foil of ^{48}Ca approximately 1.08 mg/cm² thick. The composition of the target as determined by the Isotopes Division of Oak Ridge National Laboratory is listed in Table I. The target was stored in vacuum when not in use and transferred to the scattering chamber in vacuum via a target-transfer system.⁸

Inelastic proton spectra were taken every 5° from 13 to 97°. The over-all energy resolution was 25–30 keV full width at half maximum. Each counter subtended an angle of about 0.5° in the scattering plane. The scattering angle was checked by comparing the positions of the H and ^{12}C contaminant peaks relative to the ^{48}Ca ground state and found to be accurate to within 0.1°. The energy of the incident protons determined by mea-

Decay of ^{170}Lu to Levels in $^{170}\text{Yb}^\dagger$

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The locations of 70 energy levels in ^{170}Yb were deduced from Compton-suppressed γ -ray singles, three-crystal γ -ray pair, conversion-electron, and $\text{Ge}(\text{Li})$ - $\text{Ge}(\text{Li})$ γ - γ coincidence measurements on the electron-capture- β^+ decay of ^{170}Lu . Both chemically separated and isotopically separated sources of ^{170}Lu were used in collecting the data. A total of 550 γ -ray transitions have been observed in the ^{170}Lu decay spectrum, 220 of which are definitely assigned to the ^{170}Yb level scheme from 112 coincidence spectra. These definitive transitions account for 93% of the total observed γ -ray intensity. An additional 118 γ -ray transitions were placed on the basis of excited-state energy differences. Eight $E0$ transitions were observed in the conversion-electron data. Each of four excited 0^+ states identified has less than 1% β decay feeding from the 0^+ parent. Spin and parity assignments are proposed for 46 levels in addition to the ground-state rotational band members. The ^{170}Yb level structure is compared with available theoretical calculations, and a preliminary interpretation of several features of the decay scheme is presented.

I. INTRODUCTION

The most complicated radioactive decay yet studied is the electron-capture (EC)- β^+ decay of 2.15-day ^{170}Lu to the levels of ^{170}Yb . Early attempts to interpret the complex γ -ray spectrum from $\text{NaI}(\text{Tl})$ data were largely unsuccessful, and until recently, the best available data consisted primarily of conversion-electron spectra.¹⁻³ With the advent of germanium detectors, however, several groups⁴⁻⁸ renewed their efforts at unraveling this very complex decay. Hansen and co-workers⁹ established 0^+ as the ground-state spin and parity of ^{170}Lu . Paperiello *et al.*¹⁰ carried out directional-correlation measurements on several of the more intense transition cascades in this decay and have definitely established the spins of 10 levels in ^{170}Yb . Concurrent with the work reported here were the recent studies reported by Bonch-Osmolovskaya and co-workers^{11,12} who employed $\text{Ge}(\text{Li})$ detectors, electron- γ , γ - γ , and electron-electron coincidences, in an effort to define the decay scheme. They placed some 177 transitions of 280 seen in the decay, thus accounting for almost 87% of the total γ -ray intensity.

In this work we report the results of extensive γ -ray singles, γ - γ coincidence, and conversion-electron measurements. Compton suppression and three-crystal pair-spectrometer techniques were used to accurately define the energies and intensities of the ^{170}Lu γ -ray transitions. Measurements at lower energies (<1.2 MeV) were carried

out with isotopically separated sources. An on-line computer and multiparameter data acquisition system were used in conjunction with two $\text{Ge}(\text{Li})$ detectors and an isotopically separated ^{170}Lu source to carry out a detailed study of the γ - γ coincidence spectra. Conversion-electron studies were carried out using chemically separated lutetium sources and a $\text{Si}(\text{Li})$ detector. On the basis of these data, we have constructed a level scheme for ^{170}Yb consisting of 70 excited states. Of 550 γ -ray transitions identified, over 200 have been placed on the basis of γ - γ coincidence data and another 118 were placed on the basis of energy differences; these two groups of γ rays account for 93 and 3% of the total γ -ray intensity, respectively. Significant differences exist between our decay scheme and that of Bonch-Osmolovskaya *et al.*,¹² and slight differences distinguish our decay scheme from the less complete level scheme of Mihelich.¹³

II. EXPERIMENTAL

A. Target and Source Preparation

Sources of ^{170}Lu were prepared by the $^{169}\text{Tm}(\alpha, 3n)^{170}\text{Lu}$ reaction by irradiating 40-mg samples of Tm_2O_3 at the Lawrence Berkeley Laboratory 88-in. cyclotron with 40-MeV α particles. 3-h irradiations at about 20- μA beam current produced about 1 mCi of ^{170}Lu activity for each experiment.

The lutetium activity was separated from other

Study of ($^3\text{He}, t$) Reactions at 70 MeV to Isobaric Analog States of ^{50}Cr , ^{62}Ni , and $^{90}\text{Zr}^\dagger$

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The analysis of ($^3\text{He}, t$) reactions at 70 MeV to isobaric analog ground states of ^{50}Cr , ^{62}Ni , and ^{90}Zr have shown an energy dependence in the extracted isospin-dependent interaction strengths consistent with results at lower energies; the interaction strengths are approximately 50% smaller than at lower bombarding energies. The shapes of the form factors in a macroscopic analysis are nuclei-dependent. A mass-three optical potential with a real strength of about 110 MeV and a volume imaginary term is strongly preferred in the ($^3\text{He}, t$) calculations.

I. INTRODUCTION

Charge-exchange reactions to isobaric analog states (IAS) of target ground states have been studied quite extensively in recent years with both (p, n)^{1,2} and ($^3\text{He}, t$)³⁻⁶ reactions at a variety of bombarding energies. The analysis of the differential cross sections for such reactions primarily has used the distorted-wave Born approximation (DWBA) in a macroscopic (generalized optical-potential) or microscopic (nucleon-nucleon interaction) framework, and has yielded information on the strength and form of the isospin-dependent interaction. Recent studies by Fadner, Kraushaar, and Hayakawa⁶ of ($^3\text{He}, t$) transitions to IAS in several nuclei at bombarding energies between 21.4 and 37.5 MeV have shown a marked energy dependence in the extracted strength of this isospin interaction and a variation in the extracted shapes of the isospin term (for the macroscopic analysis) for different nuclei. We have extended the study of ($^3\text{He}, t$) reactions to 70 MeV (the high-

est reported bombarding energy has been 50 MeV⁷) by examining transitions to IAS of the ground states of ^{50}Cr , ^{62}Ni , and ^{90}Zr to provide more information on the energy dependence of the charge-exchange interaction.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The reactions ^{50}Cr , ^{62}Ni , $^{90}\text{Zr}(^3\text{He}, t)$ were studied at a bombarding energy of 70 MeV using ^3He ions accelerated in the Michigan State University sector-focused cyclotron. The experiment was conducted in a 40-in. scattering chamber with the tritons detected in a 1-cm stack of three Si(Li) detectors. A ΔE - E particle identification program was used in conjunction with the Sigma-7 computer. An over-all resolution of 150 keV was obtained, which was detector limited. The targets were all 1-mg/cm² rolled foils. An energy spectrum for the reaction $^{62}\text{Ni}(^3\text{He}, t)^{62}\text{Cu}$ is shown in Fig. 1. At all angles the 0^+ IAS was populated

Shell-Model Calculations for ^{22}Na and ^{22}Ne

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Shell-model calculations have been performed for the nuclei ^{22}Na and ^{22}Ne . The model space is made up of all Pauli-allowed combinations of six particles in the orbits $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$. An inert ^{16}O core is assumed. The two-body interaction which is employed has been obtained by empirically modifying some of the matrix elements of Kuo's interaction in order to achieve an rms best fit between the observed energies of 72 levels in the $A=18-22$ region and the corresponding shell-model eigenvalues. Single-particle energies are taken from the ^{17}O spectrum. Calculated results for excitation energies, electromagnetic transition strengths, and spectroscopic factors for single-nucleon transfer are presented and compared with existing data.

I. INTRODUCTION

The shell model has been used successfully to describe the low-lying spectra of nuclei near neutron and proton closed shells. With the advent of sophisticated computer codes,¹ it has become possible to calculate the properties of nuclei further from closed shells. In particular, it has been shown that many aspects of the collective features of nuclei several nucleons removed from ^{16}O in the s - d shell can be well reproduced by shell-model calculations in which all of the s - d nucleons are active.²⁻⁵

Several aspects of the $A=22$ nuclei make them of particular interest from the standpoint of attempting to understand collective nuclear phenomena in terms of many-body microscopic calculations. These systems appear to be among the most highly deformed nuclei in the light-mass region. In addition, there have been extensive experimental studies of ^{22}Na and ^{22}Ne which have assigned spins and parities to many low-lying levels and have measured the strengths of many electric quadrupole and single-nucleon transfer transitions.

Since one wants to observe the fullest consequences of the two-body part of the nuclear Hamiltonian, it is desirable to study systems with as many active particles as possible. If the active particles are distributed without restriction over the three sd -shell orbits, the shell-model states for $A=22$ have dimensions as large as can be handled straightforwardly with our techniques. The $A=22$ systems thus constitute the best place to study the many-particle shell-model structure in

this region if one is to avoid introducing the additional complication of basis truncation within the s - d shell space itself.

Finally, the $A=22$ systems are of interest because, despite significant successes in explaining some features of their behavior, several aspects of the structure of the low-lying levels seemed to be reproduced poorly by previous calculations.^{2,3,5} In general, the results of shell-model calculations reproduce the detailed features of doubly odd nuclei less successfully than those of doubly even and even-odd nuclei. Thus a fully successful accounting for the properties of ^{22}Na would significantly increase confidence in the shell-model description of the structure of nuclei in this region.

II. TECHNIQUES OF CALCULATION

The shell-model calculations presented here are of the same type as those presented in Ref. 2, hereafter referred to as HMWP, and the notations and conventions of this reference are used in the present paper. The derivation of the Hamiltonian used in the present work is discussed in detail in Ref. 6. Briefly, the single-particle energies were taken from the observed spectrum of ^{17}O . For the $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$ orbits they are equal to -4.15 , -3.28 , and $+0.93$ MeV, respectively. The two-body matrix elements were obtained by adjusting selected two-body matrix elements of the " $K + ^{17}\text{O}$ " interaction used in HMWP so as to reach an rms best fit between 72 experimental-level energies in the $A=18-22$ region and the corresponding shell-model eigenvalues.

The " $K + ^{17}\text{O}$ " interaction of HMWP is one of the

Widths of Analog States in Bi and Po from (p, n) Spectra*

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Isobaric analog states have been observed in the neutron spectra of (p, n) reactions on targets of ^{206}Pb , ^{207}Pb , ^{208}Pb , and ^{209}Bi . After removal of instrumental resolution effects, the natural widths are, respectively, 196 ± 26 , 203 ± 32 , 202 ± 34 , and 151 ± 34 keV. Except in the ^{206}Pb case, these widths are substantially smaller than those observed in p spectra from $(p, n\bar{p})$ experiments on the same target nuclei but are in agreement with (p, p') resonance results in the two cases that have been measured.

I. INTRODUCTION

Recent $(p, n\bar{p})$ experiments on the lead isotopes¹ and on ^{209}Bi ² indicate a discrepancy between the total widths of the isobaric analog states (IAS) measured in these experiments and the widths obtained from (p, p') resonance experiments.^{3,4} The greatest discrepancy was for the IAS in ^{207}Bi , where the $^{207}\text{Pb}(p, n\bar{p})$ reaction gave a width greater than 500 keV, whereas the width of the same state measured by $^{206}\text{Pb}(p, p')$ was merely 170 keV.³ The only other case directly comparable was that of the IAS in ^{208}Bi , where the $^{208}\text{Pb}(p, n\bar{p})$ reaction gave a width of 317 ± 24 keV, compared to 220 ± 20 keV obtained from the $^{207}\text{Pb}(p, p')$ reaction.⁴ The IAS in ^{209}Po was similar to the ^{208}Bi case. Surprisingly, the total width for the IAS in ^{208}Bi measured by the $^{206}\text{Pb}(p, n\bar{p})$ reaction was quite small (230 ± 38 keV) and thus more in line with the resonance systematics, although a direct comparison could not be made because the required target (^{206}Pb) is unstable.

Since the decay channels available in the $(p, n\bar{p})$ and (p, p') experiments are the same and the formation channels are different, one might expect the latter to be the source of the discrepancy in the observed width of the IAS. Perhaps the (p, n) reaction populates the states underlying the IAS in a

significantly different manner than the resonance reaction. If so, one might expect to see evidence of this in the neutron spectrum of the (p, n) reaction. Previous (p, n) data on ^{208}Pb ⁵ did not have sufficient energy resolution to determine the total width of the analog state.

To help cast further light on this question, the (p, n) reaction was measured on the isotopes ^{206}Pb , ^{207}Pb , ^{208}Pb , and ^{209}Bi with good enough resolution to directly determine the intrinsic widths of the corresponding analog states.

II. EXPERIMENT

The experiment used the neutron time-of-flight facility of the Michigan State University Cyclotron Laboratory. This system⁶ makes use of the natural bunching of the cyclotron beam pulses. The neutron detector is the liquid scintillator NE-213, deoxygenated and encapsulated in a 2-in.-diameter $\times 3/4$ -in.-thick glass cell mounted on an RCA-8575 photomultiplier. Start and stop timing signals are derived from a constant-fraction discriminator on the photomultiplier and from the cyclotron rf voltage through a divide-by-2 scaler, respectively. Two-dimensional pulse-shape analysis is used to distinguish neutrons from γ rays.

In order to achieve both high-neutron energy

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Calculations of Allowed Beta Decay in the $(0d, 1s)$ Shell*

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Allowed β -decay transition rates and half-lives have been calculated for $(0d, 1s)$ shell nuclei with $A = 17-22$, $23-24$, $27-29$, $30-34$, and $35-39$. For nuclei with $A = 17-22$ and $34-39$, the calculated $\log ft$ values have a rms deviation of 5% from experiment, with no discrepancies greater than 12%. For nuclei nearer the middle of the shell there are more significant discrepancies between experiment and theory. The calculated $\log ft$ values are used to predict the half-lives of some light elements. The predicted half-lives for which there are no experimental measurements are: ^{20}Mg (0.1 sec), ^{21}O (1.2 sec), and ^{22}O (0.15 sec). The $\log ft$ values relevant to the solar neutrino experiment are discussed.

I. INTRODUCTION

This paper presents calculations of strengths of allowed β -decay transitions for the $(0d, 1s)$ shell nuclei with $A = 17-22$, $23-24$, $27-29$, $30-34$, and $35-39$. The shell-model wave functions of Wildenthal *et al.*¹⁻⁶ are used to describe the initial and final nuclear states. We present calculated $\log ft$ values for the approximately 100 transitions for which there are experimental measurements, and we give predictions for approximately an equal number of decays which may be measurable. We also use these calculated $\log ft$ values to predict β -decay half-lives. As will be seen, the agreement between the present calculations and experiments is consistently quite good for the nuclei for which the complete $(0d, 1s)$ shell-model basis space could be used. On the other hand, agreement with experiment is not as consistently good for calculations in the middle of the shell where significant truncations of the model space were necessary.

The calculation of β -decay transition rates is interesting for several reasons. (1) There are few uncertainties in the operators involved and in the connection between the experimentally measured quantities and those predicted by the theory. (2) Because the β -decay operators only connect single-particle states which have the same orbital angular momentum and because the initial and fi-

nal states are in different nuclei, the matrix elements of the β -decay operators tend to be sensitive to aspects of wave functions not extensively tested in comparisons of theoretical results with nucleon transfer and γ -decay data. Hence, we have the opportunity to learn more about the detailed efficacy of the extant sets of wave functions in the $(0d, 1s)$ shell. (3) As indicated above, there are a large number of experimentally measured decays which can be compared with calculated values. (4) If the calculations turn out to be reasonably successful, the results can be used to predict the half-lives of some of the neutron- and proton-rich nuclei which have not yet been observed. Such predictions might aid in designing experiments to observe these nuclei. And (5) calculated β -decay transition rates are needed to evaluate the results of Davis's experiment⁷ to measure the solar neutrino flux using the $^{37}\text{Cl} + \nu \rightarrow ^{37}\text{Ar} + e$ reaction.

II. DESCRIPTION OF THE CALCULATION

A. Operators

β -decay transition rates are expressed in terms of a $\log ft$, where t is the partial half-life for the decay to a given final state and f is a "statistical rate function" which takes account of the energy released in the decay and the Coulomb field of the final nucleus.⁸ For allowed decays, ft is given

Shell-Model Calculation for Masses 27, 28, and 29: General Methods and Specific Applications to ^{27}Al , ^{28}Si , and ^{29}Si

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A shell-model calculation for $A=27$, 28, and 29 nuclei has been carried out in a truncated $0d_{5/2}-1s_{1/2}-0d_{3/2}$ basis space with a modified-surface- δ -interaction Hamiltonian. A comparison of the calculated results for level energies, single-nucleon spectroscopic factors and $E2$ and $M1$ transition strengths in ^{27}Al , ^{28}Si , and ^{29}Si with the corresponding experimental values indicates that a unified and quantitative explanation of nuclear structure around $A=28$ can be obtained via shell-model techniques.

I. INTRODUCTION

We present here a description of a shell-model calculation for the mass region $A=27-29$ and some specific results for ^{27}Al , ^{28}Si , and ^{29}Si . In associated papers are presented: (1) a detailed study of $E2$ and $M1$ decays for all nuclei of this region using the present wave functions,¹ and (2) theoretical predictions based on the present work for the level energies, wave functions, and spectroscopic factors in ^{27}Mg , ^{28}Al , ^{28}Mg , and ^{29}Al .²

Despite extensive experimental investigation³ (and in another sense, because of it) and a multitude of strong-coupling and weak-coupling collective-model calculations, it seems fair to say that a fully satisfying and internally consistent understanding of the nuclear structure around ^{28}Si has not yet been achieved. The structure of ^{27}Al seems better described in a weak-coupling picture^{4,5} built on the 2^+ first excited state of ^{28}Si than it does in a simple Nilsson picture^{6,7} with the usual assumption of a prolate ground-state rotational band. However, either of these simple approaches leaves many significant features unexplained, and even more complicated collective-model calculations involving mixing⁸ of Nilsson bands or rotation-vibration mixing⁹ still fail to account for important aspects of the experimental situation. A recent suggestion¹⁰ has been that an oblate-shape assumption for the low-lying states of ^{27}Al can produce an accounting for $B(E2)$ and spectroscopic-factor observations.

The energy levels of ^{28}Si are clearly not typical of either the simple rotational or simple vibrational model. Calculations have been carried out

with Hartree-Fock¹¹ and SU_3 ¹² techniques with some success. Projected Hartree-Fock techniques together with vibration-interaction corrections^{13,14} give a better accounting for energies and $B(E2)$ properties in ^{28}Si , but the single-particle characteristics of these wave functions have not been thoroughly explored yet.

The structure of ^{29}Si is generally well accounted for with either a straightforward band-mixed Nilsson calculation^{15,16} or with an intermediate core-coupling approach^{17,18} and seems to offer the least resistance to theoretical interpretations of any set of phenomena in this region.

A particularly interesting feature of this region is that ^{29}Si has long been known to require an oblate deformation for a Nilsson-type interpretation¹⁹ and ^{27}Al , to the extent that the same model applied, seemed to require a prolate shape. Hartree-Fock calculations for ^{28}Si tended to yield ambiguous results concerning the shape of this nucleus until measurements of the quadrupole moment of the $J^\pi=2^+$ first excited state indicated oblateness. Thus one outstanding challenge to a theory for the region is to predict, rather than incorporate as parameters, the phenomena corresponding to this nominal change of shape occurring in the progression from ^{27}Al to ^{29}Si .

Our present study presents a simultaneous, internally consistent treatment of this mass region, in which the only essential variation between ^{27}Al , ^{28}Si , and ^{29}Si is the change in active particles from 11 to 12 to 13. We examine level energies, single-nucleon-transfer properties, and electromagnetic decays. The results are in consistent reasonable accord with experimental data and

States in Odd-Odd ^{62}Cu Populated by the Decay of ^{62}Zn

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The decay of 9.2-h ^{62}Zn to states in odd-odd ^{62}Cu has been studied with the aid of large-volume Ge(Li) γ -ray detectors. 19 γ rays were found to belong to this decay, and all were placed in a decay scheme containing states in ^{62}Cu at 0 ($J^\pi=1^+$), 40.94 (2^+), 243.44 (2^+), 287.98 (2^+), 426.3 (3^+), 548.4 (1^+), 637.5 (1^+), 915.6 ($[11^+]$), 1142.5 ($[0,11^+]$), 1280.8 ($[0,11^+]$), and 1429.9 keV ($[1,0^+]$). These were combined with existing in-beam γ -ray particle-transfer data to yield a rather complete ^{62}Cu level scheme. The status of shell-model calculations in this nuclear region is discussed, and it is demonstrated that a gratifying number of facts about the low-lying ^{62}Cu states can be explained using simple odd-odd configurations as predicted by the neighboring odd-mass nuclei.

I. INTRODUCTION

The odd-odd nuclide, $^{62}\text{Cu}_{33}$, contains a single proton and five neutrons outside the doubly closed $f_{7/2}$ shell. Consequently, its states should be amenable to interpretation in fairly straightforward shell-model terms. Also, many states and trends in nearby odd-mass nuclei are known, providing reasonably trustworthy input for predicting the properties of its odd-odd states. Unfortunately, relatively few states are known in ^{62}Cu itself, and even fewer have been well characterized. In this paper, we reexamine the decay of 9.2-h ^{62}Zn to ^{62}Cu , using the largest Ge(Li) γ -ray detectors we have been able to obtain in order to pick up weak feedings that previously had gone undetected. We then correlate our findings with those of previous investigators and with data from scattering reactions in an attempt to obtain a more coherent understanding of the structures of the ^{62}Cu states.

Since the discovery of ^{62}Zn in 1948 by Miller, Thompson, and Cunningham,¹ it has been studied by many groups. Hayward² determined the end-point energy of its β^+ spectrum to be 0.66 ± 0.01 MeV and observed K and L conversion electrons from a 41.8 ± 0.2 -keV transition, the K/L ratio indicating it to be $E1$ or $M1$. Nussbaum *et al.*³ determined that the first excited state of ^{62}Cu lies at 41.3 ± 0.3 keV and that $(36 \pm 3)\%$ of the ^{62}Zn feeding passes through this state. From α_K and $K/(L+M)$ they assigned the 41.3-keV transition an $M1$ multipolarity.

The first reasonably complete decay scheme was formulated by Burn, Meyerhof, Kraushaar, and Horen,⁴ who performed extensive electron

and NaI(Tl) γ -ray spectroscopy, including coincidence and γ - γ angular correlation experiments. They deduced states in ^{62}Cu at 0, 0.042, 0.30, 0.55, 0.63, and 0.70 MeV.

In the last few years there has been a flurry of activity about the neutron-deficient members of the $A=62$ mass chain. Four groups⁵⁻⁸ have reported Ge(Li) γ -ray studies on the decay of ^{62}Zn , and two other groups^{9,10} have reported on the decay of 9.7-min ^{62}Cu itself. Antman, Pettersson, and Suarez⁵ performed the first high-resolution Ge(Li) γ -ray experiments (in conjunction with electron experiments), and they and Roulston, Becker, and Brown⁶ demonstrated conclusively the doublet nature of the ≈ 245 -keV γ -ray peak and the existence of a 507.6-keV γ ray. These data were essential to the construction of a correct decay scheme, and the two groups arrived at almost identical decay schemes containing the first five excited states in ^{62}Cu that are populated by ^{62}Zn decay. The most precise half-life determination for ^{62}Zn , 9.2 ± 0.1 h, is also the work of Antman, Pettersson, and Suarez. Bakhru⁷ also performed high-resolution Ge(Li) γ -ray spectroscopy, including coincidence experiments, and he measured the half-life of the 42-keV state to be 2.5 ± 0.1 nsec. His decay scheme, however, differs in several placements from the others. And the most recent paper on ^{62}Zn decay, by Hoffman and Sarantites⁸ and again including results from γ - γ coincidence experiments, shows a decay scheme almost identical to those of Refs. 5 and 6.

Nuclear reaction and in-beam studies have been reported, also. Davidson *et al.*¹¹ have used the $^{62}\text{Ni}(p, n\gamma)$ reaction to study the decay of the ex-

Proton Capture by ${}^7\text{Be}$ and the Solar Neutrino Problem*

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It is shown theoretically that the ${}^7\text{Be}(p,\gamma){}^8\text{B}$ reaction cross section contains substantial contributions from p and d partial waves at laboratory energies, and extrapolations to stellar energies based on the assumption of pure s -wave capture are therefore erroneous. However, there is no change in the predicted solar neutrino flux, because the calculated low-energy cross-section factor, 31 eV b, is essentially the same as the empirical value in current use.

I. INTRODUCTION

The recent experiments of Davis¹ have set an upper limit of 1.0 SNU on the neutrino flux from the sun (1 SNU = 10^{-36} captures per target atom per sec), in sharp disagreement with the theoretical prediction of 9 SNU, calculated by Bahcall and Ulrich.² The rare termination of the p - p chain ${}^7\text{Be}(p,\gamma){}^8\text{B}(e^+\nu)2\alpha$ results in energetic neutrinos and is calculated to contribute 7.3 SNU. It is therefore important to have an accurate estimate of the rate of this reaction in the solar interior. Very detailed measurements of the cross section for ${}^7\text{Be}(p,\gamma){}^8\text{B}$ have been carried out by Kavanagh *et al.*³ (see Barnes⁴) at laboratory energies $E_p = 0.165$ to 10.0 MeV. A theoretical extrapolation to lower energies based on a calculation by Tombrello⁵ yielded a zero-energy cross-section factor⁶ $S(0)$ of 0.034 keV b, where, if σ is the cross section and E_p the lab proton energy in MeV,

$$S(E_p) = 0.87441 \sigma E_p \exp(3.9734 E_p^{-1/2})$$

for the ${}^7\text{Be}(p,\gamma){}^8\text{B}$ reaction. A calculation by Aurdal⁷ similar to that of Tombrello gave $S(0) = 0.044$ keV b, but the new data of Kavanagh *et al.* were not used in that extrapolation. The value $S(0) = 0.030$ keV b actually adopted by Bahcall and

Ulrich² is lower than either of these, and is presumably the result of an empirical extrapolation.

Proton capture by ${}^7\text{Be}$ involves the radiative transition of a proton in a continuum state to the 2^+ ground state of ${}^8\text{B}$, bound by 137.2 keV. Only dipole radiation is of importance at the energies considered here. Because the spin and parity of ${}^7\text{Be}$ are $\frac{3}{2}^-$, capture from the s and d partial waves leads to $E1$ radiation, and from the p wave, $M1$. Higher partial waves cannot contribute to dipole radiation. The calculations of Tombrello⁵ and Aurdal⁷ assumed that only s -wave capture was significant. The present work shows that while this is approximately true in the solar environment ($E_p \approx 20$ keV), it is not the case at laboratory energies, even as low as 150 keV. The small binding energy of ${}^8\text{B}$ results in a spatially extended wave function, enhancing capture from the p and d partial waves.

II. DERIVATION OF THE CROSS SECTION

The total cross section for dipole capture in the reaction $A(a,\gamma)B$ is

$$\sigma_1 = (16/9)\pi E_\gamma^3 (\hbar c)^{-4} (M_a c^2 / 2E_a)^{1/2} \times \sum_{\mu m_A m_B} (2s+1)^{-1} (2J_A+1)^{-1} |T_1^\mu|^2,$$

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Mass-25 Isobaric Multiplets*

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High-precision mass determinations have now been made for all four members of the lowest two $T = \frac{3}{2}$ states in the $A = 25$ system. The results are used to compute the coefficients of the isobaric-mass-multiplet equation.

I. INTRODUCTION

The isobaric-mass-multiplet equation relates the masses of the $2T+1$ members of a multiplet with isobaric spin T . The equation is usually given as

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

where T_z is the z component of the isobaric spin, $T_z = \frac{1}{2}(N - Z)$. The coefficients a , b , and c are functions of the mass number A and spin J^π of the levels as well. The equation, in principle, relates the masses of any multiplet of analogous levels.

Deviations from the predictions of the isobaric-multiplet equation are usually measured by citing the magnitude of d , the coefficient of a cubic term required to fit the masses. In terms of the mea-

sured masses $M(T_z)$, the d coefficient has a very simple form for a $T = \frac{3}{2}$ system, i.e.,

$$d = \frac{1}{6} \{ M(\frac{3}{2}) - M(-\frac{3}{2}) - 3[M(\frac{1}{2}) - M(-\frac{1}{2})] \},$$

where $M(T_z)$ is the mass of the level in the T_z nucleus.

Thus the result $d=0$ implies that the spacing between inner members is $\frac{1}{3}$ the spacing between the outer members. One can also see from the above equation that the uncertainty in d is 3 times more sensitive to the accuracy of the masses of the $T_z = \pm\frac{1}{2}$, $T = \frac{3}{2}$ levels than it is to the $T_z = \pm\frac{3}{2}$ levels.

In the present paper we are discussing the lowest two $T = \frac{3}{2}$ levels in the $A = 25$ nuclei. These are the ground and first excited states of ^{25}Si and ^{25}Na and the lowest two $T = \frac{3}{2}$ states in ^{25}Al and ^{25}Mg with

Shell-Model Calculations for $A = 18, 19$, and 20 Nuclei with Core Excitation Included Explicitly

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Eigenvalues and eigenvectors for all low-lying positive- and negative-parity nuclear states of $A=18, 19$, and 20 are calculated in a shell-model basis of all Pauli-allowed $0p_{1/2}-0d_{5/2}-1s_{1/2}$ configurations outside an inert ^{12}C core. Two different effective Hamiltonians are used. One is based on a reaction matrix treatment of the Hamada-Johnston potential. The second one is obtained by varying the 33 effective Hamiltonian matrix elements to reach a least-squares fit between 153 experimental level energies in nuclei in the $A=13-22$ region and the corresponding shell-model eigenvalues. The energy level spectra and single-nucleon spectroscopic factors from these calculations are compared to the available experimental data in this region. The calculations are also examined for the existence and characteristics of sequences of levels which might be called "rotational bands."

I. INTRODUCTION

The conventional nuclear shell model has been applied with considerable success to the study of properties of low-lying states of nuclei at the beginning ($A=18-22$) of what is called the $s-d$ shell.¹ In these calculations, an inert ^{16}O is assumed, and active particles are distributed in the $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$ single-particle orbits. This model is obviously limited, since there is ample evidence that ^{16}O is not an ideal closed-shell nucleus. Some of this evidence involves the existence of excited states in the observed spectrum of ^{16}O and the existence of negative-parity states at low excitation energies in $A=17, 18$, and 19 nuclei. Zuker, Buck, and McGrory² (ZBM) have studied the structure of ^{16}O in a conventional shell-model calculation with the assumption of an inert ^{12}C core and active $0d_{5/2}$, $1s_{1/2}$, and $0p_{1/2}$ orbits. In this model space, there exist numerous excited states in the $A=16$ system, and the ZBM calculation accounted for many of the observed properties of the spectrum of ^{16}O below 15 MeV. Calculations in this same model space were subsequently made for ^{17}O and for the $A=18$ system,^{3,4} in each case with considerable success.

There are many interesting properties of nuclei with $A=19$ and 20 which cannot be explained by the conventional shell model with an inert ^{16}O core. These include the existence of an apparent $K=\frac{1}{2}^-$ rotational band of states in ^{19}F which is all but degenerate with the ground-state $K=\frac{1}{2}^+$ band in that nucleus, the observed "extra" 0^+ and 2^+ states in ^{20}Ne between 6 and 8 MeV, the existence

of possibly two low-lying negative-parity rotational bands in ^{20}Ne , and the occurrence of several states in observed spectrum of ^{20}F which do not occur in any "good" shell-model calculation with an ^{16}O core. It is of interest to see if the ^{16}O -core-excited model which accounts so well for the properties of ^{16}O , ^{17}O , and the $A=18$ nuclei can account for some of these "anomalous" properties of $A=19$ and 20 nuclei. A preliminary study has indicated that such is the case.⁵ In the present paper, we present in some detail the results of calculations for nuclei with $A=18-20$ in terms of a $0p_{1/2}-0d_{5/2}-1s_{1/2}$ ("pds") configuration shell model. We restrict ourselves here to discussion of excitation energies and spectroscopic factors for single-nucleon transfer reactions, deferring to a later paper a discussion of electromagnetic properties of states in these nuclei as calculated in terms of this model.

In Sec. II, we describe the calculation in detail. In Sec. III we present a nucleus-by-nucleus discussion of energy levels and spectroscopic factors. In Sec. IV we briefly discuss the core excitation present in the model calculations. In Sec. V, we compare our calculations with other calculations of these nuclei. The results are summarized in Sec. VI.

II. DESCRIPTION OF THE CALCULATIONS

In the following sections, we will discuss the results of three different shell-model calculations of the properties of low-lying states in $A=18-20$ nuclei. In two of the calculations an inert ^{12}C is

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Study of ^{173}Hf Levels Populated in the Decay of ^{173}Ta

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The decay of ^{173}Ta was studied using high resolution Ge(Li), Si(Li), and Si surface-barrier detectors in singles and coincidence modes. The ^{173}Ta activity was produced via the reaction $^{165}\text{Ho}(^{12}\text{C}, 4n)^{173}\text{Ta}$, at a carbon beam energy of 6.3–6.9 MeV per nucleon. All spectra were obtained from chemically separated Ta sources. Besides the previously known energy levels of ^{173}Hf , the following levels in keV were determined: 255.5, 451.9, 508.9, 635.8, 775.5, 785.3, 811.7, 927.5, 942.5, 1020.3, 1111.4, 1127.0, 1192.8, 1248.3, 1450.0, 1574.2, 1655.6, 1667.1, 1694.3, and 2263.3. Rotational bands based on the $(1/2)^- [521]$ (g.s.), $(5/2)^- [512]$ (107.2 keV), and $(7/2)^+ [633]$ (197.5 keV) Nilsson states were observed. The half-lives of the $(5/2)^- [512]$ and the $(1/2)^+ [633]$ band heads were determined to be (182 ± 20) nsec and (160 ± 40) nsec, respectively. The probability of the radiative $E1$ transition between the $[633]$ and $[512]$ band heads was calculated within the framework of Nilsson model including the pairing and Coriolis interactions. From measurement of the β^+ end-point energy, the mass difference between ^{173}Ta and ^{173}Hf was determined to be 3670 ± 200 keV.

1. INTRODUCTION

In-beam γ -ray spectroscopic studies have recently revealed substantial deviations from the strong coupling model^{1,2} in the even-parity bands of odd-neutron deformed nuclei in the rare-earth

region. This development initiated new interest in the investigation of the level structure of these nuclei as populated in radioactive decay. The quieter environment of radioactivity experiments as compared with the in-beam work enables one to perform experiments crucial for the confirma-

$^{90}\text{Zr}(p,p')^{90}\text{Zr}^*$ Reaction at 40 MeVR. A. Hinrichs[†] and D. Larson[‡]*Cyclotron Laboratory, § Michigan State University, East Lansing, Michigan 48823*B. M. Freedom[¶]*Department of Physics, University of South Carolina, Columbia, South Carolina 29208*W. G. Love^{||}*Department of Physics, University of Georgia, Athens, Georgia 30601*

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Differential cross sections for the excitation of the 0^+ (1.75-MeV), 2^+ (2.18-MeV), 5^- (2.32-MeV), 4^+ (3.08-MeV), 6^+ (3.45-MeV), 8^+ (3.60-MeV), and the 2^+ (3.31-MeV) levels in ^{90}Zr by 40-MeV protons have been measured between 15° and 115° . The data are compared with the results of distorted-wave (DWA) collective-model calculations and DWA microscopic-model calculations. Both macroscopic and microscopic treatments of core polarization are considered. Effects from noncentral components in the projectile-target interaction have been investigated and an imaginary central component has been included in this interaction in the cases where a completely microscopic model is used for the target nucleus. A coupled-channels calculation has been performed in order to investigate multiple excitation contributions to the cross section for the 0^+ (1.75-MeV) state.

I. INTRODUCTION

In recent years the $^{90}\text{Zr}(p,p')^{90}\text{Zr}^*$ reaction has been a favorite subject for physicists working on the microscopic model for inelastic proton scattering.¹⁻³ The main reason for this is the substantial range of multipolarities available in the transitions from the ground state of this nucleus to its first excited 0^+ , 2^+ , 4^+ , 5^- , 6^+ , and 8^+ states, whose wave functions consist mainly of two protons distributed in the $2p_{1/2}$ - and $1g_{9/2}$ -shell model orbitals. The present paper reports on a new experimental study of this nucleus carried out with 40-MeV incident protons. Differential cross sections have been measured for the excitation of the six states named above, as well as for the excitation of the state at 3.31 MeV. These data, combined with the results of earlier experiments at 12.7,² 18.8,¹ and 61.2 MeV,³ give a reasonably complete picture of the energy dependence of the cross sections from 10–60 MeV. The angular distribution for the $L=0$ transition, however, had previously been measured only at the comparatively low energy of 12.7 MeV.² Thus the present measurement significantly extends our knowledge of this monopole transition and can provide an additional test for various aspects of the reaction theory.

The microscopic model for inelastic proton scattering has undergone considerable development in recent years. It is now fairly well estab-

lished that cross sections can be understood in calculations with "realistic interactions,"⁴⁻⁹ provided that "knock-on" exchange contributions are included and reasonable target wave functions are used. Most calculations have previously considered only the real central components of the projectile-target interaction. However, recent studies have pointed out that the shapes of differential cross sections can be improved by including an imaginary component in the interaction^{10,11} and also that the two-body spin-orbit force may be important for transitions of high multipolarity.¹²

In the case of ^{90}Zr , reasonable target wave functions require consideration of core polarization effects.^{2,3} This can be done using macroscopic^{13,14} or microscopic^{7,15,16} models for the core. In the first model the contributions from core polarization are described in terms of a single parameter which can be treated phenomenologically or determined from other data such as effective charges when they are available. In the second model, core-excited admixtures in the valence wave functions are estimated perturbatively using "realistic" coupling interactions. It is interesting to note that inelastic scattering is one of the few methods by which the effect of core polarization in transitions of high multipolarity can be studied.

The data from the present experiment have been analyzed using both the collective model and the microscopic model. The deformation parameters

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(p, n) Isobaric Analog Transitions in Targets of ^{27}Al , ^{51}V , and ^{90}Zr at 22, 30, and 40 MeV*

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Angular distributions for (p, n) transitions to isobaric analog states of ^{27}Al , ^{51}V , and ^{90}Zr targets have been measured at proton energies of 22, 30, and 40 MeV. The data have been compared with results of macroscopic distorted-wave Born-approximation calculations employing various form factors: pure volume, pure surface, and mixtures of real volume with imaginary surface. The comparisons show that: (i) The surface interaction describes the data rather well, particularly at the lower energies, whereas the volume interaction is adequate only at 40 MeV; (ii) complex mixtures of volume and surface give good descriptions of most of the data if the mixture is a variation of the isospin part of the Becchetti-Greenlees potential with either increased surface-to-volume ratio or increased imaginary radius; (iii) use of the unmodified Becchetti-Greenlees geometry gives a poor fit to much of the data; (iv) the strength of the isospin interaction decreases with increasing energy, in general agreement with other charge-exchange work. Most of the decrease here occurs between 22 and 30 MeV. This is true for the surface interaction and for each of the two complex interactions.

I. INTRODUCTION

In (p, n) transitions between isobaric analog states (IAS) the isospin interaction may be the main, in many cases the total, interaction causing the transition. Consequently, the most direct manner of studying the isospin interaction is through these transitions. Several such studies¹⁻⁵ have been reported, but there is as yet no clear-cut indication of underlying simplicities or systematics in the interaction. The earlier studies, reviewed by Satchler,⁶ have raised questions as to the radial form of the isospin interaction, that is, whether or not it is surface peaked. Also, there is very little evidence as to whether the interaction must be complex⁷ or energy dependent.⁸⁻¹⁰ To answer such questions will likely require a rather thorough study in which a wide range of target nuclei and proton bombarding energies are employed.

We describe here the measurements and analyses of (p, n) transitions to ground-state analogs of the target nuclei ^{27}Al , ^{51}V , and ^{90}Zr at incident proton energies of 22, 30, and 40 MeV. The experimental angular distributions were compared with macroscopic distorted-wave Born-approximation (DWBA) calculations employing both a real

(volume or surface-peaked) and a complex isospin interaction. Since the interaction was taken to be spherically symmetric, only monopole transitions were used in the calculations for both even- A and odd- A targets.

II. EXPERIMENTAL PROCEDURE

Thin targets of ^{27}Al (6.2 mg/cm²), ^{51}V (7.9 mg/cm²), and 97.8% enriched ^{90}Zr (2.0 mg/cm²) were bombarded with protons from the Michigan State University cyclotron. The resulting neutron spectra were measured with a time-of-flight system¹¹ which makes use of the natural bunching of the cyclotron beam pulses. The neutron detector is the liquid scintillator NE-213, deoxygenated and encapsulated in a 2-in.-diam $\times$ $\frac{3}{4}$ -in.-thick glass cell mounted on an RCA-8575 photomultiplier. Start and stop timing signals are derived from a constant-fraction discriminator on the photomultiplier and from the cyclotron rf voltage through a divide-by-2 scaler, respectively.

Two-dimensional pulse-shape analysis is used to distinguish neutrons from γ rays. An isometric display of a typical two-dimensional spectrum is shown in Fig. 1, where the number of events is plotted against the variables pulse height and decay

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Three-Neutron Pickup Reaction on $^{13}\text{C}^\dagger$

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Angular distributions of ^6He particles from the three-neutron pickup reaction $^{13}\text{C}(^3\text{He}, ^6\text{He})^{10}\text{C}$ have been measured for transitions to the two lowest states of ^{10}C , the $J^\pi = 0^+$ ground state and 3.35-MeV $J^\pi = 2^+$ state. Observed anomalies in the shapes and magnitudes of these distributions cannot be explained theoretically by zero-range distorted-wave Born-approximation calculations.

I. INTRODUCTION

The $(^3\text{He}, ^6\text{He})$ reaction has been used over the past three years principally for the precise measurement of masses of proton-rich nuclei in the $2s-1d$ shell.¹ These nuclei, such as ^{25}Si , are the $T_z = -\frac{3}{2}$ member of isospin multiplets, and the resulting masses have provided a test of the isobaric multiplet mass equation. This reaction has also been recently used to extend our knowledge of proton-rich nuclei in the $1f_{7/2}$ shell and also to obtain the spectra of these nuclei.² The extremely small cross sections which have been measured for the $(^3\text{He}, ^6\text{He})$ reaction have inhibited the measurement of detailed angular distributions for most targets. A partial angular distribution for the $^{12}\text{C}(^3\text{He}, ^6\text{He})^{10}\text{C}$ reaction measured earlier,³ together with some angular distribution data on various targets, showed enough structure to make a strong case that a direct-reaction mechanism is principally involved in this reaction.

The present experiment is aimed at testing the reaction mechanism by studying a case in which both initial and final states are well known, the $^{13}\text{C}(^3\text{He}, ^6\text{He})^{10}\text{C}$ reaction. The initial interest was inspired by a measurement of ^6He spectra at θ_{lab}

$= 9^\circ$ in which the yield to the $J^\pi = 2^+$, 3.35-MeV level of ^{10}C was found to be about 40 times greater than the yield to the $J^\pi = 0^+$ ground state. This ratio aroused theoretical curiosity and also led to the present measurement of a more complete angular distribution for this reaction.

II. EXPERIMENTAL METHOD AND RESULTS

The $^{13}\text{C}(^3\text{He}, ^6\text{He})^{10}\text{C}$ reaction was induced with 70.3-MeV ^3He from the Michigan State University cyclotron. The reaction particles were detected in an Enge split-pole spectrograph. The position on the focal plane was measured in a detection system consisting of a single-wire proportional counter with $\frac{1}{2}$ -mil Kapton entrance and exit windows.⁴ A thin plastic scintillator mounted on a photomultiplier tube was placed behind the proportional counter and provided time-of-flight information and also some particle discrimination based on the energy loss in the plastic scintillator.

A block diagram of the electronics used in the experiment is shown in Fig. 1. The setting of the various coincidence requirements is considerably simplified by the use of partial coincidence requirements. Thus the spectrum corresponding to

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Properties of γ -Ray Transitions in ^{56}Co from ^{56}Ni Decay and $^{56}\text{Fe}(p, n\gamma)^{56}\text{Co}$

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The ^{56}Ni ϵ decay and the $^{56}\text{Fe}(p, n\gamma)^{56}\text{Co}$ reaction with beam energies between 5.5 and 8.4 MeV have been used with Ge(Li) spectrometers to study the properties of γ rays from states of ^{56}Co below 2.86 MeV excitation. From ^{56}Ni ϵ decay both the γ -ray spectrum and γ - γ coincidences were studied. γ - γ coincidences, γ -ray excitation functions, γ -ray angular distributions, and absolute cross sections were measured for the $^{56}\text{Fe}(p, n\gamma)^{56}\text{Co}$ reaction. An ϵ decay scheme for ^{56}Ni , which includes six γ rays, and an energy-level diagram for ^{56}Co , which includes 35 γ rays (14 of which are reported for the first time) from 20 excited states, are presented. Comparison of the data from $^{56}\text{Fe}(p, n\gamma)^{56}\text{Co}$ with predictions of the statistical compound-nuclear model have resulted in spin assignments (in parentheses) for the following states (energies in keV) of ^{56}Co : 158.4(3), 576.6(5), 829.7(4), 970.3(2), 1009.2(5), 1114.6(3), 1450.8(0), and 1720.3(1). Branching ratios are presented for 14 γ rays from these eight states and multipole mixing ratios are given for 12 of these γ rays (10 are predominantly $M1$). The data are consistent with a spin-4 assignment to the ground state. Contrary to previous suggestions, evidence from all experiments indicates that only one state (believed to be the antianalog of the ^{56}Fe ground state) exists in ^{56}Co in the neighborhood of 1451 keV excitation. The level energies, γ -ray multipole mixing ratios, and γ -ray branching ratios agree, in general, with shell-model predictions of McGrory.

I. INTRODUCTION

The earliest investigations¹⁻⁴ of the low-lying excited states of ^{56}Co began with the ϵ decay of ^{56}Ni . These studies, which included measurements of the ^{56}Ni half-life,¹ the γ -ray spectrum,^{1,3,4} γ - γ angular correlations,^{1,3} the internal-conversion electron spectrum,² and lifetimes of some

^{56}Co states,¹ produced valuable information. However, only selected states below 2.1 MeV could be populated and unambiguous spin assignments for these states could not be made.

More recently, experiments involving the two-particle transfer reactions, $^{54}\text{Fe}(^3\text{He}, p)^{56}\text{Co}$,⁵⁻⁹ $^{54}\text{Fe}(\alpha, d)^{56}\text{Co}$,¹⁰ $^{58}\text{Ni}(p, ^3\text{He})^{56}\text{Co}$,¹¹ and $^{58}\text{Ni}(d, \alpha)^{56}\text{Co}$,^{6,7,9,12,13} and the charge-exchange reactions,

ELASTIC AND INELASTIC SCATTERING OF PROTONS FROM ${}^6\text{Li}$ BETWEEN 25 AND 45 MeV

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Abstract: The elastic and inelastic scattering of protons from ${}^6\text{Li}$ has been studied at incident energies of 25.9, 29.9, 35.0, 40.1 and 45.4 MeV. The 2.18 MeV (3^+ , $T = 0$) first excited state of ${}^6\text{Li}$ was found to be strongly excited, but the 3.56 MeV (0^+ , $T = 1$) second excited state was quite weakly excited. Angular distributions for excitation of the 2.18 MeV level were measured at all five energies, while angular distributions for excitation of the 3.56 MeV level were extracted only at 25.9 and 45.4 MeV. To test the applicability of the optical model for the scattering of protons from such a light nucleus the elastic scattering angular distributions have been analyzed using the eleven-parameter search code SEEK. Available polarization angular distributions were included in the analysis. Reasonable fits to the data have been obtained with an average geometry potential. Theoretical estimates of the real part of the optical potential and the inelastic scattering differential cross sections have been made using the microscopic model for proton-nucleus scattering. Both phenomenological and realistic forces have been considered and the necessary nuclear transition densities have been extracted from experimental elastic and inelastic electron scattering data. An estimate of a possible spin-spin term in the optical potential has also been made.

1. Introduction

Various groups have previously reported measurements of elastic and inelastic cross sections for proton scattering from ${}^6\text{Li}$ in the energy region 25–50 MeV [refs. ^{1–4}]. One of the purposes of the present experiment was to improve the knowledge of the energy dependence of the ${}^6\text{Li} + p$ elastic cross sections. This is important in the case of such a light nucleus as there may be contributions from resonances in the compound system at some energies and information about the optical potential extracted at a single energy could prove to be misleading. An analysis of the elastic data has been made using a conventional phenomenological optical potential. Existing polarization

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STUDY OF THE $^{27}\text{Al}(^3\text{He}, p)^{29}\text{Si}$ REACTION

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Abstract: The $^{27}\text{Al}(^3\text{He}, p)^{29}\text{Si}$ reaction has been studied at bombarding energies between 9 and 14 MeV. Comparison of the experimental angular distributions at 14 MeV incident energy with two-nucleon transfer distorted-wave Born approximation (DWBA) calculations is made to test shell-model wave functions of the target ground state and the residual ground and excited states.

E NUCLEAR REACTIONS $^{27}\text{Al}(^3\text{He}, p)$, $E = 9\text{--}14$ MeV; measured $\sigma(\theta)$. Natural target.

1. Introduction

The differential cross sections of two-nucleon transfer reactions such as $(^3\text{He}, p)$ are sensitive to correlations in nuclear wave functions¹⁾ which may not be examined in other types of experiments. Hence, the experimental study of such processes, and comparison of the results with the predictions of nuclear structure calculations, should provide a rather unique tool for testing the theoretical wave functions and the residual interactions used in the Hamiltonians.

The present work is part of a systematic investigation of the $(^3\text{He}, p)$ reaction on nuclei in the $2s\text{--}1d$ shell. In this paper we discuss the reaction $^{27}\text{Al}(^3\text{He}, p)^{29}\text{Si}$. Shell-model calculations have recently been performed for both the initial and final nuclei in a truncated $1d_{5/2}\text{--}2s_{1/2}\text{--}1d_{3/2}$ basis space with a “modified” surface delta interaction (MSDI) Hamiltonian²⁾. The model space in which these calculations are made includes, for ^{27}Al , all 11-particle configurations with 8 or more particles occupying the $d_{5/2}$ orbit and, for ^{29}Si , the configuration with 8 particles in the $d_{5/2}$ orbit, 4 particles in the $s_{1/2}$ and 1 particle in the $d_{3/2}$ orbit plus all 13-particle combinations with occupation numbers of the $d_{5/2}$ orbit greater than or equal to 9.

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INVESTIGATION OF THE $^{32}\text{S}(^3\text{He}, \text{p})^{34}\text{Cl}$ REACTION

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Abstract: The $^{32}\text{S}(^3\text{He}, \text{p})^{34}\text{Cl}$ reaction has been studied at an incident energy of 24 MeV. The proton spectra were analysed with a multiangle magnetic spectrograph and angular distributions have been measured for states in ^{34}Cl up to 3.4 MeV of excitation energy. Two sets of shell-model wave functions, which use the same configuration space but different treatments of the effective residual interaction, are tested by comparing two-nucleon transfer DWBA calculations with the experimental angular distributions.

E

NUCLEAR REACTIONS $^{32}\text{S}(^3\text{He}, \text{p})$, $E = 24$ MeV; measured $\sigma(\theta)$.
 ^{34}Cl levels deduced J, π, L . Natural target.

1. Introduction

The basic feature of a two-nucleon transfer reaction is its coherence property. These coherence effects complicate on one hand the extraction of spectroscopic information from the experimental data but at the same time can be exploited to test not only the magnitudes but also the relative phases of various components in shell-model wave functions. Much of this latter information is inaccessible by other kinds of observation. The present work is part of a systematic study of $(^3\text{He}, \text{p})$ reactions on target nuclei in the upper half of the 2s-1d shell. The aim is to make a sensitive test of various shell-model calculations which have been performed for this mass region¹⁻⁴). In this paper results for the reaction $^{32}\text{S}(^3\text{He}, \text{p})^{34}\text{Cl}$ are reported. For both the initial and final nuclei shell-model calculations have recently been performed^{2,3}) in a truncated $(1d_{3/2})^{n_1}(2s_{1/2})^{n_2}(1d_{5/2})^{n_3}$ vector space, where n_1 , the number of particles occupying the $1d_{3/2}$ orbit, is greater than or equal to 10. Two different empirical Hamiltonians were used in these calculations. One set makes use of the modified surface delta interaction (in the following referred to as MSDI wave functions), whereas the second set starts from the same interaction and treats the two-body

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ENERGY LEVELS IN ^{142}Nd

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Abstract: The excited states of ^{142}Nd were studied by means of the decay of 40 sec ^{142}Pm and the $^{142}\text{Nd}(p, p')$ reaction via isobaric analog resonances. Approximately sixty levels of ^{142}Nd were observed below 5.3 MeV excitation, including several neutron particle-hole states excited strongly in (p, p') at $f_{7/2}$, $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ analog resonances. We have collected together all known energy levels in ^{142}Nd and have proposed J^π assignments for 22 excited states. We have also compared the experimental level spectrum (positive-parity states only) with a calculated one based on the shell model.

RADIOACTIVITY ^{142}Pm ; measured $T_{1/2}$, E_γ , I_γ . ^{142}Nd deduced levels, J , π , γ -branching.

NUCLEAR REACTIONS $^{142}\text{Nd}(p, p')$ at analog resonances, $E = 9.505, 10.245, 10.805$ and 11.070 MeV; measured $\sigma(E_p, \theta)$. ^{142}Nd deduced levels, J , π , particle-hole states.

1. Introduction

The nucleus $^{142}_{60}\text{Nd}_{82}$ is interesting from a nuclear structure viewpoint because of its closed core of 82 neutrons. Most of the low-lying states of ^{142}Nd should, therefore, arise from proton couplings in the $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$ and $1h_{9/2}$ shell-model orbits. A

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SHELL MODEL CALCULATIONS FOR MASSES 27, 28 AND 29: SPECIFIC APPLICATION TO $^{27,28}\text{Mg}$ AND $^{28,29}\text{Al}$

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Abstract: A shell model calculation has been performed in a truncated $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$ configuration space with a modified surface-delta-interaction Hamiltonian for the $T = 1$, $\frac{3}{2}$ and 2 nuclei of $A = 27$ –29. The parameters of the model Hamiltonian were obtained from a fit to experimental data from $T = 0$ and $T = \frac{1}{2}$ nuclei of the same region. Excitation energies, single-nucleon spectroscopic factors, electric quadrupole moments and transition strengths and magnetic dipole moments and transition strengths were calculated. Decay properties of the $T = 2$ and $T = 1$ multiplets in $A = 28$ and the $\Delta T = 1$, M1 transitions from $T = \frac{3}{2}$ levels in $A = 27$ and 29 nuclei have been studied in particular. The results indicate that the present shell model is able to describe quantitatively the nuclear structure around mass 28 in a unified approach in a fashion similar to the excellent descriptions available in this same theoretical framework for lighter and heavier mass regions of the sd shell.

1. Introduction

Nuclei around mass 28, where the nuclear shape changes from prolate to oblate¹⁾, have been the object of many extensive theoretical and experimental studies, of which the results are compiled in ref. ²⁾. Discussions in terms of collective models are mostly concentrated on a few aspects of particular nuclei. The collective models frequently account very well for certain characteristics ^{4, 5, 9, 10)} but they all fail, variously, to explain at the same time many other significant features in $A = 27$ –29 nuclei. Of the four nuclei considered here, only the structure of ^{27}Mg is reasonably well understood in terms of the single-particle Nilsson model ^{3–9)}, and even here deformation parameters of different signs are required to explain the transition rates ^{4, 5)} and the spectroscopic factors ⁹⁾. No significant evidence was been found so far to place ^{28}Al [ref. ¹¹⁾] and ^{29}Al [refs. ^{12–15)}] in a simple rotational picture, while an intermediate-coupling version of the SU(3) model ¹⁶⁾ reproduces only some of the characteristics of the ^{28}Mg energy spectrum.

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Germanium-64

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The new isotope ^{64}Ge has been produced via the reaction $^{64}\text{Zn}(^3\text{He}, 3n)^{64}\text{Ge}$, chemically isolated, and its decay studied. Since ^{64}Ge is therefore nucleon stable, it can in principle have an important role in the synthesis of mass 64 by α capture during explosive stellar events, as proposed by Arnett, Truran, and Woosley. However, from the measured half-life (62.3 ± 2.0 sec) and β -decay systematics, it appears that this mechanism is probably responsible for a negligible fraction of the observed abundance of mass 64.

Recently Arnett, Truran, and Woosley¹ (ATW) have shown that the elements on the high-mass side of the iron peak in the elemental abundance curve can be synthesized in an explosive stellar event. The process involves, for example, a quasiequilibrium among ^4He , ^{56}Ni , ^{60}Zn , and ^{64}Ge , and the resulting abundances for mass 60 and 64 depend primarily on the corresponding binding energies. Since ^{64}Ge has never been observed ex-

perimentally, ATW used for that isotope a value of the binding energy calculated by Garvey *et al.*² The abundances obtained¹ for masses near 64 are typically 2 orders of magnitude smaller than those observed in nature.

This discrepancy could possibly be removed if ^{64}Ge were more tightly bound, since production of that nuclide by radiative α capture would then be enhanced. In that hope, a number of intensive

New Proton-Rich Nuclei in the $1f_{7/2}$ Shell*I. D. Proctor, W. Benenson, J. Dreisbach,[†] and E. Kashy*Cyclotron Laboratory and Department of Physics, Michigan State University, East Lansing, Michigan 48823*

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We have measured the masses of ^{43}Ti and of the previously unknown nuclei ^{47}Cr , ^{51}Fe , and ^{55}Ni . These proton-rich members of $1f_{7/2}$ -shell mirror pairs are important for extensions of nuclear mass relationships to the $Z > N$ region.

In this Letter, we report mass measurements of $1f_{7/2}$ shell nuclei which have $Z = N + 1$, and are thus members of the heaviest mirror pairs known. The present measurements represent the first observation of ^{47}Cr , ^{51}Fe , and ^{55}Ni . The heaviest previously known nucleus with $Z > N$ was ^{49}Mn , whose mass was found by Cerny *et al.*¹ to be consistent with a predicted value of -37.72 ± 0.08 MeV in an experiment with the $^{40}\text{Ca}(^{12}\text{C}, t)$ reaction. The mass of ^{43}Ti has also been previously determined by the reaction $^{40}\text{Ca}(\alpha, n)^{43}\text{Ti}$.² The line of nuclear stability in the $1f_{7/2}$ shell is at least two neutrons from the $N = Z$ line, and the observation of $T_z = -\frac{1}{2}$ nuclei in this shell requires the transfer of three or more particles. Since all possible higher- Z targets have a neutron excess of at least four, we have extended the (^3He , ^6He) reaction to its maximal value as a probe for the study of proton-rich nuclei.^{3,4}

Beams of 65- to 75-MeV ^3He ions from the Michigan State University sector-focused cyclotron were used to perform these experiments. The ^6He particles were analyzed and detected in the focal plane of an Enge split-pole magnetic spectrograph. The energy scale was determined from a number of well-known Q values including those for the (^3He , ^6He) reaction on ^{46}Ti , ^{13}C , and ^{12}C . Detection of the ^6He particles was performed variously with photographic emulsions, silicon position-sensitive detectors, and gas-filled resistive wire proportional counters. In each case different techniques were used to enhance the discrimination of the ^6He particles relative to the dominant background of protons, deuterons, and α particles.

Most of the data were taken with a wire propor-

tional counter. In this case a novel technique was employed to discriminate against the background particles. The time of flight of the particles was measured using a signal from a plastic scintillator behind the wire counter. The total energy signal from the plastic was also used to aid the identification. The flight path in the spectrometer (about 3 m) is very well suited to this method since it produces about a 25-nsec time difference between the ^6He particles and the major source of background, α particles. The stop signal for the clock was provided by the radio

FIG. 1. Energy spectrum of ^6He from the reaction $^{54}\text{Fe}(^3\text{He}, ^6\text{He})^{51}\text{Fe}$. The ^3He bombarding energy is 70.8 MeV and the laboratory scattering angle is 9° .

Some Comments on the Cross Section of ^{37}Cl for Solar Neutrino Absorption*

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Nuclear wave functions from recent shell-model calculations are used to evaluate the $\log(ft)$ values relevant to the neutrino absorption cross section of ^{37}Cl .

In order to understand better the causes and/or consequences of the unexpectedly low yield of the solar neutrino experiment,¹ we have re-examined some of the assumptions which underlie the calculation of the neutrino absorption cross section of ^{37}Cl . As has been pointed out,^{2,3} there is very little uncertainty in the calculated absorption cross section for low-energy neutrinos ($E_\nu < 2.22$ MeV) in the reaction $\nu + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^-$ since this calculation depends only upon the measured electron capture rate of ^{37}Ar and other known quantities. However, there are unmeasured quantities which enter into the calculation of absorption cross sections for neutrinos with energies greater than 2.22 MeV.

These uncertainties result from the lack of experimental β -decay $\log(ft)$ values for some of the transitions which connect the ^{37}Cl ground state with excited states of ^{37}Ar . Under the standard assumption that isospin is a good quantum number, the measurement of the delayed proton spectrum from the β decay of ^{37}Ca provides $\log(ft)$ values for transitions to the excited states of ^{37}Ar above 3 MeV⁴ relative to the superallowed transition to the $J = \frac{3}{2}$, $T = \frac{3}{2}$ state at 4.993 MeV in ^{37}Ar . (This latter state is the isobaric analog of the ^{37}Cl ground state.) Transitions to excited states below 3 MeV have not been observed and the absolute rate for the 4.993-MeV isobaric analog state has not been measured. Hence, estimates for their contributions to the neutrino capture cross section must be based on nuclear structure calculations.

When the solar neutrino experiment was first proposed, Bahcall made simple shell-model estimates of these $\log(ft)$ values based on the assumption that the relevant low-lying states of ^{37}Ar and ^{37}Cl could be described by couplings of three nucleon holes in the $0d_{3/2}$ shell-model orbit.² In this note we report values for these transitions based on the most complete nuclear wave functions presently available. These wave functions span the full $0d_{5/2}-1s_{1/2}-0d_{3/2}$ space. Single-nucleon transfer and $E2$ and $M1$ strengths calculated with these wave functions agree well with experimen-

tal results from the $A = 35-38$ region.⁵ In particular, the wave functions yield predictions for stripping and pickup to ^{37}Ar that are consistent with recent experimental results.^{6,7} These same experimental results point up the inadequacy of Bahcall's simple model for the lowest $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states. The transitions which are in question proceed to the levels in ^{37}Ar at 1409 keV ($J^\pi = \frac{1}{2}^+$), at 2797 keV ($J^\pi = \frac{5}{2}^+$), and at 4993 keV ($J^\pi = \frac{3}{2}$, $T = \frac{3}{2}$). We have calculated the $\log(ft)$ values for the corresponding shell-model states with both the "11.0h + ASPE" and "12.5p + ^{17}O " wave functions of Ref. 5. The results are substantially the same. We discuss the results from "11.0h + ASPE" because there is some indication that this set gives a slightly better accounting for $A = 37$ and 38 data than does "12.5p + ^{17}O ." The predicted $\log(ft)$ values for the ^{37}Ar transitions are shown in Table I and Fig. 1. These numbers were obtained as part of a general study of β decay in this region of the nuclear chart.⁸ We have calculated all the β decays for which experimental data exist in the mass ranges $A = 17-23$ and $34-39$ and the overall percentage rms deviation between calculated and experimental $\log(ft)$ values in these nuclei was 5%.

We show in Fig. 1 the calculated and experimental energies and $\log(ft)$ values for the states of ^{37}Ar (^{37}K). By examining this figure, one sees

TABLE I. The calculated $\log(ft)$ values for transitions which connect the ground state of ^{37}Cl with excited states in ^{37}Ar . These $\log(ft)$ values are needed to predict the solar neutrino absorption cross section.

J_f	T_f	E_x (keV)	$\log(ft)$	
			Bahcall	Present calculation
3/2	1/2	0	(5.06) ^a	5.14
1/2	1/2	1409	4.48	5.44
5/2	1/2	2797	4.34	4.36
3/2	3/2	4993	3.28	3.30

^a This is an experimental number, based on the electron capture of ^{37}Ar .

Collective and Higher-Order Effects Shown by the (p, t) Reaction on the Deformed Nucleus ^{159}Tb

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The reaction $^{159}\text{Tb}(p,t)^{157}\text{Tb}$ at 30 MeV strongly populates collective states in the residual nucleus. Angular distributions of β and γ vibrational and ground-state rotational band members are presented and compared with distorted-wave Born-approximation predictions. We also include evidence supporting the importance of indirect multiple-step processes accompanying the (p,t) reaction. The (p,t) reaction is shown to be a powerful spectroscopic tool for populating higher-lying rotational band members in odd-mass deformed nuclei.

The (p,t) reaction on ^{159}Tb continues a general study of the characteristics of the (p,t) reaction on odd-mass rare-earth elements. From a previously completed investigation¹ of the (p,t) reaction on the closed-shell nucleus ^{141}Pr , it was found that this reaction proceeds predominantly through a direct mechanism at the bombarding energies used in this study, and that large cross sections exist for the population of collective vibrational states within the residual nucleus ^{139}Pr . However, unlike the previous study, the present investigation involves permanently deformed target and residual nuclei. These provide a very suitable system for studying and further testing the collective characteristics previously associated with the (p,t) reaction. The (p,t) reaction is shown to be a powerful spectroscopic tool for populating higher-lying rotational band members in odd-mass deformed nuclei.

In this study an $\approx 300\text{-}\mu\text{g}/\text{cm}^2$ metallic target of ^{159}Tb was bombarded with 30-MeV protons accelerated by the Michigan State University sector-focused cyclotron. The scattered tritons were analyzed with an Enge split-pole magnetic spectrometer and collected on photographic plates. Spectra were taken between 10° and 75° at 5° intervals in the lab system with an overall energy resolution of 15–20 keV, although higher-resolution spectra (10 keV full width at half-maximum) have also been obtained at some angles.

From previous radioactivity studies,^{2,3} rotational bands built upon the ground state and a β vibrational excitation of the ground state have been identified in the ^{157}Tb nucleus. In addition, the presence of a $K = \frac{1}{2}$ band based at 598 keV of

excitation was also indicated. There are two possibilities for the origin of such a $K = \frac{1}{2}$ band in this nucleus. It can be explained as a rotational band superimposed either on the $\frac{1}{2}^+[411]$ single proton state expected in this region, or on a γ vibrational state based on the $\frac{3}{2}^+[411]$ ground state. The vibrational origin of these states is strongly suggested both from systematics and from the very small decoupling parameter associated with this band. The empirical value of this decoupling parameter is $\approx \frac{1}{20}$ of the calculated value² for a $\frac{1}{2}^+[411]$ band based on a nuclear deformation of $\eta = 5$, and it is of opposite sign. However, experimentally determined K -conversion coefficients imply significant $M1$ admixtures in transitions de-exciting this band to the ground band; these should be formally forbidden for states having a vibrational origin, although band mixing could easily account for this phenomenon.

The $^{159}\text{Tb}(p,t)$ triton spectrum taken at the lab scattering angle of 20° appears in Fig. 1. The most striking feature of this spectrum is the strong population of the ground-state rotational band, with members certainly up to $\frac{13}{2}^+$ and possibly as high as $\frac{17}{2}^+$ being excited. At 598 keV one finds three states that, within experimental uncertainty, correspond to the first three members of the previously discussed $K^\pi = \frac{1}{2}^+$ rotational band. In addition, if one generates the $\frac{7}{2}^+$ and $\frac{9}{2}^+$ members of this band by parametrizing the simple rotational energy relationship, one finds two additional states populated by this reaction which appear to be the next two members of this (γ vibrational) band. In light of the established tendency of the (p,t) reaction to populate collec-

INELASTIC PROTON SCATTERING FROM ^{138}Ba AND ^{144}Sm AT 30 MeV *

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Measurements of the inelastic scattering of 30 MeV protons from ^{138}Ba and ^{144}Sm have been carried out with 7–10 keV energy resolution. Differential cross sections were measured for levels up through 3.4 MeV excitation energy. For most of these states J^π assignments are suggested on the basis of angular distributions distinctly characteristic of angular momentum transfer $L = 2, 3, 4$, or 6.

The stable $N = 82$ nuclei are interesting because they allow one to study the effects of adding from four to twelve valence protons to a doubly closed $Z = 50, N = 82$ core. We have measured excitation energies and angular distributions in ^{138}Ba (6 valence protons) and ^{144}Sm (12 valence protons) with the (p, p') reaction. The results indicate that high resolution inelastic proton scattering with ≈ 30 MeV beams can be an effective tool for making J^π assignments in this mass region as well as for identifying levels and measuring their precise energies.

The present data were taken with the Michigan State University cyclotron and Enge split-pole spectrograph. Energy resolutions obtained with nuclear emulsions varied between 7 and 10 keV, FWHM, for the inelastic proton groups. A spectrum for ^{144}Sm is shown in fig. 1. The identical configuration of experimental equipment and the same momentum calibration of the spectrograph were used in both the ^{138}Ba and ^{144}Sm measurements. The spectrograph calibration used as final reference values the known excitation energies of some previously observed levels in ^{138}Ba and ^{144}Sm (see table 1).

Average values of excitation energies measured in the present work are listed in table 1. The results for ^{138}Ba are in almost complete agreement, both as regards the number of levels up to $E_x = 2.9$ MeV and their precise energies, with the consensus of previous investigations [1–3, 9]. Our results for ^{144}Sm represent a considerable addition to the experimental knowledge [4, 5] of this nucleus.

Angular distributions for some of the ^{138}Ba and

Fig. 1. Spectrum from $^{144}\text{Sm}(p, p')$ at 40° . The resolution is about 7 keV. The broad bumps under certain of the peaks correspond to protons which scatter from ^{24}Mg and ^{28}Si impurities and hence lie a different focal plane in the spectrograph. The 3^- peak at 1811 keV was too intense to be counted on this plate.

$^{144}\text{Sm}(p, p')$ transitions are shown in fig. 2. (The cross section normalization ($\pm 15\%$) is based on a comparison of our measured elastic scattering to optical model predictions using the parameters of Becchetti and Greenlees [6].) Inspection of the angular distributions shows that the shapes of the distributions for each of the known 2^+ states are essentially identical. And, although fewer samples are available, similar statements can be made for the distributions, respectively, for 3^- , 4^+ and 6^+ states. We have derived empirical "characteristic" shapes for the different L -value transitions by averaging over the data for all states reached by a particular known L . These shapes are also shown in fig. 2.

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SPINS OF STATES IN ^{19}O NEAR 2.7 MeV EXCITATION*

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A distorted-wave analysis of angular distributions from the $^{17}\text{O}(t, p)^{19}\text{O}$ reaction leads to spin-parity assignments of $9/2^+$, $7/2^+$, and $3/2^+$ for the states at $E_x = 2.37$, 2.78, and 3.07 MeV, respectively, in agreement with recent γ -ray decay data, but not with assignments commonly quoted in the literature.

It has been known for many years that the nucleus ^{16}O is a reasonably good closed-shell nucleus. The nuclei in the immediate vicinity of ^{16}O are expected, therefore, to exhibit simple structure and to be easily amenable to interpretation in terms of the shell model. In particular, the low-lying states of ^{19}O , which differs from ^{16}O only by the addition of three neutrons, are known to be well described by $(sd)^3$ configurations. The nucleus ^{19}O is rather difficult to investigate experimentally; it can be conveniently studied only by means of the $^{17}\text{O}(t, p)^{19}\text{O}$ and $^{18}\text{O}(d, p)^{19}\text{O}$ reactions. A level scheme for the low-lying states of ^{19}O is shown in fig. 1; the spin-parity assignments include those of the present work. Because of the limited means available for studying the nucleus ^{19}O , an examination of the $^{17}\text{O}(t, p)^{19}\text{O}$ reaction by means of distorted wave analysis and shell-model wave functions was undertaken.

In a recent compilation [1], spin-parity assignments of $(3/2^+)$, $9/2^+$, and $(3/2, 5/2, 7/2)^+$ are given for the levels at 2.37, 2.78, and 3.06 MeV, respectively. The principal evidence for a $3/2^+$ assignment to the 2.37 MeV level is an apparent $l_n = 2$ angular distribution in a study [2] of the $^{18}\text{O}(d, p)^{19}\text{O}$ reaction at a bombarding energy of 5 MeV. This assignment, however, is not required by data on the same reaction obtained at higher bombarding energies [3–5]. The $^{17}\text{O}(t, p)^{19}\text{O}$ angular distribution to this state has been tentatively as-

signed $L = (2)$ [6, 7] and the γ -ray decay is solely to the $5/2^+$ ground state [8, 9]. The $9/2^+$ assignment for the 2.78 MeV state appears [1] to rest only on the observation of an $L = 2$ angular distribution for this state in the $^{17}\text{O}(t, p)^{19}\text{O}$ reaction [3, 6, 7]. This level also decays solely to the ground state [2, 8, 9]. A recent

Fig. 1. Energy level diagram of ^{19}O for the states below 3.5 MeV excitation.

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MICROSCOPIC (p, p') CALCULATIONS AND POLARIZATION CHARGES WITH LARGE BASIS SHELL-MODEL WAVE FUNCTIONS*

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Techniques have been developed for performing microscopic model DWBA calculations of inelastic nucleon-nucleus scattering using large basis shell-model wave functions to describe the nuclear states involved. For the case of ^{138}Ba at a bombarding energy of 30 MeV, we obtain good fits to the data by including the exchange amplitude in the DWBA and assuming a state and multipole independent polarization charge.

Major advances in the microscopic description of inelastic proton scattering are being made through the use of realistic effective interactions [1, 2], the treatment of "core polarization" [3-8], and inclusion of the exchange amplitude in the distorted wave calculation [1, 9-11]. The evolution from a ubiquitous collective model approach to a realistic microscopic approach has recently been reviewed by Satchler [12]. Microscopic analyses of the (p, p') reaction have to date concentrated on doubly closed shell nuclei such as ^{16}O and ^{40}Ca , for which particle-hole wave functions are available, and on nuclei with one or two valence nucleons, where simple shell-model wave functions can be used. This note describes the expansion of such microscopic analyses to the much larger number of nuclei which have many active valence particles and whose states can be described by large basis shell-model wave functions.

We have made an initial application to the $N = 82$ nucleus ^{138}Ba . For ^{138}Ba , we obtain good fits to the shapes of the angular distributions and find polarization charges which are essentially independent of the multipolarity of the transition.

The experimental data, shown in figs. 1 and 2, were obtained at 30 MeV bombarding energy, using protons from the MSU sector-focussed cyclotron and an Enge split-pole spectrograph to detect the scattered particles. Energy resolution was approximately 8 keV, FWHM. A full discussion of the experimental work will be given elsewhere [13].

Proton [14, 15] and neutron [16, 17] transfer reactions on the $N = 82$ nuclei indicate that $Z = 50$, $N = 82$ forms a good doubly closed core. The $N = 82$ nuclei are formed by adding protons to this core; ^{138}Ba has six such valence protons. The basis space for the shell-model wave functions we use [18] consists of the $1g_{7/2}$ and $2d_{5/2}$ orbits, plus one-proton excitations from this subspace into the $3s_{1/2}$ or $2d_{3/2}$ orbits. The two-body interaction for the shell-model calculation was parameterized in terms of the modified surface delta interaction (MSDI), with the four single particle energies and the two MSDI parameters fixed by fitting to energy levels of known J^π in the $N = 82$ nuclei from ^{136}Xe through ^{140}Ce . Eigenvalues and eigenfunctions calculated for $N = 82$ nuclei from $A = 134 - 140$ with this interaction give good agreement with experimentally known energy levels, pickup and stripping spectroscopic factors and electromagnetic data [18, 19].

In order to calculate inelastic scattering cross sections from these wave functions, it is necessary to obtain the structure amplitudes $S(J_i J_f J; T_i T_f T; j_1 j_2)$, where the notation is that of Madsen [9, 20]. We have modified the Oak Ridge-Rochester shell-model codes [21] to calculate these amplitudes in a form convenient for use in DWBA calculations. The distorted wave calculations in the present case were performed with the code DWBA 70 [22] of Raynal and Schaeffer, which includes the knock-on exchange amplitude. This code is based on a helicity formalism [23] which automatically accounts for all values of orbital angular momentum L and spin angular momentum S that can be transferred in a given transition. The exchange contribution is

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EFFECTS OF OPERATOR RENORMALIZATION ON INELASTIC SCATTERING CALCULATIONS IN $^{40}\text{Ca}^\dagger$

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Transition densities are calculated in TDA which include effects of both wave function and transition operator renormalization. These densities are used to calculate (e, e') form factors and (p, p') cross sections. Results are compared with experiment.

In most theoretical calculations of inelastic scattering one needs a normalization constant in order to obtain a (p, p') angular distribution or (e, e') form factor whose magnitude agrees with the corresponding experimental result. This constant, often referred to as the "effective charge", is typically about 1.5 for protons and 0.5 for neutrons.

The need for an "effective charge" arises from the fact that shell model calculations are of necessity performed in truncated vector spaces. However, as has been pointed out by a number of authors [1], the use of a truncated model space need not introduce errors if the operators employed in the calculation are properly renormalized. This has been recognized in a number of structure calculations [2], where instead of the "bare" two body interaction the investigators used an effective interaction obtained by taking core polarization effects into account. In addition, Gillet [3] and collaborators have achieved considerable success in their RPA calculations of transition moments and transition densities. These latter authors did not use a "realistic" force, however, but a force whose parameters were adjusted to produce agreement with experimental energy spectra.

The purpose of the present work is to examine the effect of operator renormalization on transition densities in cases when a "realistic" two-body interaction — in this case Sussex matrix elements — is employed.

The results presented here are particle-hole calculations for the lowest 3^- and 5^- states of ^{40}Ca . The cal-

culations were done in TDA in a model space consisting of p-f shell particle states and s-d shell hole states. Correction effects, including ground state correlations, were included via second order perturbation theory, i.e. all terms linear in the energy denominator were retained in renormalizing both the two-body interaction and the transition operators. Graphs representing the various terms are shown in fig. 1. In these graphs an average energy denominator of $2\hbar\omega$ was used, with the exception of the ground state correlation graphs in which the exact single particle energies were employed.

The particle-hole amplitudes resulting from these calculations are given in table 1. They differ from the previously reported [4] amplitudes due to the inclusion here of single particle-hole excitations of $3\hbar\omega$. Using these amplitudes and harmonic oscillator radial wave functions (oscillator constant $\alpha = 0.498$) we constructed renormalized charge and matter transition densities, $\rho_J(r)$ and $g_J(r)$, for transitions of multipolarity J , which are the reduced matrix elements

$$\langle J^\pi || \sum_i \frac{\delta(r - r_i)}{r_i^2} Y_J(r_i) || 0 \rangle,$$

with the sum running over protons for $\rho_J(r)$ and over protons and neutrons in $g_J(r)$.

In Born approximation the form factor for inelastic electron scattering [5] is related to the charge transition density by

$$|F(q)|^2 = \frac{4\pi}{Z^2} \frac{2J_f + 1}{2J_i + 1} \left| \int_0^\infty j_J(qr) \rho_J(r) r^2 dr \right|^2$$

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THE MASS OF $^{29}\text{S}^*$

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The mass of ^{29}S has been measured with the $^{32}\text{S}(\tau, ^6\text{He})$ reaction at 70 MeV. The mass excess is -3.16 ± 0.05 MeV.

The ground state of ^{29}S is the fourth member ($T_z = -3/2$) of a mass quartet which includes the lowest $T = 3/2$ states in ^{29}Si ($T_z = 1/2$) and ^{29}P ($T_z = -1/2$) and the ground state of ^{29}Al ($T_z = +3/2$). The half-life of ^{29}S has been measured [1] to be 195 ± 8 ms by observing the delayed protons following the proton bombardment of natural S and P targets. Previous attempts to measure its mass have only shown it to be consistent with the predictions of the isobaric multiplet mass equation and Coulomb energy systematics [2].

The present measurement consisted in observing the $^{32}\text{S}(\tau, ^6\text{He})^{29}\text{S}$ reaction at 7.5° and 10° in a split-pole spectrograph. Fig. 1 gives a schematic representation of the apparatus. A 70.5 MeV ^3He beam was produced by the Michigan State University Cyclotron. The position on the focal plane was measured by a charge division wire proportional chamber. A plastic scintillator behind the proportional counter was used for particle identification by time-of-flight and total energy. This information plus the energy loss in the wire counter produced spectra which are virtually 100% ^6He particles.

The main difficulty of the experiment consisted in producing and maintaining a thin target containing sulfur. A self-supporting CdS foil with $800 \mu\text{g}/\text{cm}^2$

areal density was used, and did not flake off or change thickness under bombardment. This is crucial to the experiment since target thickness is an important source of error in measurements of this type. The best spectrum obtained is shown in fig. 2. A much shorter run on a Mg target, which provided one of the calibrations, is also shown in fig. 2. The background in the CdS spectrum is due to the cadmium isotopes which produce prolific ^6He particles leaving the final nuclei in highly excited states (15–20 MeV). At 10° the ^{29}S yield was reduced significantly, and at 12° no peak corresponding to ^{29}S was observed in the spectrum.

The mass determination was made by comparing the rigidity of the ^6He particles leading to ^{29}S to those from the $^{24}\text{Mg}(\tau, ^6\text{He})^{21}\text{Mg}$ [3] and $^{58}\text{Ni}(\tau, ^6\text{He})^{55}\text{Ni}$ [4] reactions. The target thickness of the three targets ^{24}Mg , ^{58}Ni , and CdS was measured with americium α -particles both before and after the experiment. The resulting mass excess for ^{29}S is -3.16 ± 0.05 MeV.

The isobaric multiplet mass equation, with the most accurate values for the mass of the three other members [5], predicts a mass excess of -3.14 ± 0.03 MeV for ^{29}S . Hence the present experiment is consistent with a quadratic T_z dependence. A cubic fit to the four masses of the form $M(T_z) = a + bT_z + cT_z^2 + dT_z^3$ gives $a = -11\,137 \pm 9$, $b = -5\,025 \pm 16$, $c = 200 \pm 13$ and $d = 3 \pm 11$ keV.

The c -coefficient obtained can be compared to a shell model calculation [6] which used the simplest possible configuration for the $5/2^+$ spin and parity found for the ground state of nucleus ^{29}Al . The

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COLLECTIVE CONTRIBUTION TO ESCAPE WIDTH OF ANALOG RESONANCES*

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The collective isovector monopole state decreases escape widths of analog states by 10–20%. Thus spectroscopic factors determined in previous calculations are too small by this amount. The monopole has a much greater influence on the spreading widths; the reason it is less important in the decay width is that the transition density is more external to the nucleus.

The first calculations of the decays of analog states neglected many-body effects, and their successes made it appear that nothing further was needed [e.g. 1]. Later, more detailed calculations showed that in fact predicted spreading widths were much too large [2–4]. By spreading width is meant the excess width of the analog over the sum of the partial widths due to proton decays. It arises from the mixing of the analog with more complicated nuclear states. The problem was resolved by Mekjian who noted that the Coulomb interaction induces spreading mainly via an isovector monopole state [5]. As a result of the collectivity of this state, spreading is much reduced.

The importance of the collective isovector monopole excitation was first stressed by Bohr, Damgaard and Mottelson [6], in the question of corrections to superallowed beta decay. Other physical phenomena which may be influenced by this state include isotope shifts [7] and Coulomb energies [8], although the effect is smaller than ref. [8] indicates [9]. We here treat the effect of the monopole on escape widths of analogs. It will be seen that the monopole collectivity reduces the widths by 10–20%. This is in contrast to the situation with spreading widths, which are reduced by a factor of five or so. The reason for the difference is that the transition density for particle decay is peaked several fm from the nuclear surface, while the monopole transition density and the damping transition density are concentrated at the surface.

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To derive the decay width of analogs, we shall use the following expression for decay amplitude;

$$\gamma = \langle \phi_c | V_c | A \rangle + \frac{\langle \phi_c | V_N | M \rangle \langle M | V_c | A \rangle}{E - E_M - i\Gamma_M/2} \quad (1)$$

In this equation $|A\rangle$ is the analog state, defined with the isospin lowering operator on the parent state $|\pi\rangle$ as $|A\rangle = (T^-/\sqrt{2T})|\pi\rangle$. The state $|M\rangle$ is the isovector monopole of the residual nucleus, with a mean energy E_M and width Γ_M . The interaction V_c is the one-body central Coulomb field, and V_N is the two-body nuclear interaction. Finally, ϕ_c is the continuum wavefunction of the ejected particle plus the residual nucleus. Eq. (1) may be derived as an approximation from the general theory of analog states given in ref. [4]. The relation between the amplitude in eq. (1) and the observed escape width is given in the same reference. The continuum wavefunction ϕ_c may be determined from an optical potential, and should be orthogonal to the single particle orbits in the state $|A\rangle$.

For the calculation we shall need the transition density between the monopole state and the residual nucleus ground state,

$$\delta\rho(r) \equiv \langle M | \tau_z \psi^+(r) \psi(r) | \rangle. \quad (2)$$

We shall also need the transition potential associated with the monopole state,

$$\delta V(r) = \sum_i \langle M | V_N(r - r_i) | \rangle \quad (3)$$

For a short-range interaction and neglecting exchange, δV is proportional to $\delta\rho$. A simple estimate of the ef-

AN ANOMALOUS M1 TRANSITION IN $^{38}\text{Cl}^*$

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The observed enhancement of the M1 transition in ^{38}Cl between the 3^- state of the " $d_{3/2}$ - $p_{3/2}$ multiplet" and the 4^- state of the " $d_{3/2}$ - $f_{7/2}$ multiplet" is explained.

The analysis of the energies of the low-lying states of ^{38}Cl and ^{40}K was one of the early quantitative successes of nuclear shell model theory. [1, 2] If we speak in terms of an ^{16}O core, then the first states of ^{38}Cl should arise in lowest order from the configuration $(\nu d_{5/2})^6, (\pi d_{5/2})^6, (\nu s_{1/2})^2, (\pi s_{1/2})^2, (\nu d_{3/2})^4, (\pi d_{3/2})^4, (\nu f_{7/2})^1, (\pi f_{7/2})^1$, where ν denotes neutrons and π denotes protons. Similarly the lowest states of ^{40}K should arise from the configuration formed by adding two more protons to the $d_{3/2}$ orbit. The $d_{5/2}$ and $s_{1/2}$ orbits are thus always filled, as is the $\nu d_{3/2}$ orbit, and we describe ^{38}Cl in terms of $(\pi d_{3/2}^{-1} - \nu f_{7/2}^1)$ couplings and ^{40}K in terms of $(\pi d_{3/2}^{-1} - \nu f_{7/2}^1)$ couplings.

In the early shell model analyses of this region, these simple configurations were assumed and it was shown that the observed energies of the 2^- , 3^- , 4^- , and 5^- states in ^{40}K can be obtained almost exactly by applying the appropriate particle-hole transformation rule to the energies of the first 2^- , 3^- , 4^- , and 5^- states of ^{38}Cl . The accuracy achieved in this transformation was then, and has been since, taken as confirmation that the wave functions of the states involved did indeed closely resemble the simple initial assumptions. Subsequent measurements [3, 4] have disclosed a higher lying multiplet in each nucleus which can be described in similar fashion as couplings of a $d_{3/2}$ particle (hole) with a $p_{3/2}$ particle, although the transformation of energies is not as accurate as for the lower sets of states.

Recently, however, measurements have revealed

some characteristics of ^{38}Cl states which are difficult to reconcile with the simple description just outlined [5, 6]. Chief among these data is strong M1 transition from the 3^- state of the $(d_{3/2} - p_{3/2})$ multiplet to the 4^- state of the $(d_{3/2} - f_{7/2})$ multiplet. This transition is, of course, l -forbidden to the extent that the wave functions of the states actually follow the description given heretofore. Other data which cast doubt on the purity of these ^{38}Cl states are the spectroscopic factors for (d, p) stripping on ^{37}Cl [7]. These experiments show some admixing of $l = 1$ into the supposed $(d_{3/2} - f_{7/2}) 3^-$ state.

We have calculated energies and wave functions for ^{38}Cl , ^{39}K , and ^{40}K in a model space which includes active $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$ particles, using the codes of French et al. [8]. The two-body matrix elements used in our Hamiltonian were calculated from the Sussex relative oscillator matrix elements [9] with space truncation effects added [10], and the single-particle energies were chosen to yield calculated spectra for ^{38}Cl , ^{39}K , and ^{40}K in simultaneous best agreement with the experimental spectra. The values for $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$ are, respectively, -9.40 , -4.90 , -2.77 , -2.52 , and 0.00 MeV. Some of these results for ^{38}Cl and ^{40}K are summarized in fig. 1 and table 1. The experimental and predicted S -factors for the $^{37}\text{Cl}(d, p)^{38}\text{Cl}$ reaction are presented in table 2.

Our predictions for these observables (our M1 calculations use operators calculated from the bare-nucleon g -factors) are in uniform good agreement with the observed values. In particular, for ^{38}Cl the mixing of the $l = 1$ and $l = 3$ strengths for the 3^- states

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STATES IN ^{163}Ho AND ^{167}Tm POPULATED THROUGH THE (p, t) REACTION ON ^{165}Ho AND ^{169}Tm

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The (p, t) reaction at 30 MeV on the deformed nuclei, ^{165}Ho and ^{169}Tm , strongly populates collective states in the residual nuclei. Indirect multiple-step processes evidently play an important role, and the reaction is a powerful tool for populating higher-lying rotational band members.

Previous work involving the (p, t) reaction on the spherical ^{141}Pr nucleus [1] and the strongly deformed ^{159}Tb nucleus [2] has demonstrated the potential of this reaction as a very powerful tool for probing collective characteristics. In particular, the study of the $^{159}\text{Tb}(p, t)$ reaction revealed large cross sections associated with the population of β - and γ -vibrational and ground-state rotational band members.

In the present study $\approx 400 \mu\text{g}/\text{cm}^2$ metallic targets of the elements were bombarded with 30 MeV protons accelerated by the Michigan State University sector-focused cyclotron. The scattered tritons were analyzed with an Enge split-pole magnetic spectrometer and collected on nuclear emulsions. All spectra were taken at the scattering angle of 20° with an overall energy resolution of ≈ 10 keV FWHM.

A triton spectrum obtained from ^{165}Ho is shown in fig. 1. In this spectrum one finds a strong population of the $K^\pi = \frac{7}{2}^-$ [523] ground-state rotational band with level spacings similar to those occurring in the same band in ^{159}Tb . From Coulomb excitation experiments conducted on ^{165}Ho by Seaman et al. [3], one would expect from systematics to observe the $K^\pi = \frac{3}{2}^-$ and $\frac{11}{2}^-$ γ -vibrational bands at ≈ 500 keV

and ≈ 700 keV, respectively. And indeed one does observe a set of states originating at 562 keV which appear to have some intensity interrelationships. If one assumes that the 562 and 618 keV states are the first two members of the $K = \frac{3}{2}$ γ -vibrational band and that higher members are generated by parameterizing the simple $I(I+1)$ energy relationship, one finds convincing evidence for the presence of additional members up to a spin of $\frac{15}{2}$. However, no evidence for the presence of a $K = \frac{11}{2}$ γ -vibrational band could be found in our spectrum.

As in the case of ^{159}Tb [2], the (p, t) reaction on ^{165}Ho is found to strongly populate rotational as well as vibrational states in the residual nucleus. The present study has identified six members of the $K = \frac{7}{2}$ ground-state rotational band and seven members of the $K = \frac{3}{2}$ γ -vibrational band. Moreover, with the single exception of the 791 keV peak, these states completely exhaust the (p, t) reaction strength occurring below the pairing gap in the ^{163}Ho nucleus. The origin of the strongly excited 791 keV state cannot be determined from our data since it does not appear to have any relationship to any other states in our spectra. Being below the pairing gap, this state certainly must be a collective excitation, but whether it be a β , γ or octupole state is not clear from our data alone.

The triton spectrum from the $^{169}\text{Tm}(p, t)$ reaction appears in fig. 2. As in the previous results, the ground-state rotational band of ^{167}Tm is found to be strongly

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FUTURE CYCLOTRONS*

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ABSTRACT

This paper reviews future trends in cyclotron design, first briefly from the point-of-view of cyclotrons now in construction and second from the point-of-view of design features. The topics covered include the choice of a conventional or separated-sector magnet, the use of dees or cavities for acceleration, possible flat-topping of the rf wave, the impact of new technologies on design and operation, and extensions of the cyclotron concept to higher energies.

INTRODUCTION

From the earliest times humans have derived pleasures from listening to the pronouncements of enlightened prophets regarding what lies ahead. The pleasant sensations are particularly keen and meaningful if the prophet is a person with convincing super-natural power. To be convincing it helps to refer to tangible evidence—tea leaves, lines in the hand, and crystal balls have been widely used. In addition the prophet enjoys an important credibility advantage if his view of the future is pleasant. In this paper I will employ these time-tested techniques. A proper substitute for tea leaves at a cyclotron conference is obviously to study the mystic patterns of orbitry from the great God DigiComptus. And in order to have an optimistic picture of the future I will specifically exclude all references to money, thus clearly leaving only pleasant things to consider. With these stipulations understood, let us go on to a happy hour of dreams.

Thinking of how to look at the future, two different, mutually interesting perspectives occur. One is to look from the point-of-view of projects—machines being built or proposed. The other is to look from the point-of-view of design features—what are likely to be the main features of new cyclotrons, how will they resemble present machines, how will they differ? Many other papers at this conference present material telling us about the future as seen from the project point-of-view; the main emphasis of this paper will therefore be on design features. To begin with though it is useful to take a brief look at projects since many of the things I want to consider in the discussion of design features have their origins in present projects.

PROJECTS IN PROGRESS

Isochronous cyclotrons with proton energy of 100 MeV or greater are listed in Table I. Four of these are nearing completion—one

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DESIGN STUDY FOR A COMPACT 200 MeV CYCLOTRON*

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ABSTRACT

A preliminary study has been carried out for a variable energy, 200 MeV cyclotron which is designed for both nuclear physics and medical research. The operational and structural features of this machine are modeled closely on our present 50 MeV cyclotron. The magnet would have the same gap, but twice the diameter (3m) and twice the number of trim coils (17), and it would have four (instead of three) sectors with sufficient additional spiral. The rf system would operate in the 10-20 MHz range, with two 90° dees carrying up to 70 kV. This cyclotron would produce protons at energies up to 200 MeV, and other ions to corresponding energies. By extending our present phase selection and single turn extraction techniques to this cyclotron, the energy resolution of the extracted beam would be: $E/(\Delta E)=7000$. With proton currents of about 2 μ A, the beam emittances would be 0.3 mm-mrad radially and 2.5 mm-mrad axially. The estimated cost of the cyclotron itself would be around two million dollars.

INTRODUCTION

The MSU 50 MeV cyclotron has been outstandingly successful in producing extracted beams (particularly of protons) having exceptionally fine energy resolution and unusually small emittance.¹ This success has led us to investigate the design of a 200 MeV cyclotron having comparable performance characteristics. This 200 MeV cyclotron would possess the basic structural and operational features of our present machine including the central region geometry, the phase selection slits, and the single turn (resonance) extraction system.

The 200 MeV magnet would have the same magnet gap and the same maximum field strength as our present magnet, and would therefore have about twice the pole diameter (125 in). However, this magnet would have four sectors with sufficient spiral to compensate the additional relativistic defocusing. The magnet therefore resembles that of the Maryland 100 MeV cyclotron.²

The suggested design for the rf system of the 200 MeV cyclotron is closely modeled on the present Maryland and MSU machines. This rf system would operate in the 10-20 MHz range with two dees, about 90° in angular width, allowing for both even and odd harmonic operation. Since these dees would be positioned within the magnet gap, the maximum dee voltage would be restricted to about 70 kV.

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AN OPTIMIZED MULTI-PARTICLE CENTRAL REGION FOR
THE MICHIGAN STATE UNIVERSITY ISOCHRONOUS CYCLOTRON*

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ABSTRACT

Centered orbits are highly desirable in a cyclotron since problems with resonances are minimized and beam stability is greatly improved. The Michigan State University Cyclotron, as originally designed, produces accurately centered orbits in first harmonic operation and performs acceptably on second harmonic. Third harmonic operation, on the other hand, has never been adequate due to very large centering errors. The basic origin of these centering problems is the gap crossing resonance, and the effect of this resonance is highly sensitive to the angular width of the dees. Studies herein show that with a proper selection of both the central region geometry and the dee angle this centering problem can be effectively eliminated. Appropriate configurations have been worked out for harmonics $H=1, 2$, and 3 , using 138° , 90° , and 60° dees respectively, and confirmed in electrolytic tank studies. To implement this new design, a major cyclotron improvement program has been initiated based on a system of interchangeable dees. Basic features of this new design and computational results for the optimized geometries are discussed.

INTRODUCTION

In the Michigan State University Cyclotron, third harmonic operation (rf frequency three times the orbital frequency) is essential for producing the most important heavy ion beams, as well as very low energy protons and deuterons. Third harmonic operation has, however, thus far not been adequate for experimental needs due to large orbit centering errors. In view of this we decided some time ago to restudy and redesign the central region with the objective of improving third harmonic performance.

The advantages of centered orbits in a cyclotron have been widely discussed; problems with resonances are minimized, beam stability is greatly improved, and extraction is easier. The major problem in centering third harmonic orbits is the so-called gap crossing resonance¹ in which the acceleration process drives orbits off center as a result of a resonant interaction between the three sector magnet geometry and the basically two sector electric gap geometry. Moreover, when the orbits are off center, resultant rf phase deviations from gap to gap tend to drive the orbits still further off center. Since this latter effect increases with harmonic number, the centering problem is fundamentally more severe as the harmonic number increases.

* Supported by the U.S. National Science Foundation.

APPLICATION OF A NEW FIELD TRIMMING PROGRAM TO THE MSU CYCLOTRON*

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ABSTRACT

In order to improve the performance of isochronous cyclotrons, a new computer program "Fielder" has been developed which carries out field trimming calculations on a more rational basis. Using an iterated least-square process, this program adjusts the trim coil currents and the rf frequency so as to fit the (central ray) phase-energy curve to a prescribed function, including a given non-zero initial phase value. In addition, the least-square fitting is subjected to constraints which serve to produce "energy stability" as well as "energy focusing" in the extracted beam. This program has been applied to the MSU cyclotron for a wide range of operating conditions, and has invariably produced significant improvements in the resultant phase-energy curves.

INTRODUCTION

Variable energy cyclotrons require an efficient system for determining the multitude of "knob settings" necessary to produce a specific ion beam with a given energy. The MSU cyclotron has operated successfully for a long time with the use of a computer program "Set-op" which provides these knob settings as part of its output.¹

In order to achieve certain operational improvements, it was decided to rewrite the main part of the Set-op program which calculates the trim coil currents and the rf frequency. As a result, we have developed a completely new field trimming program "Fielder" which systematically determines the values of these parameters on a more rational basis.

In this paper we present a brief description of the Fielder program together with some of the results obtained from its application to our 50 MeV cyclotron. This program was also used in the design study for a compact 200 MeV cyclotron which was described in an earlier paper.²

Although the techniques employed in Fielder should be generally useful, this program was specifically designed to fulfill the more demanding requirements of those cyclotrons which operate under a separated turn regime. A copy of this program (Fortran listing), together with a more complete description, can be obtained by writing to the authors.

*Supported by the U.S. National Science Foundation.

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OPTIMIZED USE OF A CYCLOTRON FOR
HIGH RESOLUTION STUDIES OF NUCLEI*E. Kashy, H.G. Blosser, and D.A. Johnson
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ABSTRACT

The effectiveness of an accelerator in nuclear physics research hinges heavily on the energy resolution which can be obtained in actual experiments. Contributions to the resolution from the energy spread and incoherent phase space distribution of the beam, the kinematic effects in the nuclear reaction proper, the energy loss in the target, and the aberrations, must all be included. Optimization for one or the other of these factors is in some cases at the expense of a broadening in other contributions and a compromise point is actually the choice for minimum line width. A manually adjusted optimization system has been in use for some time in our laboratory and has given momentum resolutions of 1 in 20,000 in a variety of test situations and of 1 in 10,000 on a rather regular basis in extended runs. A second generation optimization system is being developed which will make more extensive use of the computer both for calculating best values and for on-line control of system elements.

INTRODUCTION

Particle beams are an essential tool in the study of nuclear phenomena. Practically all of the information on nuclear systems is obtained from measurements of the scattering of particles by nuclei and the emission of ensuing electromagnetic radiation. Nuclei exist in "energy states" which live for varying times and whose properties are generally widely different. Thus our ability to extract the information required for a better understanding of nuclei is intimately tied to our ability to resolve various nuclear states.

When investigating nuclear properties with charged particle beams, we recognize two distinctly different situations in high resolution studies. In the first, the nuclear states of interest belong to the compound system formed by the merging of the incident projectile and the target nucleus. Such processes give highly excited states for the given system of nucleons, and it is the total energy spread in the beam at the target which controls the resolution. Electrostatic accelerators are best suited in such instances, but excellent results can be obtained with cyclotrons by selecting a fraction of the total beam with the required energy spread.¹ At MSU, for example, we have done experiments of this type with a resolution of 1 keV in beams with energies of 5 MeV.

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Nuclear Data Sheets for A = 101

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Abstract: The 1961 version of the Nuclear Data Sheets for A = 101 has been revised on the basis of experimental data published prior to September 1, 1972. The present evaluation contains information obtained from approximately 70 papers.

There are currently nine nuclei known for A = 101. Only the presumed ground states and half-lives have been determined for ^{101}Zr and ^{101}Cd . Decay-scheme studies of ^{101}Zr and ^{101}Cd have established two levels in ^{101}Nb and ^{101}Ag , respectively.

The identification of levels in ^{101}Mo and some subsequent spin and parity assignments depend primarily on recent sub-Coulomb stripping results. The identification of levels in ^{101}Mo fed by the β -decay of ^{101}Nb is somewhat uncertain at this time. Nine levels in ^{101}Pd have been identified from the β -decay study of ^{101}Ag , but the data are not sufficient to assign spins and parities. e/β^+ -decay studies of ^{101}Pd have established approximately 19 levels in ^{101}Rh and have resulted in some tentative spin and parity assignments.

During the course of the compilation, the results of 72Co16 and 72Co17 concerning the β -decay of ^{101}Mo were communicated to the compilers. This study resulted in the identification of 152 transitions and the placement of approximately 45 levels in ^{101}Tc . In addition, conversion-electron work resulted in the identification of previously unobserved levels in ^{101}Tc at 0.009317 and 0.015601 MeV, requiring a reassignment of level energies in ^{101}Tc . The stable nucleus ^{101}Ru has been studied via β -decay, γ -decay, and Coulomb excitation. As a result, a number of spin assignments for low-lying states are firm.

Some additional gaps and uncertainties remain in the data. The relative intensities of transitions depopulating the same levels in ^{101}Ru as observed in β -decay, Coulomb-excitation, and γ -decay studies do not agree in some cases. Reaction studies would help to confirm the spins of low-lying states in ^{101}Tc and ^{101}Rh and provide additional information on higher spin states in ^{101}Mo . The existing data on levels in ^{101}Pd populated by the β -decay of ^{101}Ag were obtained in early work with semi-conductor detectors and are probably incomplete at this time.

Acknowledgments: The compilers wish to thank W. B. Cook, M. W. Johns, J. S. Geiger, and R. L. Graham for making data available to them prior to publication. They also thank D. J. Horen, R. L. Auble, and R. A. Warner for many helpful comments, discussions, and suggestions. And we are especially grateful to Mrs. Mamar Blosser for her precise drafting of the figures.

†Nuclear Information Research Associate. Work supported by the National Science Foundation through the National Academy of Sciences - National Research Council, Committee on Nuclear Science

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††Alfred P. Sloan Fellow, 1972-1974

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ISOSPIN IMPURITIES IN NUCLEI

5522

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1. INTRODUCTION

The isospin quantum number, introduced to nuclear physics by Heisenberg in 1932, was applied by Wigner (1) in 1937 to describe the symmetry of the nuclear wavefunction with respect to the exchange of neutrons with protons. The operator T_3 is defined as having a value of $+1/2$ for neutrons and $-1/2$ for

¹ Guest of the Weizmann Institute while most of this review was prepared.

The Numerical Accuracy of ^3He Optical-Model Calculations at 70 MeV*R. R. DOERING,[†] A. I. GALONSKY, AND R. A. HINRICHS[‡]*Cyclotron Laboratory, Department of Physics,
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Received November 8, 1972

Small differential cross sections, such as those measured at back angles for 70 MeV ^3He elastic scattering (typically below 10^{-4} mb/sr past 130°), are difficult to calculate accurately when they result from considerable cancellation in the partial-wave sum. The codes GENOA, GIBELUMP, SNOOPY3, and DWUCK differ by as much as $2\frac{1}{2}$ orders of magnitude on $\sigma(\theta)$ for an optical-model potential describing $^{60}\text{Ni}(^3\text{He}, ^3\text{He})^{60}\text{Ni}$ scattering at 71 MeV. This calculation is repeated, with a modified version of GIBELUMP, for wide ranges of the parameters affecting numerical accuracy. A study of errors in scattering matrix elements and cross sections, as functions of these parameters, reveals that criteria commonly used to determine the matching radius and number of partial waves employed in optical-model calculations yield insufficient values in this case.

1. INTRODUCTION

There is increasing evidence that the well known ambiguities in optical-model potentials for complex projectiles may be at least partially resolved through analyses including large angle elastic scattering data [1-5], especially at relatively high bombarding energies. In particular, S. M. Smith and D. A. Goldberg [1] have noted a sensitivity of back-angle deuteron, helion, and alpha-particle elastic scattering to real well depth at incident energies above 60 MeV. The characteristic feature of such data is a monotonic fall (with increasing angle) beyond the diffraction region. Such behavior is illustrated in Fig. 1, which presents 70 MeV ^3He elastic angular distributions, taken from targets of ^{50}Ti and ^{51}V with the MSU Sector-Focused Cyclotron [2]. Similar data have been obtained by C. B. Fulmer and J. C. Hafele. They also stress the importance of the small, back-angle cross sections for suppressing ambiguities in the ^3He optical-model parameters [3].

Unfortunately, we find that unusual care is required for the accurate calculation of such small cross sections, since they result from a great deal of cancellation

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DOUBLE GAMMA DECAY IN LIGHT NUCLEI

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(Received September 5, 1972)

The $0^+ \rightarrow 0^+$ double gamma decay is calculated for the nuclei C^{12} , O^{16} , Ca^{40} , Ge^{72} and Zr^{90} , using a model of the states with spherical and deformed components. Due to the similarity in the structure of the components, double gamma decay is always greatly hindered. However, for O^{16} , the calculated transition matrix is too large by at least a factor of 3; in Ca^{40} there is agreement with a recently reported measurement.

INTRODUCTION

A recent measurement of double gamma decay [1] in the transition $Ca^{40}(0_2^+ \rightarrow 0_1^+)$ makes a review of the theory of nuclear double gamma decay worthwhile. In the previous theoretical literature [2-6], estimates of transition rates are either highly inaccurate or otherwise unreliable. An improved estimate is derived below, making use of the energy-weighted dipole sum rule.

The $0^+ \rightarrow 0^+$ transitions between low-lying levels are interesting because there is still much uncertainty about the structure of excited 0^+ states. The decay normally proceeds by pair production or by internal conversion, which depend on the transition matrix element

$$M_{EO} = \sum_p r_p^2 \quad (1)$$

This matrix element is of the order of a few fm^2 which is what one would expect from a single-particle transition. Double gamma decay is proportional to the second order $E1$ matrix element,

$$M_{2\gamma} = \sum_{p,p',i} z_p \frac{\langle i | \sum_j r_j | i \rangle}{E_i - E_0} z_{p'} \quad (2)$$

SECTION IV
ABSTRACTS OF PAPERS IN PRESS
(after June 30, 1973)

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ABSTRACT

A fast numerical method for calculating nuclear excitation properties with δ -type interactions is described. The method is applied to Pb^{208} , and we find properties of the nucleus as: (i) the quadrupole strength has two main pieces, one a low state and one identifiable as the giant quadrupole; (ii) excitations with $L > 2$ do not seem to have high-energy collective parts; (iii) the giant dipole $L=1$ $T=1$ is too low unless the interaction has a strong momentum dependence.

[†]Supported in part by the National Science Foundation.

ISOSPIN MIXING FROM THE EFFECTIVE
NUCLEON INTERACTION*

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ABSTRACT

Effective interactions determined from closed-shell-plus-two-particle spectra have a charge dependence which predicts isospin mixing for more complicated nuclei. We infer the isospin mixing in $A=44$, 46, 48 and 52 on the basis of the observed $A=42$ spectra. Agreement is reasonable in 4 out of 6 cases; the best example is ^{44}Sc , where we verify that the n - p effective residual interaction is stronger than the n - n interaction. We also compare predictions for $A=20$ l , from the charge dependence seen in the $A=18$ spectrum.

[†]Supported by the National Science Foundation.

Isobaric Mass Quartets in the Mass-21
and Mass-37 Nuclei*

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ABSTRACT

The $^{40}Ca(^3He, ^6He)^{37}Ca$ reaction has been used to measure the mass of ^{37}Ca in its ground and first excited states. The mass of ^{37}Ar and ^{37}K in their lowest $T=3/2$ states were also measured. The $^{24}Mg(^3He, ^6He)^{21}Mg$ reaction was used as a calibration, and consequently the energies of several excited states of ^{21}Mg were measured. The mass-37 measurements give new precision values for the coefficients of the isobaric multiplet mass equation, and the excited states in ^{21}Mg are members of quartets in the mass-21 nuclei.

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A High Resolution Study of $^{48}Ca(p,t)^{46}Ca$ at $E_p=39$ MeV*

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ABSTRACT

The ^{46}Ca nucleus was studied using the (p,t) reaction. A number of spin-parity assignments are clarified for the low-lying states. Many new energy levels are reported up to an excitation energy of 6.3 MeV including an additional 0^+ state at 4.76 MeV. Distorted wave calculations with f - p shell wave functions give reasonable agreement for the first 0^+ , 2^+ , 4^+ , and 6^+ states and for two weak 0^+ states near 5.5 MeV which were strongly excited in the $^{44}Ca(t,p)$ reaction.

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A Determination of the Mass and Some

Energy Levels of the Nuclide ^{44}Ar *

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ABSTRACT

The mass and some energy levels of the nuclide ^{44}Ar have been determined from the $^{48}\text{Ca}(^3\text{He}, ^7\text{Be})^{44}\text{Ar}$ reaction.

The lifetime of the nucleus ^{44}Ar has been reported [1,2] but until now its mass and energy levels were unknown. This letter reports the mass of ^{44}Ar and the excitation energies of several of its excited states as determined from the $^{48}\text{Ca}(^3\text{He}, ^7\text{Be})^{44}\text{Ar}$ reaction at 70 MeV ^3He bombarding energy.

The ^3He beam was produced by the MSU variable energy sector focused cyclotron. The reaction products were analyzed by an Enge split-pole magnetic spectrograph [3]. Detection of ions in the focal plane of the spectrometer was accomplished by means of a system composed of a plastic scintillator photo-multiplier unit behind a 25 cm single wire charge division gas

*Work supported by the National Science Foundation.

Excitation of Giant Resonances by Inelastic
 ^3He Scattering*

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ABSTRACT

Inelastic ^3He scattering at 71 MeV on 12 nuclei ranging from ^{27}Al to ^{209}Bi shows an enhancement of the continuum very similar to that observed in electron and proton scattering. The effect is ascribed to a giant multipole state. The strength of the excitation indicates an E2 character for the state.

*Supported by the National Science Foundation.

35 MeV Proton Inelastic Scattering from Low-Lying
States in ^{207}Pb *

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ABSTRACT

Differential cross sections for the excitation of the first four excited states in ^{207}Pb via the inelastic scattering of 35 MeV protons have been compared with microscopic model predictions. Contributions from non-central forces are important in a valence orbital model and the effects of exchange and core polarization have been investigated. Addition of an imaginary part to the microscopic form factor was also investigated and gave the best predictions of observed transition strengths.

*Supported in part by the National Science Foundation.

Measuring Nuclear Excitation Energies and Q-Values
With a Cyclotron-Magnetic Spectrograph System.*

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ABSTRACT

Nuclear excitation energies and reaction Q-values have been measured with the M.S.U. cyclotron-magnetic spectrograph system with uncertainties on the order of 1 keV or less. The method involves a spectrograph calibration procedure which utilizes a combination of momentum-matching and kinematics techniques. The calibration lines used in the present work are independent of any previous spectrograph based on the $^{210}\text{Po}(\alpha)$ energy scale. The present work is also largely independent of Ge(Li) gamma detector measurements, and provides independent consistency checks on previous measurements at the 1 keV uncertainty level. Sample results include checks on the excitation energies of the first excited state of ^{12}C and the third excited state of ^{24}Mg . The excitation energy of the first excited state of ^{11}C and the Q-values for the reactions $^{24}\text{Mg}(p,d)^{23}\text{Mg}$ and $^{24}\text{Mg}(p,t)^{22}\text{Mg}$ are also presented.

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at 70 MeV^a

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ABSTRACT

Small differential cross sections, such as those measured at back angles for 70 MeV ³He elastic scattering (typically below 10⁻⁴ mb/sr past 130°), are difficult to calculate accurately when they result from considerable cancellation in the partial-wave sum. The codes GENOA, GIBELUMP, SNOOPY3, and DWUCK differ by as much as 2-1/2 orders of magnitude on $\sigma(\theta)$ for an optical-model potential describing ⁶⁰Ni(³He,³He)⁶⁰Ni scattering at 71 MeV. This calculation is repeated with a modified version of GIBELUMP for wide ranges of the parameters affecting numerical accuracy. A study of errors in scattering matrix elements and cross sections, as functions of these parameters, reveals that criteria commonly used to determine the matching radius and number of partial waves employed in optical-model calculations yield insufficient values in this case.

^a Research supported by the National Science Foundation.
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Mass of ³¹S^a

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ABSTRACT

A high-resolution study of the ³²S(p,d)³¹S reaction shows a discrepancy with the current table of mass values. The ³²S(p,d)³¹S reaction Q-value is found to be -12817.8[±]1.5 keV, 45.6 keV more positive than the published value, which carried an 11-keV uncertainty. Similar studies of the (p,d) reaction on ²³Na, ²⁷Al, ³³S, ³⁴S, ³⁵Cl, and ³⁷Cl indicate no discrepancies with the Q-values (of 1 to 2 keV accuracy) tabulated for these nuclei. Possible sources for the sulfur discrepancy are discussed.

NUCLEAR REACTIONS ²³Na, ²⁷Al, ^{32,33,34}S, ^{35,37}Cl(p,d),
E=35 MeV, measured Q, deduced new value for the mass of ³¹S.

^a Supported in part by the U.S. National Science Foundation.

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ABSTRACT

Shell-model calculations for the A=24, T=2 system are presented which use an empirically modified version of Kuo's realistic two-body interaction and a large, but truncated, sd-shell basis space. Using the same two-body matrix elements, single-particle energies and effective charges that were found to be successful in the full sd space for A=19-22, good agreement with experimental measurements is obtained for ²⁴Ne levels and other members of the A=24, T=2 system. Some predictions are made for the unreported isotope ²⁴Si.

^a Work supported by the National Science Foundation.

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FAST AQUEOUS CHEMISTRY ON-LINE WITH CYCLOTRON-PRODUCED ACTIVITIES

USING A HELIUM-JET RECOIL-TRANSPORT SYSTEM

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Abstract:

A relatively simple system is described that can be used to perform fast on-line chemical separations (sl sec) on activities transported to low background areas in the relatively short times provided by a helium-jet recoil-transport system. The helium-jet recoil-transport system is run with its low-pressure end at atmospheric pressure, thereby eliminating the need for vacuum pumps and their associated apparatus.

ENERGY LEVELS IN ^{142}Nd

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Abstract: The excited states of ^{142}Nd were studied by means of the decay of 40 sec ^{142}Pm and the $^{142}\text{Nd}(p,p')$ reaction via isobaric analog resonances. Approximately sixty levels of ^{142}Nd were observed below 5.3 MeV excitation, including several neutron particle-hole states excited strongly in (p,p')

*Research jointly sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation and by the National Research Council of Canada and the U.S. National Science Foundation. Preliminary results were reported previously³⁶.

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An Experimental Demonstration of Backbending

from a Band-Crossing in ^{154}Gd *

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ABSTRACT

The members of the ground- and β -bands in ^{154}Gd have been identified to spin 18. Plots of $2J/\hbar^2$ vs ω^2 yield backbending curves for both the β - and yrast states. It is shown that the backbending in the yrast sequence results from a band-crossing and it is speculated that the twin backbending may arise from the intersection of the ground- and β -bands by a third "intersecting band."

* Work supported by the U. S. Atomic Energy Commission and the U. S. National Science Foundation.

The $^{207}\text{Pb}(p,d)^{206}\text{Pb}$ Reaction and Some
Matrix Elements of the Effective Interaction.*

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ABSTRACT

The cross-sections for the $^{207}\text{Pb}(p,d)^{206}\text{Pb}$ reaction have been measured relative to the cross-sections for the $^{208}\text{Pb}(p,d)^{207}\text{Pb}$ reaction to the single neutron hole states in ^{207}Pb . The reactions were studied with 35 MeV protons and a final deuteron resolution of 5 keV (FWHM). By making the same assumptions as are usually made in model calculations of ^{206}Pb , the matrix elements of the effective interaction of a $p_{1/2}$ neutron with neutrons in other orbits are derived from the experimental results.

*Work supported by the National Science Foundation.

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LBL-1626

ELECTRON AND PROTON INELASTIC SCATTERING FROM ^{40}Ca , ^{120}Sn , AND ^{208}Pb [†]

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January 1973

Abstract

Theoretical (e,e') form factors and (p,p') differential cross sections for the first 3^- and 5^- excitation in ^{40}Ca , the first 3^- excitation in ^{208}Pb , and the first 2^+ and 3^- excitations in ^{120}Sn are presented and compared with experiment. Results are also presented which test the hypothesis that the proton and neutron transition densities for these transitions are related by the condition $\rho_n = (N/Z)\rho_p$. A simple modified Born approximation has been used in the electron scattering calculations. The long range part of the Kallio-Kolltveit potential has been used for the projectile-target interaction in the proton scattering calculations and "knock-on" exchange contributions have been included approximately.

[†]Supported in part by U. S. Atomic Energy Commission and NSF.

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ABSTRACT

Particle-hole multiplets in ^{208}Bi corresponding to the coupling of the $h_{9/2}$ proton with neutron-holes in the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, $i_{13/2}$, $f_{7/2}$, and $h_{9/2}$ shells have been observed by the $^{209}\text{Bi}(p,d)^{208}\text{Bi}$ reaction at 35 MeV with an overall resolution of 5 keV in the deuteron spectra. The results generally show excellent agreement with the weak coupling model except for the $h_{9/2}$ hole states. However the observed $h_{9/2}$ multiplet states do contain a large fraction of the strength. There is also substantial agreement with earlier (d,t) work except for some spin assignments and in the location of the 2^- member of the $h_{9/2}v^{-1}i_{13/2}$ multiplet.

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LBL-1693

CONFIGURATION MIXING OF TWO-QUASI-PARTICLE
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ABSTRACT

Evidence of configuration mixing of higher K bands in deformed even nuclei is surveyed. A general formulation for configuration mixing due to a two-body neutron-proton force is developed. A fit to the energy-splittings of Gallagher-Moszkowski pairs in odd-odd nuclei is made to obtain an effective central force except for the undetermined Wigner component. With force, off-diagonal band-mixing matrix elements are calculated for various configurations in ^{176}Hf , ^{178}Hf , and ^{174}Yb . By solving BCS equations, the relevant occupation amplitudes are calculated. The effective n-p Wigner force component is fixed to give best over-all agreement to experimental band-mixing information. The resulting force is compared with the Amaratunga-Schiff force for spherical nuclei.

Inelastic Proton Scattering from ^{138}Ba and ^{144}Sm at 30 MeV*

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ABSTRACT

Measurements of the inelastic scattering of 30 MeV protons from ^{138}Ba and ^{144}Sm have been carried out with better than 10 keV energy resolution. Differential cross sections were measured for levels up through 3.4 MeV excitation energy. Spin and parity assignments are suggested for most of these states on the basis of angular distributions distinctly characteristic of angular momentum transfer $L=2,3,4$, or 6.

*Research supported by the National Science Foundation.

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Abstract:

The yrast levels have been determined to spin 16 or 18 in $^{182,184,186}\text{Os}$ and to spin 12 in ^{188}Os from γ -ray excitation functions, anisotropies, and coincidence data from $^{182,184,186}\text{W}(\alpha,4n)$ and $^{186}\text{W}(\alpha,2n)$ reactions. A fork is observed in the ^{186}Os yrast band at spin 12. Above spin 12 the J vs. ω^2 curves for $^{182,184,186}\text{Os}$ display "backbending" behavior. Such behavior has not been reported for any other nuclei with more than 96 neutrons.

* Work supported in part by the U. S. Atomic Energy Commission and
in part by the U. S. National Science Foundation.

SHELL-MODEL CALCULATIONS FOR $A=6-14$
NUCLEI WITH A REALISTIC INTERACTION

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ABSTRACT

Shell model calculations are performed on the normal parity states of $0p$ shell nuclei with $A=6-14$. The Hamiltonian is diagonalized in the full $0p$ basis, and the effective two-body interaction is computed from the Sussex relative harmonic oscillator matrix elements. The second-order corrections to the two-body matrix elements are calculated for all intermediate states up to $2M\omega$ excitation energy. The harmonic oscillator size parameter is taken to be constant at 1.7 fm for all nuclei, and the $p_{3/2} - p_{1/2}$ single particle energy splitting is determined for each mass number by a least-squares rms fitting to the experimental spectrum. Static and dynamic properties of the energy levels are calculated and found to be usually in good agreement with experiment.

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Abstract

Astrophysically interesting cross sections for the production of isotopes of lithium, beryllium and boron in the proton-induced spallation of ^{14}N were measured for proton energies between 17 and 42 MeV. A time-of-flight method was used for mass identification, supplemented at one energy by radioactivity analysis. Gas targets were used throughout. The astrophysical significance of the results is discussed.

* Research supported in part by the National Science Foundation.

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* Part of this work was performed while the authors were NAS-NRC Research Associates at the Aerospace Research Laboratories of Wright Patterson AFB, Ohio 45433.

SECTION V

PH.D. THESIS TITLES

(July 1972-June 1973)

V. Ph.D. Thesis Titles (July 1972-June 1973)

Department of Physics

Amos, Thomas Marshall, Jr.	Neutron Yields from Proton Bombardment of Thick Targets
Fox, Stanley Haim	$^{14}\text{N}(p,p')$ at 29.8, 36.6, and 40.0 MeV and the Strength of the Tensor Force in Nuclear Reactions
Larson, Duane Clark	Inelastic Proton Scattering from ^{138}Ba and ^{144}Sm and its Microscopic Interpretation
Panggabean, Lolo Marangkup	Proton Induced Spallation of ^{20}Ne and the Astrophysical Production of the Lithium Isotopes
Proctor, Ivan Dwight	A Study of ^{17}O and ^{17}F Through Charged Particle Reactions
Rice, James Allen	A Study of Several Odd-Odd s-d Shell Nuclei Via the (p,d) Reaction at 35 MeV
Samuelson, Lawrence Edward	Properties of Gamma-Ray Transitions in ^{56}Co from ^{56}Ni Decay and $^{56}\text{Fe}(p,n\gamma)^{56}\text{Co}$
Trilling, Richard	Simple Excitations of Doubly Closed Shell Nuclei